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A New Calculation Method for Multi-unit Cascade Accidents

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1. Introduction

Due to the Fukushima nuclear accident in Japan in March 2011, radioactive materials were released from multiple units. Since then, there has been an increased awareness of the need to protect people's lives from radioactive materials released into the environment in the event of a serious accident that exceeds design standards. As a result, various studies related to Multi-Unit Probabilistic Safety Assessment (MUPSA) for two or more nuclear power plant units located on the same site are being conducted domestically and abroad [1-11]. Additionally, studies related to time-dependent Probabilistic Safety Assessment (PSA) of nuclear accidents are also being conducted [12-13].

Currently, there are more than six nuclear power plant units operating closely together on one site in Korea, with densely populated areas located near the site. As a result, the Level 3 MUPSA method for evaluating the effects of radioactive materials released during multi-unit nuclear power plant accidents on residents and the environment has become an increasingly important issue.

Although studies and methodologies for the Level 3 Single Unit Probabilistic Safety Assessment (SUPSA) method have been developed, applying this method to multi-unit results in overestimated or underestimated results and unrealistic limitations. The existing code or method has been developed for single units and does not account for the spatial and temporal differences that exist in multi-unit accidents. For instance, overestimation can occur when calculations assume that nuclear power units located in different spatial locations are located in the same location, or when accidents occur at different times. Therefore, there is a need to develop a new Level 3 MUPSA method that accounts for these factors in multi-unit accidents.

The Level 3 MUPSA that uses the Gaussian plume model assumes that all nuclear power plant units on a site are located at the same position. As a result, when radioactive materials are released into the environment and spread, the radionuclide concentration and exposure dose are overestimated at the centerline of the Gaussian plume, and underestimated at distances from the centerline, leading to unrealistic results. To address these issues, previous studies [14-17] used the radionuclide concentration summation method with each unit in its original position to calculate the radionuclide concentration more realistically.

Additionally, accidents may not occur simultaneously in every unit, even if the cause is the same at a nuclear power plant. Furthermore, the time at which radioactive materials are released can vary. However, the current Level 3 PSA uses the time-integrated radionuclide concentrations and total exposure doses during the emergency response period. This method assumes that multiple nuclear accidents occurred simultaneously since the result is an integration with respect to time. However, in reality, the release of radioactive materials in a multi-unit accident is likely to occur with a time lag. Therefore, the time-integrated result may overestimate the risk. To respond appropriately in the early phase of an accident, it is necessary to apply a cascade accident calculation that determines the concentrations and exposure doses of radioactive materials over time.

2. Existing MUPSA methods and issues

2.1 Current MUPSA methods and issues

MACCS [18-20] and RASCAL [21-22] are two representative codes used for calculating major nuclear accidents [23]. However, the Level 3 PSA codes that use the Gaussian plume model assume that all units are in the same location in multi-unit calculations and sum the source terms. In the case of MACCS, the MACCS input is generated by combining the source terms of each unit from the Level 2 PSA result [24-25]. RASCAL provides a 'Source Term Merge' function as a code utility [21]. However, this method can result in an overestimation of the radionuclide concentration at the centerline of the Gaussian plume and an underestimation at distances from the centerline.

The Level 3 PSA codes, MACCS and RCAP [26], use the Gaussian plume model to calculate the time-integrated air concentration of radionuclide and the maximum ground concentration without considering changes over time. Additionally, the risk is calculated based on the total exposure dose during a given exposure time. However, since time is not considered, a low dose received over a long period of time and a high dose received at once are calculated as the same level of risk. In the case of a multi-unit cascade accident, the time difference is not considered, and the risk is calculated as if all units released radionuclides at the same time. This can result in an overestimation of risk and the need for new methods that consider the timing of releases from each unit in a multi-unit accident.

2.2 Existing MUPSA method [14-17]

Fig. 1 illustrates the method used in MURCC [14-17] for calculating the radionuclide concentration in a multi-unit nuclear power plant accident. In such accidents, the release point of radioactive materials for each unit is different, resulting in a different origin of the Gaussian plume for each unit. To evaluate the off-site effect of a multi-unit accident, the radionuclide concentration for each Gaussian plume should be added.

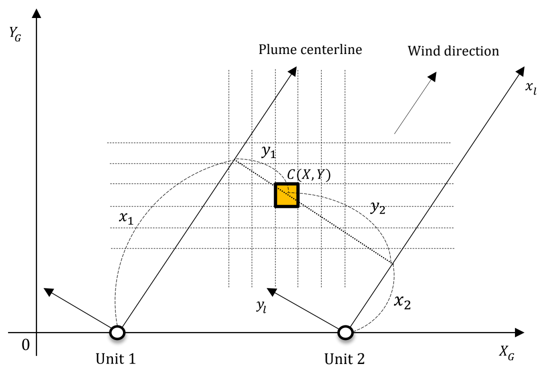

Fig. 1. Radionuclide concentration calculation at *(X,Y)* [15].

The multi-location method uses one global coordinate system and a local coordinate system corresponding to each unit. In Fig. 1, each unit has a local coordinate system with the unit as the origin, and each unit is located at one position in the global coordinate system. After calculating the radionuclide concentration for each corresponding unit in its local coordinate system, the radionuclide concentration of all units in the same global coordinate system are added.

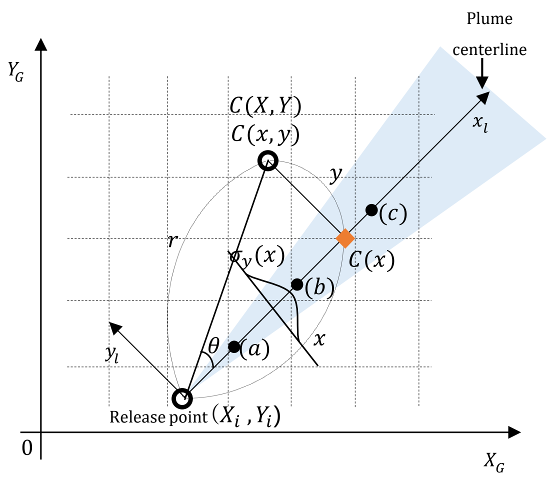

Fig. 2. Global and local coordinate systems [15].

In Fig. 2, the receptor's location is represented by global coordinates (*X*,*Y*), which are converted to local coordinates (*x*,*y*). The centerline of the Gaussian plume corresponds to the x-axis of the local coordinate system, and specific locations where MACCS values are output are labeled as points (a), (b), and (c).

To calculate the coordinate values of the local coordinate system, we need to determine the distance r from the release point (the origin of the local coordinate system) to the receptor's location and the angle theta formed between the x-axis and the line connecting the release point and the receptor. Then, the local coordinate values can be calculated using trigonometric functions.

The MACCS code calculates information about the centerline of the Gaussian plume. To obtain the radionuclide concentration at any arbitrary location, a relational expression using the resulting value must be established. The Gaussian plume formula used in MACCS is as follows.

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

where, χ is time-integrated air concentration [$\mathrm{Bq} \cdot \mathrm{sec}/m^3$], Q is radionuclide release amount [Bq], σ_y , σ_z are horizontal and vertical dispersion coefficients [m], *H* is release height [m], *u* is wind speed [m/s].

The MACCS calculation result provides several types of Gaussian plume information, such as the time-integrated ground-level air radionuclide concentration for the centerline of the plume, the maximum ground radionuclide concentration deposited on the ground surface, and the horizontal and vertical atmospheric dispersion coefficients. Eq. (1) can be used to calculate the concentration of radionuclide at the centerline of the Gaussian plume at ground level, as expressed in Eq. (2).

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

Additionally, to apply the multi-unit multi-location method, the airborne radionuclide concentration must be calculated at a specific location on the ground level. Eq. (3) can be used to calculate the airborne radionuclide concentration at ground level.

$$\chi(x,y,0) = \frac{Q}{\pi\sigma_y\sigma_z\bar{u}} exp\left(-\frac{y^2}{2\sigma_y^2}\right) exp\left(-\frac{H^2}{2\sigma_z^2}\right) \quad (3)$$

In order to calculate the radionuclide concentration in the air at ground level from the MACCS results, the following relational expression can be obtained from Eqs. (2) and (3).

$$\chi(x,y,0) = \chi(x,0,0) exp\left(-\frac{y^2}{2\sigma_y^2}\right) \quad (4)$$

Since the Gaussian plume is assumed to have a normal distribution, the radionuclide concentration at the centerline of the Gaussian plume is multiplied by the term corresponding to the normal distribution in the y direction, as shown in Eq. (4), to obtain the radionuclide concentration at an arbitrary location at the surface height. At this time, the radionuclide concentration and atmospheric dispersion coefficient for an arbitrary position x of the centerline of the Gaussian plume are calculated using the interpolation method from the MACCS results.

3. New calculation method for multi-unit cascade accidents

3.1 Necessity of new calculation method

Fig. 3 shows a schematic diagram showing the positions of the units and the locations of the receptors to illustrate the multi-unit cascade accident. Radioactive material is released with a time difference between Unit 1 and Unit 2, travels in the direction of the wind, and passes through Receptor 1 and Receptor 2.

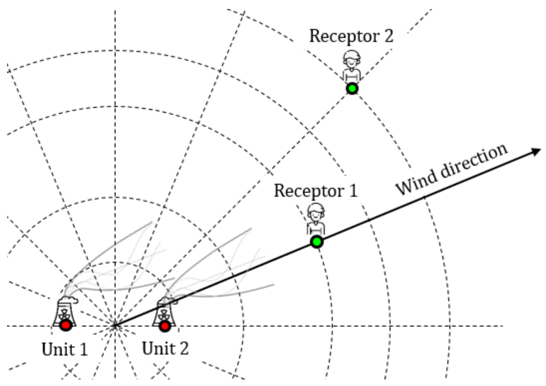

Fig. 3. NPP unit positions and receptor locations.

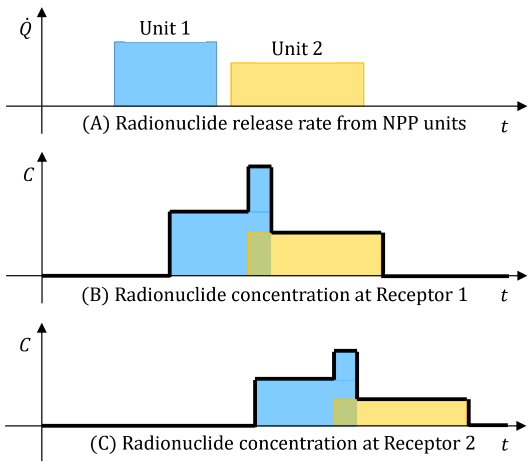

Fig. 4. Radionuclide release rate and air concentration.

Fig. 4 consists of three graphs. Graph (A) shows the release of radioactive material over time for each unit, with blue and yellow representing the total released amount. Graphs (B) and (C) display the radionuclide concentration over time at receptor locations 1 and 2, respectively. The maximum concentration occurs when the two Gaussian plumes overlap at the receptor location. However, the time-integrated concentration is the same regardless of the time at which the radioactive material is released from the two units, and it can be calculated as the area under the concentration-time curve.

In multi-unit cascade accidents, the concentration of radioactive materials at the receptor location changes over time, and the resulting exposure dose also varies accordingly. The use of time-integrated radionuclide concentration and total exposure dose assumes that all units release radioactive materials at the same time, which gives the same result as multi-unit simultaneous accidents. In reality, however, the release of radioactive materials from each unit in a cascade accident is likely to occur with a time lag. As a result, the time-integrated result may overestimate the risk. To calculate multi-unit cascade accidents accurately, it is necessary to estimate the release rate of radioactive materials over time for each unit and calculate the radionuclide concentration and exposure dose over time at each receptor location. Furthermore, applying the cascade accident, which calculates the exposure dose over time instead of the total exposure dose, is essential for calculating the accurate risk.

3.2 New calculation method

MACCS calculates the time-integrated air concentration of radionuclide at the centerline of the Gaussian plume and at ground level, as well as the maximum ground radionuclide concentration. It also calculates the total exposure dose for each organ of the body based on the exposure pathway. However, since MACCS only performs single-unit calculations, in order to calculate multi-unit multi-location or multi-unit cascade accidents, it is necessary to perform additional calculations using the obtained results from MACCS.

Multi-unit multi-location calculation uses the existing method in Section 2.2. To calculate the multi-unit cascade accident, as shown in the graphs (B) and (C) of Fig. 4, the effects of each unit can be summed up at the location of the receptor. Therefore, it is necessary to calculate the nuclide concentration and exposure dose for each time interval for each unit.

To apply MACCS results to multi-unit cascade accidents, it is necessary to obtain the radionuclide concentration over time from the time-integrated radionuclide concentration (χ) calculated by MACCS. Here, the MACCS input includes the total release amount (Q), release time (t_{dur}), and release delay time (t_{delay}).

For the convenience of calculation, we assume that the release rate ($\dot{Q}$) is constant and the wind speed (u) is also constant. The release rate graph is shown in Fig. 5, and the graph of radionuclide concentration in the air over time at the receptor location (*x*,*y*) is shown in Fig. 6.

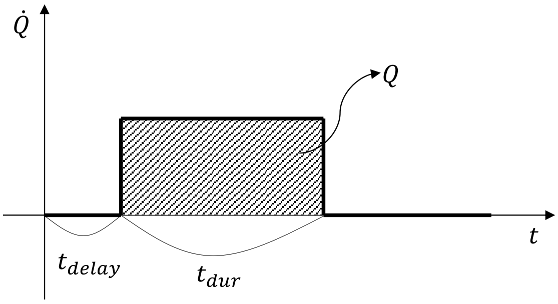

Fig. 5. Radionuclide release rate.

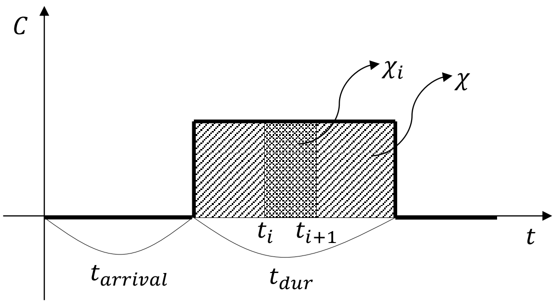

Fig. 6. Air radionuclide concentration at receptor

The arrival time of the Gaussian plume at the receptor location is given by Eq. (5) in Fig. 6. At this time, the duration it takes for the plume to pass through the receptor is the same as the release time of the radioactive material, regardless of the wind speed.

$$t_{arrival} = t_{delay} + x/u \tag{5}$$

Furthermore, based on Eq. (1), as the radionuclide concentration and the release amount are proportional, the time-integrated air radionuclide concentration (χ_i) from the time interval t_i to t_{i+1} in Fig. 6 can be expressed as follows.

$$\chi_i = \chi \frac{Q_i}{Q} \tag{6}$$

Here, Q is given as the MACCS input and χ is the MACCS calculation result. To calculate Q_i, it can be obtained by integrating the release rate with respect to time as shown in Eq. (7). In Fig. 5, even if the rate of release of radioactive materials is constant, the arrival time of Gaussian plume in Q_i is different depending on the location of the receptor, so the integral value may change because the integration interval changes.

$$Q_i = \int_{t_i - x/u}^{t_{i+1} - x/u} \dot{Q}\,(t) dt \tag{7}$$

3.3 New calculation method procedure

A cascade accident is an incident in a multi-unit nuclear power plant where the failure of each unit or release of radioactive material does not occur simultaneously, but with a time difference. A good example is the Fukushima nuclear power plant accident in Japan, where despite having the same cause, the progression of the accident differed for each unit and the release time of radioactive materials varied. Therefore, in multi-unit accidents, if the timing of the release of radioactive material is not considered and a simultaneous accident is assumed, the risk may be overestimated.

For the Level 3 PSA calculation, it is assumed that the release rate of radioactive materials is constant when only the total amount of radionuclide release and the release time are known as source term information. However, in a nuclear power plant accident, the release rate of radioactive materials generally changes over time. Therefore, the radioactive material release rate over time can be obtained from the Level 2 PSA code result, or the source term information over time can be calculated using the RASCAL code. Fig. 7 illustrates the cascade accident calculation procedure when using RASCAL.

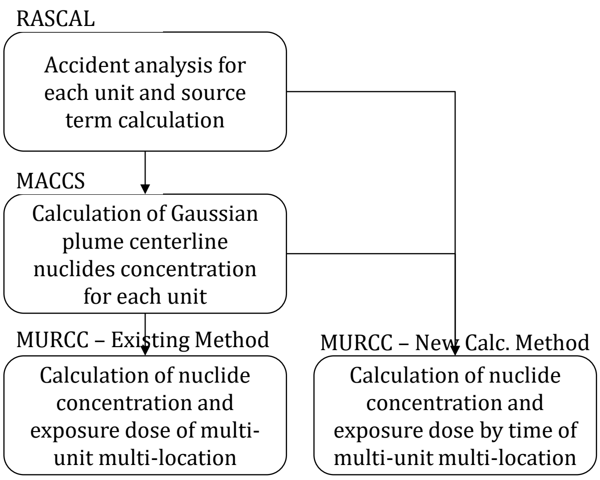

Fig. 7. Multi-unit cascade accident calculation procedure

The multi-unit multi-location calculation method calculates time-integrated radionuclide concentration and total exposure dose at any receptor location based on total release information. However, for calculating multi-unit cascade accidents, time-dependent release information is necessary. Therefore, the source term information calculated by RASCAL is required.

4. Results of multi-unit cascade accidents

4.1 Benchmark for multi-unit cascade accidents

To calculate the source term for a nuclear power plant accident, it is necessary to first calculate the Level 1 PSA and Level 2 PSA. This requires understanding each level and using the corresponding code. However, the RASCAL code can be used to calculate the source term based on the accident scenario.

To simplify the calculation of a cascade accident, the Vogtle Nuclear Power Plant provided by RASCAL can be used, assuming the same accident for units 3 and 4 with a capacity of 3,415 MWt and a 2-hour difference in the release of radioactive materials. Fig. 8 shows a satellite image of the Vogtle site and the locations of key points, while Fig. 9 provides a schematic diagram. In Fig. 9, receptor 1 is located at R_1, and receptor 2 is located at R_2.

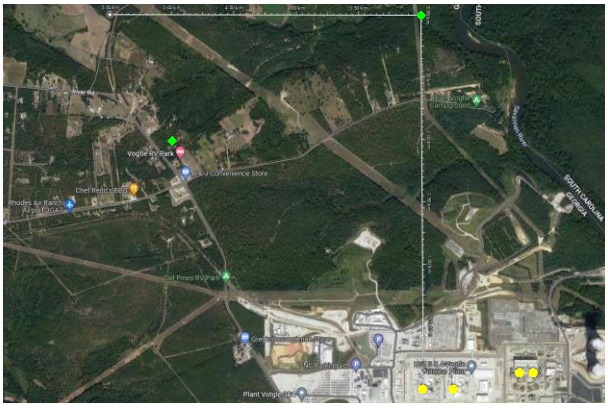

Fig. 8. Satellite image of Vogtle site and receptors

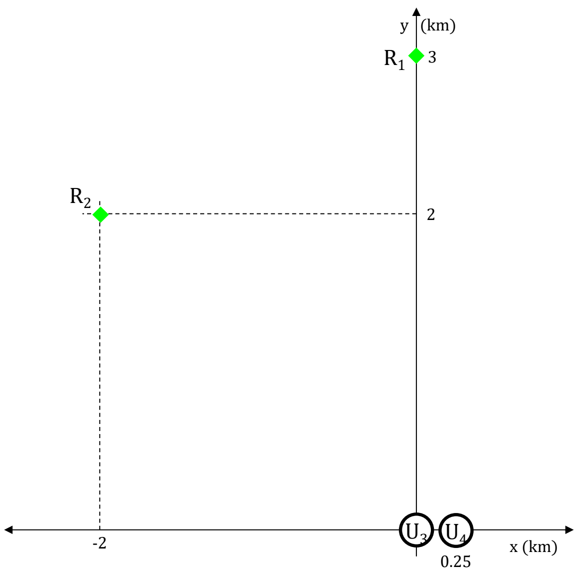

Fig. 9. Site layout of NPP units and receptors

4.2 Source term calculation using RASCAL

To calculate the source term, it was assumed that both units experienced Long Term Station Blackout (LTSBO) accidents, and that radioactive materials were released for 4 hours. A 2-hour difference was assumed between the start of the release of radioactive materials in the two units. Table 1 shows the main items of the accident scenario for Vogtle units 3 and 4.

Table 1. Accident information at Vogtle unit 3·4

Reactor power	3,415 MWt
Accident type	Long Term Station Blackout
Core recovered	No
Release pathway	PWR – Containment Leakage
Leak rate	0.1% / day
Sprays	Off
Release time	4 hour

Table 2 presents the total release of radionuclides, which is the source term information calculated by RASCAL.

Table 2. List of all radionuclides released with total activity

Nuclide	Bq	Nuclide	Bq
Am-241	1.70E+01	Pu-241	6.60E+06
Ba-139	9.70E+08	Rb-86	2.80E+11
Ba-140	1.60E+12	Rb-88	4.40E+12
Ce-141	8.70E+07	Rh-103m	4.30E+12
Ce-143	5.80E+07	Rh-105	2.40E+12
Ce-144	7.10E+07	Ru-103	4.40E+12
Cm-242	2.20E+06	Ru-105	3.00E+11
Cs-134	2.00E+13	Ru-106	1.20E+12
Cs-136	7.90E+12	Sb-127	1.00E+13
Cs-137	1.40E+13	Sb-129	3.80E+12
Cs-138	1.60E+06	Sr-89	8.30E+11
I-131	1.50E+14	Sr-90	6.40E+10
I-132	2.00E+14	Sr-91	3.50E+11
I-133	1.90E+14	Sr-92	2.50E+10
I-134	3.30E+09	Tc-99m	5.50E+13
I-135	6.50E+13	Te-127	1.50E+13
Kr-83m	1.30E+11	Te-127m	2.30E+12
Kr-85	2.30E+12	Te-129	6.30E+12
Kr-85m	6.80E+12	Te-129m	9.70E+12
Kr-87	4.50E+10	Te-131	5.00E+12
Kr-88	5.00E+12	Te-131m	2.20E+13
La-140	2.10E+10	Te-132	1.90E+14
La-141	6.20E+06	Xe-131m	3.80E+12
La-142	1.00E+05	Xe-133	5.40E+14
Mo-99	5.80E+13	Xe-133m	1.50E+13
Nb-95	9.00E+07	Xe-135	1.90E+14
Nb-95m	7.00E+04	Xe-135m	1.40E+13
Nb-97	2.60E+06	Y-90	5.30E+08
Nd-147	3.40E+07	Y-91	2.20E+08
Np-239	9.50E+08	Y-91m	8.40E+10
Pm-147	1.60E+04	Y-92	3.60E+09
Pr-143	7.90E+07	Y-93	1.80E+07
Pr-144	7.10E+07	Zr-95	8.80E+07
Pu-238	3.00E+01	Zr-97	4.60E+07
Pu-239	5.00E+01		

For the major radionuclides, the time dependent released amount in Bq is shown in Table 3.

Table 3. Time dependent release of major radionuclides

Time	Cs-137	I-131	Xe-135
12:00	8.13E+08	8.79E+09	7.16E+10
12:15	1.42E+09	1.53E+10	1.42E+11
12:30	1.86E+09	2.01E+10	2.10E+11
12:45	2.19E+09	2.37E+10	2.77E+11
13:00	5.86E+09	6.66E+10	6.93E+11
13:15	8.59E+09	9.82E+10	1.10E+12
13:30	5.63E+11	4.53E+12	7.36E+12
13:45	9.72E+11	7.79E+12	1.35E+13
14:00	1.25E+12	1.25E+13	1.74E+13
14:15	1.68E+12	1.86E+13	2.12E+13
14:30	1.65E+12	1.83E+13	2.12E+13
14:45	1.61E+12	1.80E+13	2.12E+13
15:00	1.58E+12	1.78E+13	2.13E+13
15:15	1.55E+12	1.77E+13	2.14E+13
15:30	1.53E+12	1.75E+13	2.15E+13
15:45	1.50E+12	1.73E+13	2.16E+13

Fig. 10 shows the release rates for the major nuclides as graphs.

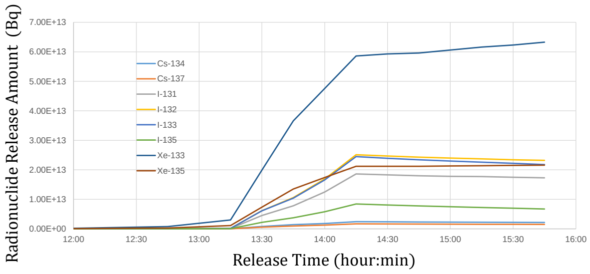

Fig. 10. Time dependent release of major radionuclides

4.3 Calculation of Gaussian plume centerline radionuclide concentration using MACCS

For the meteorological conditions required for MACCS calculation, constant weather conditions were used as shown in Table 4 for the convenience of calculation.

Table 4. Constant weather conditions for Vogtle site

Wind direction	N (South to north)
Wind speed	2.5 m/s
Precipitation	0 mm/hr
Mixing layer height	1,000 m
Atmospheric stability	D (Neutral)

In the radioactive material release information, the Gaussian plume release time was set to 4 hours and the effective plume height was set to 10 m. Atmospheric dispersion must be calculated using MACCS for all radionuclides in the source term calculated by RASCAL.

Table 5 shows the main items of the atmospheric dispersion calculation results for the Cs-137 nuclide.

Table 5. Atmospheric dispersion results for Cs-137

Distance	GL AIRCON	PLSIGY	PLSIGZ
50	3.49×10^{9}	18.9	24.6
200	1.25×10^{9}	45.8	28.5
400	6.12×10^{8}	79.5	33.3
600	3.82×10^{8}	112.0	37.8
800	2.66×10^{8}	143.0	42.0
1,000	1.99×10^{8}	173.0	46.0
1,200	1.55×10^{8}	203.0	49.9
1,400	1.25×10^{8}	232.0	53.5
1,600	1.03×10^{8}	261.0	57.1
1,800	8.69×10^{7}	290.0	60.5
2,000	7.44×10^{7}	318.0	63.8
2,200	6.45×10^{7}	346.0	67.1
2,400	5.66×10^{7}	374.0	70.2
2,600	5.01×10^{7}	402.0	73.3
2,800	4.47×10^{7}	429.0	76.3
3,000	4.01×10^{7}	456.0	79.3
3,200	3.63×10^{7}	483.0	82.2
3,400	3.30×10^{7}	510.0	85.0
3,600	3.02×10^{7}	537.0	87.8
3,800	2.77×10^{7}	563.0	90.6
4,000	2.55×10^{7}	590.0	93.3
4,200	2.36×10^{7}	616.0	95.9
4,400	2.19×10^{7}	642.0	98.6
4,600	2.04×10^{7}	668.0	101.0
4,800	1.90×10^{7}	694.0	104.0
5,000	1.78×10^{7}	720.0	106.0
5,200	1.67×10^{7}	746.0	109.0
5,400	1.57×10^{7}	771.0	111.0
5,600	1.48×10^{7}	797.0	114.0
5,800	1.39×10^{7}	822.0	116.0
6,000	1.32×10^{7}	848.0	118.0

The description of each item of the atmospheric dispersion calculation result is shown in Table 6.

Table 6. MACCS output items [18]

Item	Description	Unit
Distance	distance to the center of the spatial interval	m
GL AIRCON	centerline ground-level integrated air concentration from this plume segment averaged over the spatial interval's length	Bq · sec $/m^3$
PLSIGY	horizontal dispersion parameter averaged over the spatial interval's length	m
PLSIGZ	vertical dispersion parameter averaged over the spatial interval's length	m

4.4 Multi-unit cascade accident calculation using MURCC

The existing multi-unit multi-location calculation method applies the RASCAL source term to the MACCS input to calculate the Gaussian plume centerline radionuclide concentration for each radionuclide of the source term. The multi-unit multi-location method uses MURCC to calculate the radionuclide concentration and exposure dose in the 2-dimensional ground level height. However, since the MACCS result is the time-integrated radionuclide concentration and MURCC also calculates only the time-integrated result, multi-unit cascade accidents are calculated as simultaneous accidents. As a result, the risk can still be overestimated.

In order to calculate multi-unit cascade accidents, the radionuclide concentration over time or the time-integrated radionuclide concentration at each time interval is required. For this purpose, in Eq. (1), instead of the total release amount, the release rate should be used, or the release amount by time interval should be used. Given only the total release amount and release time, it can only be assumed that the release rate is constant. However, RASCAL calculates the release at 15-minute intervals based on source term information. Therefore, multi-unit cascade accidents were calculated using the RASCAL source term information.

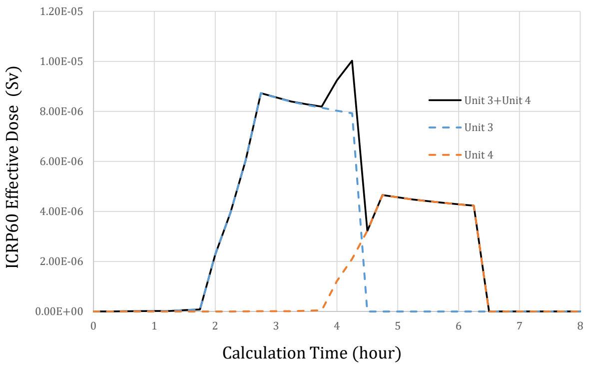

Fig. 11. External exposure dose from Gaussian plume at receptor 1

Fig. 11 shows the ICRP-60 effective dose due to external exposure to Gaussian plume at 15-minute intervals at the location of R_1 in Fig. 9. The blue dotted line is the exposure due to the Gaussian plume released from unit 3, and the orange dotted line is the exposure due to the Gaussian plume released from unit 4. The result of combining the two is the solid black line. As a result of the nuclear accident, radioactive materials are released for 4 hours. As shown in Fig. 10, less radioactive materials are emitted in the first 90 minutes of the accident, so the exposure dose is less and exposure occurs for a total of 4 hours. The exposure caused by the two Gaussian plumes occurs with a time difference of 2 hours depending on the difference in the release time of the radioactive material. The location of R_1 is on the centerline of the Gaussian plume released from unit 3 and is 250 m away from the centerline of the Gaussian plume released from unit 4, so there is a difference in exposure dose. The maximum exposure dose is 1.003×10^{-5} Sv and the total exposure dose is 1.081×10^{-4} Sv.

Fig. 12 is the external exposure dose by Gaussian plume at 15-minute intervals at the location of R_2 in Fig. 9. The location of R_2, which is 2 km and 2.25 km away from the centerline of each Gaussian plume respectively, is sufficiently far from the plumes' centerline that the difference in exposure dose is negligible. The maximum exposure dose is 8.199×10^{-8} Sv and the total exposure dose is 9.741×10^{-7} Sv.

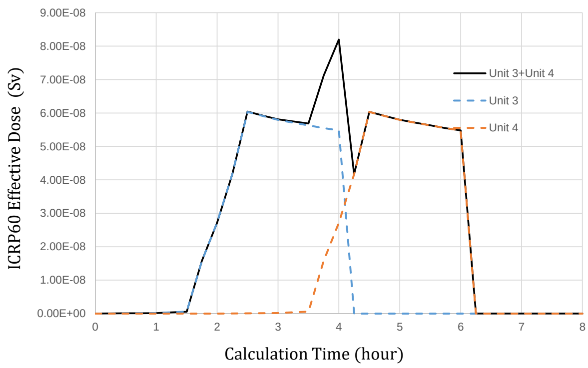

Fig. 12. External exposure dose from Gaussian plume at receptor 2

The external exposure dose due to Gaussian plumes at each time interval outputs the dose value at each location in the x-y plane of the ground height. The maximum exposure dose at any time interval is 1.398×10^{-4} Sv. Fig. 13 shows the color table for the 3D graph from Figs. 14-17.

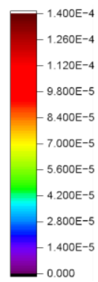

Fig. 13. Color table for 3D graph

Given that the total calculation time is 8 hours, with a time interval of 15 minutes, there are 32 3D graphs in total. Due to the release time of radioactive materials being 4 hours and the release time difference being 2 hours, the two Gaussian plumes overlap between 3 and 5 hours, as shown in Figs. 11 and 12.

Fig. 14 depicts the external exposure dose due to the Gaussian plume for a 15-minute interval starting at 3 hours and half into the calculation time. As the accident has a time difference of 2 hours, radioactive material is released from Unit 4 after 2 hours but is not represented in the graph due to the small amount released at the beginning. Moreover, as a significant amount of radioactive material was released about 1 hour and half after the start of the initial release, the Gaussian plume from Unit 4 is represented starting from 3 hours and half of the calculation time.

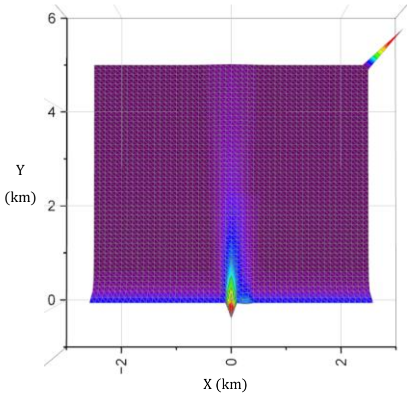

Fig. 14. External dose at 3:30 to 3:45

Fig. 15 is the external exposure dose due to the Gaussian plume for 15 minutes from 3 hours 45 minutes to 4 hours. At the end of 15 minutes, more radioactive material was released from unit 4, and the Gaussian plume became more pronounced.

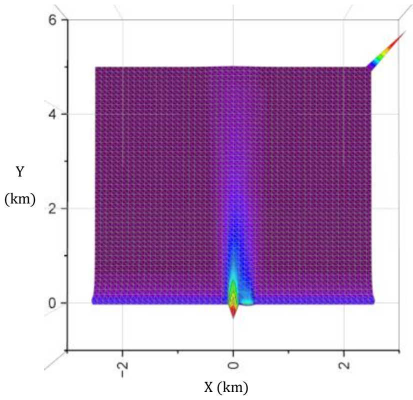

Fig. 15. External dose at 3:45 to 4:00

Fig. 16 shows the external exposure dose due to the Gaussian plume for 15 minutes from 4 hours to 4 hours 15 minutes. The Gaussian plume passed as the radioactive material was released from Unit 3 for 4 hours. At this time, since the wind speed is 2.5 m/s, the travel distance for 15 minutes is 2.25 km. Therefore, the Gaussian plume released by Unit 3 did not exist until 2.25 km away.

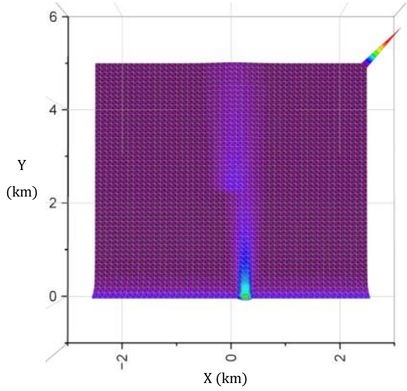

Fig. 16. External dose at 4:00 to 4:15

Fig. 17 shows the external exposure dose due to the Gaussian plume for 15 minutes from 4:15 to 4:30. The Gaussian plume released from Unit 3 passed up to 4.5 km and its appearance faded.

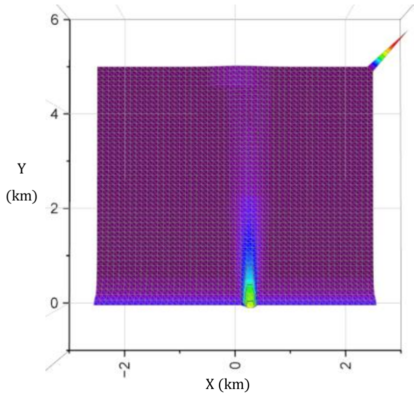

Fig. 17. External dose at 4:15 to 4:30

4. Conclusions

Multi-unit accidents can release radioactive materials at different times in each unit, which means that the current time-integrated method for evaluating risks may overestimate the actual risks associated with such accidents. The Level 3 PSA models used in this method assume that all units experience the accident simultaneously, which can lead to inaccurate risk assessments. Furthermore, the time-integrated result cannot be used in real-time response during the early phase of the accident.

To overcome these limitations, a new calculation method for multi-unit cascade accident is necessary. This method should accurately calculate radionuclide concentrations and exposure doses over time intervals, which will allow for more precise risk evaluation and real-time response in early phase accidents.

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REFERENCES

[1] T. Hakata, Seismic PSA Method for Multiple Nuclear Power Plants in a Site. Reliability Engineering and System Safety, 92, 883-894, 2007.

[2] M. Modarres, T. Zhou, and M. Massoud, Advances in Multi-unit Nuclear Power Plant Probabilistic Risk Assessment. Reliability Engineering and System Safety, 157, 87-100, 2017.

[3] S. Schroer, and M. Modarres, An Event Classification Schema for Evaluating Site Risk in a Multi-unit Nuclear Power Plant Probabilistic Risk Assessment. Reliability Engineering and System Safety, 117, 40-51, 2013.

[4] T. D. Duy, D. Vasseur, and E. Serdet, Probabilistic Safety Assessment of Twin-unit Nuclear Sites: Methodological Elements. Reliability Engineering and System Safety, 145, 250-261, 2016.

[5] T. Zhou, M. Modarres, and E. L. Droguett, An Improved Multi-unit Nuclear Plant Seismic Probabilistic Risk Assessment Approach. Reliability Engineering and System Safety, 171, 34-47, 2018.

[6] D. Mandelli, C. Parisi, A. Alfonsi, D. Maljovec, S. St Germain, R. Boring, S. Ewing, C. Smith, and C. Rabiti, Dynamic PRA of a Multi-unit Plant. INL/CON-17-42037, October 2017.

[7] Changkyung Seong, Gyunyoung Heo, Sejin Baek, Ji Woong Yoon, and Man Cheol Kim, Analysis of the Technical Status of Multiunit Risk Assessment in Nuclear Power Plants. Nuclear Engineering and Technology, 50, 319-326, 2018.

[8] Joon-Eon Yang, Multi-unit Risk Assessment of Nuclear Power Plants. Nuclear Engineering and Technology, 50, 1199-1209, 2018.

[9] Yongjin Lee, Seungwoo Lee, Daewook Chung, Jongsoo Choi, and Dohyoung Kim, Dose Assessment for Multi-unit Simultaneous Accident using MACCS. Transactions of the Korean Nuclear Society Autumn Meeting, October 24-25, 2019.

[10] Kyemin Oh, Sung-yeop Kim, Hojun Jeon, and Jeong Seon Park, Study on Multi-unit Level 3 PSA to Understand a Characteristics of Risk in a Multi-unit Context. Nuclear Engineering and Technology, 52, 975-983, 2020.

[11] Dohyun Lim, Chanwoo Park, Dongha Kim, Youngho Jin, and Moosung Jae, Sensitivity Analysis of Multiple Release Locations in Multi-unit Level 3 PSA. Transactions of the Korean Nuclear Society Spring Meeting, May 19-20, 2022.

[12] Mieczysław Borysiewicz, Aleksej Kaszko, Karol Kowal, and Sławomir Potempski, Time-dependent PSA Model for Emergency Power System of Nuclear Power Plant. Safety and Reliability of Complex Engineered Systems, 2015.

[13] Jorge Sanchez-Torrijos, Cesar Queral, Carlos Paris, Maria Jose Rebollo, Miguel Sanchez-Perea, and Jose Maria Posada, On the Use of Time-dependent Success Criteria within Risk-informed Analyses. Application to LONF-ATWS Sequences in PWR Reactors. Nuclear Engineering and Technology, 54, 4601-4619, 2022.

[14] Hye Rin Lee, Gee Man Lee, Woo Sik Jung, and Seok-Jung Han, Comparison of Two Methods for Dose Distribution Calculation of Multi-unit Site. Transactions of the Korean Nuclear Society Autumn Meeting, 2017 Autumn, 17A-161.

[15] Hye Rin Lee, Gee Man Lee, and Woo Sik Jung, A Method to Calculate Off-site Radionuclide Concentration for Multi-unit Nuclear Power Plant Accident. Journal of the Korean Society of Safety, 33(6), 144-156, 2018.

[16] Jae-Ryang Kim, Gee Man Lee, Woo Sik Jung, and Seok-Jung Han, Level 3 MUPSA at 9 Unit Nuclear Site using MACCS2 and MURCC Codes. Transactions of the Korean Nuclear Society Spring Meeting, July 9-10, 2020.

[17] Woo Sik Jung, Hye Rin Lee, Jae-Ryang Kim, and Gee Man Lee, Development of MURCC Code for the Efficient Multi-unit Level 3 Probabilistic Safety Assessment. Nuclear Engineering and Technology, 52, 2221-2229, 2020.

[18] D. Chanin, M.L. Young, J. Randall, and K. Jamali, Code Manual for MACCS2: Volume 1, User's Guide Report. NUREG/CR-6613, SAND97-0594, U.S.NRC, 1998.

[19] K. McFadden, N. E. Bixler, Lee Eubanks, and R. Haaker, WinMACCS, a MACCS2 Interface for Calculating Health and Economic Consequences from Accidental Release of Radioactive Materials into the Atmosphere: User's Guide and Reference Manual for WinMACCS Version 3. U.S. NRC, 2009.

[20] Sandia National Laboratories. MACCS Home. https://maccs.sandia.gov/maccs.aspx

[21] U.S. NRC, RASCAL 4.3: Description of Models and Methods. NUREG-1940, U.S. NRC. pp. 128-129, 2015.

[22] Radiation Protection Computer Code Analysis and Maintenance Program. RASCAL | RAMP Website. https://ramp.nrc-gateway.gov/codes/rascal

[23] Jae Kwon, Jin O Lee, Gang Woo Ryu, and Kwang Pyo Kim, Off-site Consequence Analysis of Nuclear Power Plant Severe Accident Using WinMACCS and RASCAL Computer Codes. Journal of Radiation Industry, 15(1), 55-63, 2021.

[24] Sung-yeop Kim, Yong Hun Jung, Sang Hoon Han, Seok-Jung Han, and Ho-Gon Lim, Multi-unit Level 3 Probabilistic Safety Assessment: Approaches and their Application to a Six-unit Nuclear Power Plant Site. Nuclear Engineering and Technology, 50, 1246-1254, 2018.

[25] N. E. Bixler, and Sung-yeop Kim, Performing A Multi-unit Level-3 PSA With MACCS. SAND2019-10527C. Asian Symposium on Risk Assessment and Management 2019 (ASRAM2019), 2019.

[26] Korea Atomic Energy Research Institute. RCAP (Radiological Consequence Analysis Program) - RCAP Official Site. http://www.rcap-kaeri.org/