Comparison of semi-infinite and finite clouds effects for the external exposure dose calculation in Level 3 SUPSA and MUPSA

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1. Introduction

After the Fukushima accident, the importance of the Level 3 MUPSA (Multi-Unit Probabilistic Safety Assessment) method has increased in Korea. When evaluating the effect of radiation to human and environment, we usually used to calculate exposure dose by multiplying the nuclide concentration by the DCF (dose conversion factor) [1].

Information of exposure dose is utilized for the assessment such as initial deaths, harm to organs, injuries in the short-term as well as potential cancers in the medium-term to long-term [2]. Therefore, calculation method of the realistic and accurate exposure dose is very important.

In Korea, level 3 PSA field has used codes of PAVAN and MACCS (MELCOR Accident Consequence Code System) in order to evaluate effect of radioactive nuclide in the air. Both of PAVAN and MACCS codes use the Gaussian plume model to calculate nuclide concentration in the air.

However, there are differences between the two codes. The MACCS code is used for the purpose of improving safety through realistic evaluation. The MACCS code reflects phenomena of radioactive decay, deposition due to rainfall or surface roughness [3]. The PAVAN code provides the methodology for licensing and regulation to the nuclear power plant. The PAVAN code does not take into account this realistic phenomena [4].

When calculating exposure dose, the PAVAN code assumes the semi-infinite cloud model [3]. However, the MACCS code assumes the finite cloud model [4]. That is, the MACCS code uses the finite cloud model that reflects the finite cloud dose correction factor in the semi-infinite cloud model.

This study is to compare two results of external exposure dose to semi-infinite cloud model and finite cloud model using the MURCC (multi-unit radiological consequence calculator) code [5]. So we research to evaluate the impact of the finite cloud dose correction factor when calculating the exposure dose.

2. Assumptions for dose calculation of nuclide concentration

2.1 Dose calculation of semi-infinite cloud model

The PAVAN code use the semi-infinite cloud model. Infinite cloud is the equilibrium condition when the homogeneous infinite cloud size is longer than the range of traveled the gamma ray due to mean free path. Usually, the semi-infinite cloud model is used to the assessment than the infinite cloud model. Actually, because of the presence of the Earth's surface, the gamma ray received from the cloud must actually be corrected in half [6]. Dose calculation formula of semi-infinite cloud model is as follows Eq. (1).

$$\mathrm{CldDose} = \mathrm{Cldfac} \times \sum_{i=1}^{N} \mathrm{AirCon_i}(x, y, 0) \times \mathrm{DC_i} \qquad (1)$$

where

CldDose	= External exposure dose to human organs [Sv]
Cldfac	= Shielding factor of cloud shine [unitless]
i	= Nuclide
N	= Number of nuclides
$\mathrm{AirCon_i}(x,y,0)$	= Ground level air concentration [Bq x sec/m^3]
$\mathrm{DC_i}$	= Dose coefficient of external exposure [Sv/sec/Bq/m^3]

When people exist in the semi-infinite cloud, this people is homogeneously affected by gamma rays as shown in Fig 1. Because, emission and absorption of gamma rays in the semi-infinite cloud are same. Z (m) is the height of the surface and Y (m) is perpendicular to the wind direction in Fig 1.

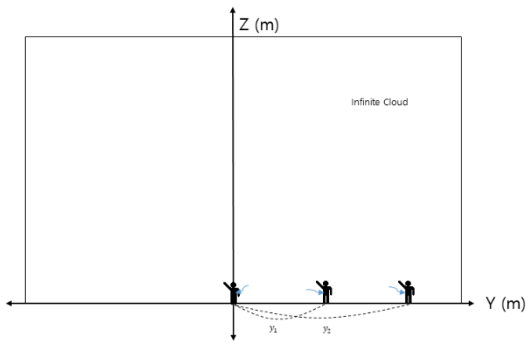

Fig. 1. Gamma rays effect of semi-infinite cloud

2.2 Dose calculation of finite cloud model

The MACCS code use the finite cloud model. Finite cloud exists as the certain height and size in the air. If the finite cloud size is small compared to the range of traveled the gamma ray due to mean free path, calculation of the gamma dose should take into account the gamma rays in various parts of the cloud [6]. Dose calculation formula of finite cloud model is as follows (2).

$$\mathrm{CldDose} = \mathrm{Cldfac} \times \sum_{i=1}^{N} \mathrm{AirCon_i(x,0,H)} \times \mathrm{DC_i} \times \mathrm{Finfac} \qquad (2)$$

where

CldDose	= External exposure dose to human organs [Sv]
Cldfac	= Shielding factor of cloud shine [unitless]
i	= Nuclide
N	= Number of nuclides
$AirCon_i$(x,0,H)	= Centerline air concentration [Bq x sec/m^3]
DC_i	= Dose coefficient of external exposure [Sv/sec/Bq/m^3]
Finfac	= Finite cloud dose correction factor [unitless]

When people exist in the finite cloud, this people is differently affected by gamma rays as shown in Fig 2, 3. Because, cloud size and distance between the source and receptor are different every centerline. Z (m) is the height of the surface and Y (m) is perpendicular to the wind direction in Fig 2, 3.

If the finite cloud becomes smaller, the effect of gamma rays dose is reduced due to the distance between the source and the receptor increases in Fig 2.

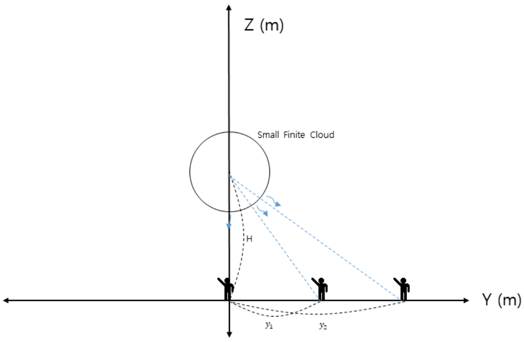

Fig. 2. Gamma rays effect of small finite cloud

If the finite cloud becomes larger, the effect of gamma rays dose is increased due to the distance between the source and the receptor closes in Fig 3.

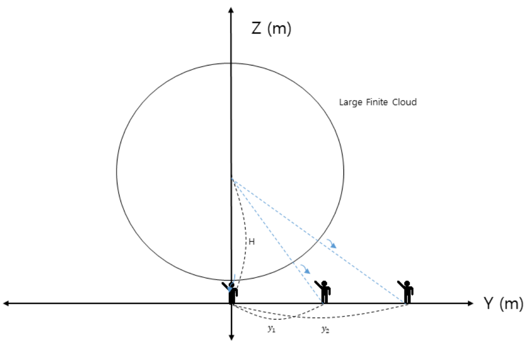

Fig. 3. Gamma rays effect of large finite cloud

2.3 Ratio of finite to semi-infinite cloud dose

The finite cloud dose correction factor is the ratio of finite to semi-infinite cloud dose. The reason for using this method is that finite cloud model formula are difficult to calculate geometry and numerical integration in equations.

The sufficiently large cloud is considered the infinite cloud. As a result, it is convenient to apply the finite cloud dose correction factor to the infinite cloud dose in order to calculate the finite cloud dose. The finite cloud dose correction factor calculation formula of finite cloud model is as follows (3).

$$\text{Finite Cloud Dose Correction Factor} = \frac{D(x,y,0)}{D_\infty(x,0,0)} \qquad (3)$$

where

D_∞ (x,0,0)	= Dose of semi-infinite cloud [Sv]
D(x,y,0)	= Dose of finite cloud [Sv]

Table 1 shows the values of finite cloud dose correction factor in the WASH-1400 report [7]. This value is reflected in the MURCC code and applied when calculating the external exposure dose. This value depends on diffusion parameter and distance (cloud centerline and receptor).

Table 1. Finite cloud dose correction factor [7]

	$\sqrt{\mathbf{y^2+z^2}}/\sqrt{\boldsymbol{\sigma_y\sigma_z}}$ (a)					
$\sqrt{\boldsymbol{\sigma_y\sigma_z}}$ (b)	0	1	2	3	4	5
3	0.020	0.018	0.011	0.007	0.005	0.004
10	0.074	0.060	0.036	0.020	0.015	0.011
20	0.150	0.120	0.065	0.035	0.024	0.016
30	0.220	0.170	0.088	0.046	0.029	0.017
50	0.350	0.250	0.130	0.054	0.028	0.013
100	0.560	0.380	0.150	0.045	0.016	0.004
200	0.760	0.511	0.150	0.024	0.004	0.001
400	0.899	0.600	0.140	0.014	0.001	0.001
1000	0.951	0.600	0.130	0.011	0.001	0.001

(a) $\sqrt{y^2+z^2}/\sqrt{\sigma_y\sigma_z}$: Distance to cloud centerline and receptor [unitless]
(b) $\sqrt{\sigma_y\sigma_z}$: Diffusion parameter [m]

3. Calculation process to the MURCC code

The process of calculating concentrations is as follows. First, Source term is calculated using the RASCAL code [8]. The option of RASCAL code should decide reactor parameters, accident scenario, release pathway, meteorology of the nuclear power plant (NPP).

Second, Information of the amount and kinds of nuclides of the single NPP should input into the ATMOS module of MACCS [3].

Third, MACCS output file of this single NPP should input into MURCC code. And finite cloud dose correction factor option of MURCC code decide on/off to calculate the external exposure dose [5].

4. Application to the MURCC code and Results

4.1 NPP Model

The MURCC code was used to calculate the external exposure dose of two cloud model by applying the scenario of most serious accident for APR-1400 model.

Table 2 shows information of reactor parameters about the APR-1400 model in RASCAL code.

Table 2. Information of reactor parameters

Reactor Parameters	APR-1400
Reactor power	3983 MWth
Average burnup	28914 MWd / MTU
Containment type	PWR Dry
Containment volume	3130000 ft^3
Design pressure	60 lb/in^2
Design leak rate	0.1 %/d
Coolant mass	292000 kg
Assemblies in core	241
Steam generator type	U-Tube
SG water mass	218000 kg

4.2 Scenario and release pathway

The scenario of severe accident is assumed the LTSBO (long-term station black out). The reactor was shut down immediately after the LTSBO. The reactor core was not recovered due to the failure of the core cooling system. Table 3 shows the information of accident scenario in RASCAL code.

Table 3. Information of accident scenario

Source Term	
Type	Long Term Station Blackout
Shutdown	00:00
Release from core starts	08:00
Core recovered	No
Inventory	Default

The amount of nuclides in NPP released due to break the containment building into the air. So, it is failed to protect human and environment by the dose. Percent leakage volume per time assumed 100 % vol/h in order to the scenario of most serious accident. Table 4 is the information of release pathway in RASCAL code.

Table 4. Information of release pathway

Release Pathway		
Type	PWR - Dry Containment Leakage or Failure	
Release height	10 m	
Release events	08:00	Leak rate (% vol) Total failure
	08:00	Sprays Off

4.3 Weather

Table 5 is information of meteorology in RASCAL code. Atmospheric stability is D. Wind speed is 4m/h. Precipitation is zero. Temperature and relative humidity are general.

Table 5. Information of meteorology

Meteorology				
Stability class	Speed [m/h]	Precipitation (Rain)	Air Temp (deg C)	Relative humidity
D	4	No	20	50% rh

4.4 Calculation result of centerline external dose

This is the results of calculating the external exposure dose of centerline (y=0km) to semi-infinite cloud and finite cloud model. It is shown in Fig 4.

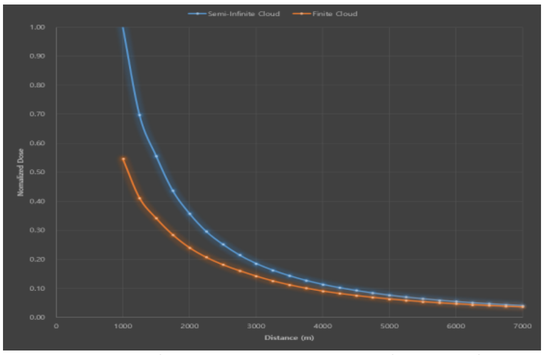

Fig. 4. Comparison of centerline dose to semi-infinite and finite cloud

Table 6 summarizes the results of calculating the external exposure dose of centerline (y=0km) to the semi-infinite and finite cloud model. The two cases of semi-infinite and finite cloud model differed by 0.45 at x=1.0 km. The two cases of semi-infinite cloud and finite cloud model differed by 0.12 at x=2 km. The two cases of semi-infinite and finite cloud model are same at x=7 km. In the two cases, the difference is large when it is close to the source of the cloud. But there is no difference if it is far from the source of cloud.

Table 6. Centerline dose comparison to semi-infinite and finite cloud

X	Semi-infinite	Finite	Difference
1.0 km	1.00	0.55	0.45
2.0 km	0.36	0.24	0.12
3.0 km	0.19	0.14	0.05
4.0 km	0.11	0.09	0.02
5.0 km	0.08	0.06	0.01
6.0 km	0.05	0.05	0.00
7.0 km	0.04	0.04	0.00

4.5 Calculation result of external exposure dose (x=0.5km)

This is the results of calculating the external exposure dose of y-axis to semi-infinite cloud and finite cloud model at x=0.5km. It is shown in Fig 5.

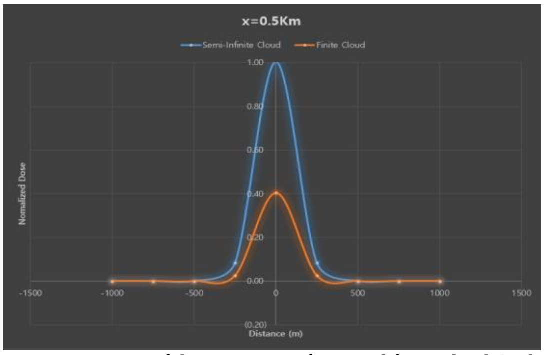

Fig. 5. Comparison of dose to semi-infinite and finite cloud (0.5km)

4.6 Calculation result of external exposure dose (x=1km)

This is the results of calculating the external exposure dose of y-axis to semi-infinite cloud and finite cloud model at x=1km. It is shown in Fig 6.

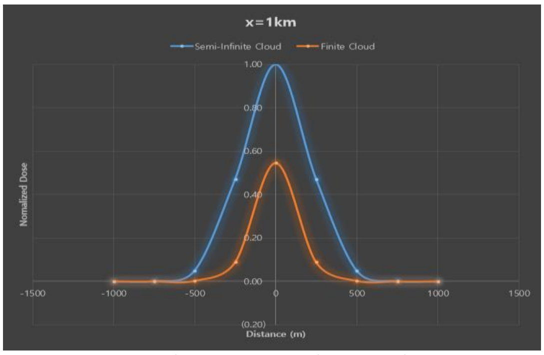

Fig. 6. Comparison of dose to semi-infinite and finite cloud (1km)

4.7 Calculation result of external exposure dose (x=5km)

This is the results of calculating the external exposure dose of y-axis to semi-infinite cloud and finite cloud model at x=5km. It is shown in Fig 7.

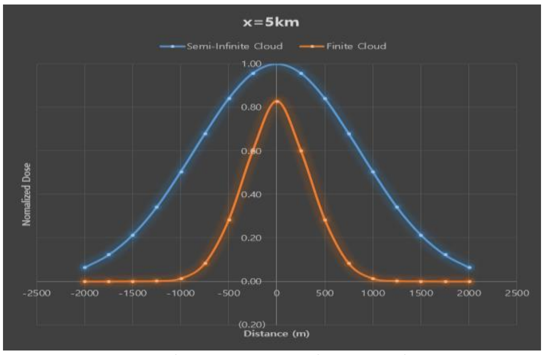

Fig. 7. Comparison of dose to semi-infinite and finite cloud (5km)

Table 7 summarizes the results of calculating the external exposure dose of y-axis (y=0.5 km) to the semi-infinite and finite cloud model at x=0.5, 1, 5 km. The two cases of semi-infinite and finite cloud model were same at x=0.5 km. The two cases of semi-infinite cloud and finite cloud model differed by 0.05 at x=1.0 km. The two cases of semi-infinite cloud and finite cloud model differed by 0.56 at x=5.0 km. In the two cases, the difference is small when it is close to the source of the cloud. But there is large difference if it is far from the source of cloud (y=0.5km).

Table 7. Dose comparison to semi-infinite and finite cloud (y=0.5km)

X	Semi-infinite	Finite	Difference
0.5 km	0.00	0.00	0.00
1.0 km	0.05	0.00	0.05
5.0 km	0.84	0.28	0.56

5. Conclusions

This study is the first research about the effects of finite cloud dose correction factor through comparison semi-infinite and finite clouds.

In summary, this study is as follows:
First, the results of calculating dose of semi-infinite cloud model showed the more conservative result than dose of finite cloud model. Therefore, the finite cloud dose correlation factor should be reflected in order to obtain more realistic dose in Level 3 MUPSA.

Second, quantitative safety objectives for NPPs have not been established in Korea. If these quantitative safety targets are legislated as mandatory regulations, the assumption of semi-infinite cloud model may violate the quantitative safety targets due to conservative results. However, if dose of finite cloud model is calculated accurately and realistically by reflecting this factor. The effect that satisfies the quantitative safety target will be expected.

Third, when calculating the external exposure dose for Level 3 MUPSA, the value larger than 5 sigma must be added to the table. Because, the external exposure dose for L3 MUPSA must be calculated from the centerline to the far distance.

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REFERENCES

[1] N. E. Bixler, “New FGR 13 Dose Conversion Factor File for MACCS”, SNL, SAND2019-13697PE, 2019
[2] U.S. DoE, “MACCS2 Computer Code Application Guidance for Documented Safety Analysis Final Report”, DOE-EH-4.2.1.4, 2004
[3] D. Chanin, M. L. Young, J. Randall, and K. Jamali, “Code Manual for MACCS2: Volume 1, User’s Guide”, NUREG/CR-6613, 1998
[4] U.S.NRC, PAVAN: “An Atmospheric-Dispersion Program for Evaluating Design-Basis Accidental Releases of Radioactive Materials from Nuclear Power Stations”, NUREG/CR-2858, 1982
[5] W. S. Jung, H. R. Lee, J. R. Kim, G. M. Lee, “Development of MURCC code for the efficient multi-unit level 3 probabilistic safety assessment,” Nuclear Engineering and Technology, 2020
[6] D. H. Slade, “METEOROLOGY AND ATOMIC ENERGY”, TID-24190, U. S. ATOMIC ENERGY COMMISSION, pp. 337-346, 1968
[7] D. L. Strange, “Models Selected for Calculation of Doses, Health Effects and Economic Costs due to Accidental Radionuclide Releases from Nuclear Power Plants, NUREG/CR-1021”, NRC, pp. 6-1 - 6-15, 1980
[8] U.S. NRC, “RASCAL 4: Description of Models and Methods”, NUREG-1940, 2015