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Analysis of Radiation Exposure from Nuclear Reactor Accident in Complex Terrain

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산악지형에서의 원자력발전소 사고시의 피폭해석

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Abstract

The Gaussian plume model is widely used to calculate the concentrations of gaseous radioactive effluents in the atmosphere. This model assumes that the terrain is flat, so that the dispersion coefficients which are the most important parameters in this model must be compensated in complex terrain such as in Korea. In this study the compensation of vertical dispersion coefficient in two dimensional $x-z$ plane has been accomplished by comparing the Gaussian plume model with numerical model. The results show that the concentractions of radioactive effluents over complex terrain are more dilluted than those expected over flat terrain.

요 약

원자력 발전소로부터 방출되는 기체상 방사성 물질에 의한 환경 영향을 평가함에 있어서 방사성 물질의 대기중에서의 수송과 확산을 기술하는 모델로써 Gaussian plume model이 널리 사용되고 있다. Gaussian plume model은 평탄한 지형에 적용하도록 만들어진 모델이므로 대부분의 국토가 복잡한 산악으로 구성된 한국의 경우에 적용하기 위해서는 모델의 수정이 필요하다.

본 논문에서는 2차원적 $x-z$ 평면에서 확산방정식을 해석한 numerical diffusion model과 Gaussian plume model을 비교하여, Gaussian plume model에서 가장 중요한 변수인 dispersion coefficient를 지형의 높이에 대하여 보정하였다. 보정된 dispersion coefficient 값을 Gaussian plume model에 적용시켜 계산을 수행한 결과를 보면, 산악지역에서의 방사성 물질의 농도는 평지에서보다 낮게 나타나고 있다.

1. Introduction

The environmental impact assessment of nuclear power plants is categorized into two situations; the one is for normal operating condition and the other is for accident case. The assessment model for normal operating condition is described in USNRC Reg. Guide 1.109 and computer code GASPAR and CHRONIC which were based on this model are usually used. The assessment model for accident case is described in WASH-1400, Reactor Safety, Study, Appendix VI, "Calculation of Reactor Accident Consequence" and computer code CRAC which was made on this model is used.[1]

The transport and dispersion mechanism of gaseous radioactive effluents is represented by Gaussian plume model for these two cases. The Gaussian plume model assumes that terrain is flat.[2,3] Many investigators have compared the results from experimental diffusion data in complex terrain with the results predicted in level terrain by using Gaussian plume model. These comparisons have been made because the Gaussian plume model is generally acceptable and is intended to be used for complex terrain as well as for level terrain.[4]

In order to apply Gaussian plume model to real situation in Korea which has very complex topography, it is required to compensate the dispersion coefficients which are the most important parameters in this model. The main purpose of this study is the compensation of the vertical dispersion coefficients in complex terrain by comparing Gaussian plume model with numerical diffusion model.

In numerical model it is very difficult to determine the diffusion coefficients for all of six atmospheric conditions, but it is relatively easy in numerical condition. In this study, the comparison of Gaussian plume model with numerical model and the compensation of dispersion coefficients in complex terrain have been performed in neutral condition.

With the compensated dispersion coefficients, early exposure doses and chronic exposure doses were calculated using dose calculation model which is adopted in CRAC computer code.[1] CRAC code consists of a sequence of models which describe as follows: the release of gaseous radioactive material as it disperse downwind from the plant, the deposition of the radioactive material onto the ground and the effects of this material on man. For this calculation, class 8 hypothetical accident sequences for PWR were assumed.

2. Atmospheric Dispersion Model

Turbulent diffusion of radioactive effluents in the atmosphere is described by the diffusion equation.

$$\frac{\partial c}{\partial t} = -\vec{\nabla}\cdot u\cdot c + \vec{\nabla}\cdot k\cdot\vec{\nabla}\cdot c + S \qquad (1)$$

where C is the cencentratien of the effluents, k is the diffusion cofficients, u is the wind field and S is the source term.[2] Since it is very difficult to determine k in the atmosphere, the Gaussian plume model which is an statistical diffusion model has been used widely.

2.1. Gaussian Plume Model

The Gaussian plume model assumes; steady-state condition, constant wind direction and-homogeneous flat terrain. With these assumptions Sutton, Pasquill and Gifford made an experiment to obtain the concentration distribution of pollutants in the atmosphere and found out that the distribution took the form of Gaussian to provide Gaussian plume equation.[2,3]

$$C = \frac{Q}{2\pi\cdot\sigma_y\cdot\sigma_z\cdot u}\cdot\exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right]$$
$$\left\{\exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right]\right.$$

$$+\exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right]\Bigg\} \qquad (2)$$

where Q is the release rate of source, H is the effective height of release and σ_y, σ_z are the dispersion coefficients in $y-$ and $z-$directions, respectively. In Eq (2), the dispersion coefficients σ_y and σ_z are given as functions of downwind distance and atmospheric stability. Meteorologists usually classify the atmospheric stability conditions into three conditions: unstable, neutral and stable. These adjectives refer to the reaction of an air parcel displaced adiabatically in vertical direction. In the dry adiabatic condition, vertical temperature gradient of the atmosphere is represented by

$$\frac{dT}{dz} = -\frac{0.98}{100}\left[\frac{°C}{m}\right] \qquad (3)$$

And the atmospheric stabilities are categorized by comparison of the actual lapse rate (i.e., environmental lapse rate) with this value (i.e., dry adiabatic lapse rate)

Unstable; $\frac{\partial T_e}{\partial z} < \frac{\partial T}{\partial z}$

Neutral ; $\frac{\partial T_e}{\partial z} = \frac{\partial T}{\partial z}$

Stable ; $\frac{\partial T_e}{\partial z} > \frac{\partial T}{\partial z}$

where T_e represents actual air temperature. Pasquill reported the curves of σ_y and σ_z shown in Fig. 1.[2]

2.2. Numerical Model

For solving the diffusion equation in complex terrain, the wind field is indispensible. In this study the variational calculus method is adopted to obtain the adjusted wind field.[5] This method estimates the wind field from input data while satisfying the physical constraint, so that the resulting wind field is mass conservative and does not introduce any artificial loss or generation term into the species mass balance. This method is based on minimization of the functional J[6],

$$J(u,\lambda) = \int_v [\alpha_i^2. \ (u-u_0)^2 + \lambda(\vec{\nabla}_x \cdot u)]dv \quad (4)$$

where u_0 is the initial wind field, u is the adjusted wind field, λ is the Lagrange multiplier and α_i is weighting parameter. The equations that minimize the functional J are derived by setting the appropriate frechet derivatives to zero.[6]

$$\frac{dJ}{d\eta}(u+\eta h, \lambda)\,|_{\eta=0} = 0 \qquad (5)$$

where h represents an arbitrary variation of the function u and η is a parameter. From Eq (5)

$$\int_v [2\alpha_i^2 \ (u-u_0)\cdot h + \lambda\vec{\nabla}\cdot h]dv = 0 \qquad (6)$$

by using divergence theorem

$$\int_v [2\alpha_i^2 \ (u-u_0) - \vec{\nabla}\cdot\lambda]\cdot h dv + \int_v \vec{\nabla}\cdot(\lambda h)dv = 0 \qquad (7)$$

Since h is an arbitrary function, Eq (7) can only be satisfied if

$$2\cdot\alpha_i^2 \ (u-u_0) = \vec{\nabla}\cdot\lambda \qquad (8)$$

$$\vec{\nabla}\cdot(\lambda h) = 0 \qquad (9)$$

Eq (8) satisfies the continuity equation

$$\vec{\nabla}\cdot u = 0 \qquad (10)$$

Substitution of Eq (8) into Eq (10) provides the partial differential equation describing in $x-z$ plane.

$$\frac{\partial^2\lambda}{\partial x^2} + \left(\frac{\alpha_1}{\alpha_2}\right)^2 \cdot \frac{\partial^2\lambda}{\partial z^2} = -2\alpha_1^2 \cdot \left(\frac{\partial u_0}{\partial x} + \frac{\partial w_0}{\partial z}\right) \qquad (11)$$

where u and w are the wind speed in $x-$ and $z-$direction, respectively. And Eq (9) provides the boundary conditions.

In this study, the $x-z$ plane is subdivided

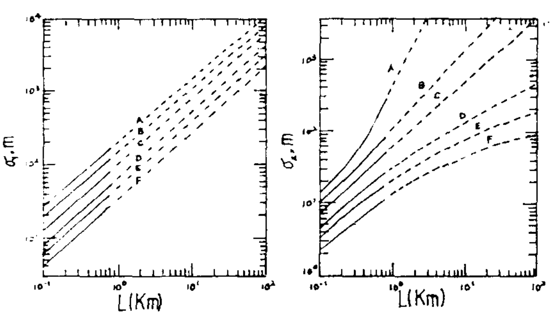

Fig. 1. Dispersion Coefficients

The dashed lines indicate that relations are tentative and unreliable beyond 1,000m.

into an array of grid points as shown in Fig. 2. At every grid point within the boundaries, Eq (11) is approximated by the finite difference form

$$\frac{A_l\cdot\lambda(i+1,k)-B_l\cdot\lambda(i,k)+C_l\cdot\lambda(i-1,k)}{\Delta x^2}+\left(\frac{\alpha_1}{\alpha_2}\right)^2\cdot\frac{A_m\cdot\lambda(i,k+1)-B_m\cdot\lambda(i,k)+C_m\cdot\lambda(i,k-1)}{\Delta z^2}=-2\cdot\alpha_1^2\left[\frac{u_0(i+1,k)-u_0(i,k)}{\Delta x}+\frac{w_0(i,k+1)-w_0(i,k)}{\Delta z}\right] \quad (12)$$

Where the subscripts i and k denote $x-$ and $z-$ coordinates respectively and l and m are integer values ranging one to eight which describe the relationship between the boundaries and grid point in $x-$ and $z-$directions.

This set of linear equations is solved iteratively with a succesive over-relaxation method.[7,8] Then the adjusted wind field are calculated by introducing the $\lambda(i,k)$ which is obtained with Eq (12) into difference formulation of Eq (8).

In this study, the aim was to compare Gaussian plume model with numerical model in complex terrain, so that the assumptions used in Gaussian plume model are employed in numerical model.

In this case the diffusion equation may be written as

$$u\frac{\partial c}{\partial x}+w\frac{\partial c}{\partial z}-\frac{\partial}{\partial z}\left(k_z\cdot\frac{\partial c}{\partial z}\right)=0 \quad (13)$$

and the mass flow around a grid is illustrated in Fig. 3. At every grid points, the conservation equation is written as[9]

$$k_{zp}\cdot\frac{\Delta x}{\Delta z}(c_p-c_n)+u_p\cdot\Delta z\cdot c_p+w_p\cdot\Delta x\cdot c_p=k_{zs}\cdot\frac{\Delta x}{\Delta z}(c_s-c_p)+u_w\cdot\Delta z\cdot c_w+w_s\cdot\Delta x\cdot c_s. \quad (14)$$

where k_z is the vertical diffusion coefficient which is calculated in neutral condition as[10]

$$k_z=0.221z \quad (15)$$

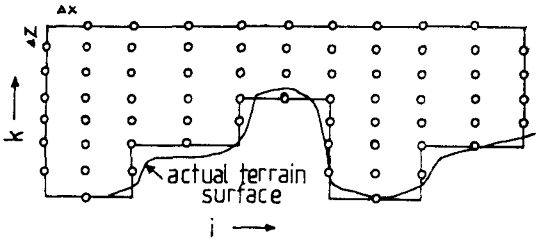

Fig. 2. Topography in Two Dimensions

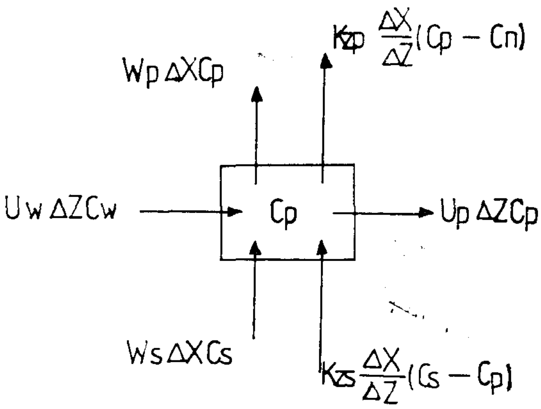

Fig. 3. Mass Diffusion in x-z Plane

Then the concentrations at each grid points can be obtained by solving the set of linear equations of Eq (14) with a successive over-relaxation method.

3. Compensation of the Dispersion Coefficients

In two dimensional flow in $x-z$ plane, the Gaussian plume equation is described by

$$C=\frac{1}{\sqrt{2\pi}\cdot\sigma_z\cdot U}\left\{\exp\left[-\frac{1}{2}\left(\frac{Z-H}{\sigma_z}\right)^2\right]+\exp\left[-\frac{1}{2}\left(\frac{Z+H}{\sigma_z}\right)^2\right]\right\} \quad (16)$$

In neutral condition, the vertical coefficient σ_z is represented by[2]

$$\sigma_z=0.113x^{0.911} \quad (17)$$

where x is the downwind distance.

In this study the $x-z$ plane is subdivided into a rectangular grid with intervals of Δx(=500m), Δz(=25m) in x-and z-directions, res-

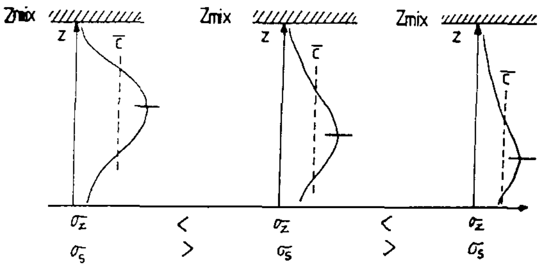

Fig. 4. The Distribution of Concentration

pectively and there are 30×40 grid points. The distribution of concentration which is obtained by Eq (16) is shown in Fig. 4 and with this figures we find out that as the downwind distance increases the vertical dispersion coefficient σ_z increases, but the standard deviation of the concentration distribution σ_s decreases. With this concept, at first the relation between the dispersion coefficient in Gaussian plume model and the concentration distribution in each column is derived. The standard deviation in each column is

$$\sigma_s=\sqrt{\frac{1}{N}\sum_{j=1}^{N}(c_j-\bar{c})^2} \qquad (18)$$

where c_j is the concentration of jth grid, $\bar{c}$ is the mean value of concentrationc in each column and N is the number of grids in z-direction.

For the purpose of knowing the extent of diffusion in each column, every standard deviation is divided by that of the first column. These ratios are shown in Fig. 5 and by taking

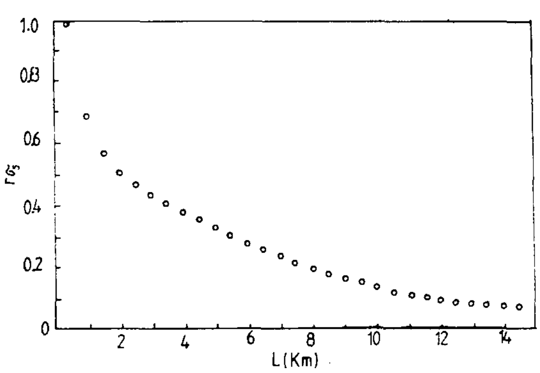

Fig. 5. The Ratios of Standard Deviations

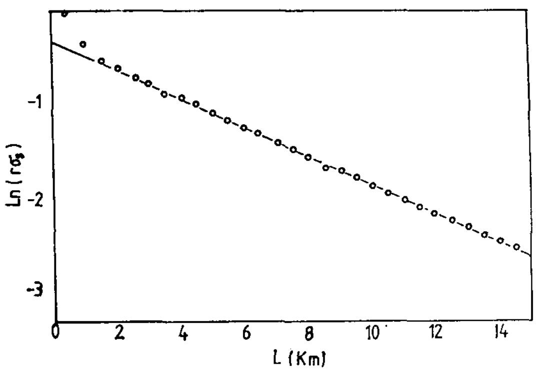

Fig. 6. The Ln Values of the Ratios of σ_s

logarithm of these ratios, a linear line is obtained and shown in Fig. 6.

The relation between the value of logarithm and the distance is represented by

$$\mathrm{Ln}(r\sigma_s)=ax+b \qquad (19)$$

where $r\sigma_s$ is the ratios of the standard deviation and a and b are constants. From Eq (19)

$$x=\frac{1}{a}\cdot[\ln(r\sigma_s)-b] \qquad (20)$$

Substitution of Eq (20) into Eq (17) provides

$$\sigma_z=0.113\left\{\frac{1}{a}[\ln(r\sigma_s)-b]\right\}^{0.911} \qquad (21)$$

From Eq (21), it is possible to obtain the compensation factor of the vertical dispersion coefficient in complex terrain

$$\beta\equiv\frac{\sigma_z}{\sigma_{zf}}=\left[\frac{\ln(r\sigma_s)-b}{\ln(r\sigma_s)_f-b}\right]^{0.911} \qquad (22)$$

where the subscript f denotes the flat terrain.

4. Dose Calculation Model

In this study, the dose calculation model which is described in WASH-1400, Appendix Ⅵ was adopted.[1] This model approaches the calculation by dividing the area around a nuclear power plant into radial annuli which are called spatial intervals, and all procedures are processed in each spatial intervals.

The concentration of each radionuclides in the air is described as

$$A_c = \frac{C}{Q} \cdot A_0 \cdot \exp\left(\frac{-0.693 \cdot t'}{T_{1/2}}\right)(1-fd) \tag{23}$$

where A_0 is the core inventory of activity of the radionuclides, $T_{1/2}$ is the half-life, t' is the time required for the radionuclide to reach the spatial interval from the time of accident and fd is the removal fraction. The estimates of doses due to external exposure to the passing cloud incorporate a semi-infinite cloud approximation. In this approximation, doses are calculated with the assumption that plume is infinitely large and compensated for real plume size. The cloudshine doses are calculated as

$$E_c = A_c^* \cdot D_c^\infty \cdot f(D_c/D_c^\infty) \cdot SF \text{ [rem]} \tag{24}$$

where A_c^* is the time-integrated air concentration, D_c is cloud dose conversion factor and D_c^∞ is semi-infinite cloud dose conversion factor, $f(D_c/D_c^\infty)$ is a correction factor used to correct the calculated semi-infinite cloud doses for a finite cloud which is dependent on the plume height and the vertical dispersion coefficient and SF is shielding factor. The passing cloud of radionuclide deposites the material on the ground by the process of wet and dry deposition. The deposited material provides a source of gamma radiation. The groundshine is calculated as

$$E_g = G_c \cdot D_g \cdot SF \text{ [rem]} \tag{25}$$

where G_c is the ground concentration of each radionuclides and D_g is a time integral dose conversion factor. During the period when individuals are immersed in the radioactive cloud, the air they breathed contains radioactive material and these are the sources of internal exposure. The quantity of radioactive material inhaled is calculated by multiplying atmospheric concentration by the breathing rate. Finally the doses from inhaled radionuclides are obtained by multiplying the dose conversion factor for each organ.

$$E_i = A_c \cdot B_r \cdot D_i \text{ [rem]} \tag{26}$$

5. Results and Discussion

In this study, the calculation is performed for the following two situations; one is for a little complex terrain and the other is for a more complex terrain. In Fig. 7 the values of $\mathrm{Ln}(r\sigma_s)$ and terrain height in a little complex terrain are shown, and in Fig. 8 those in a more complex terrain are shown. In these two figures, the height of terrain is represented by the number of grids in z-direction.

The compensation factors obtained from Eq (22) for both situations are represented in Table 1. And then with these compensation factors, the C/Q values are obtained for these two situa-

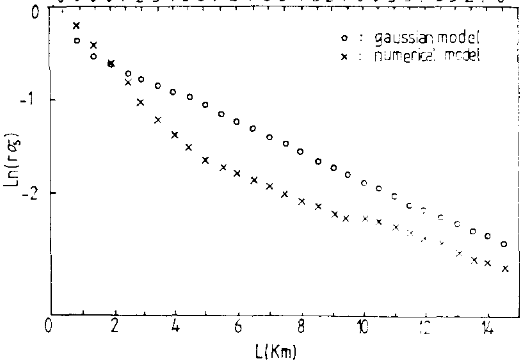

Fig. 7. The Values of Ln ($r\sigma_s$) in a little Complex Terrain

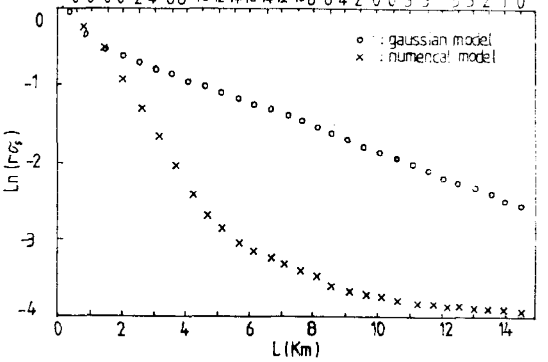

Fig. 8. The Values of Ln ($r\sigma_s$) in a more Complex Terrain

Table 1. The Compensation Factors

Distance (km)		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
β	Case 1	1.0	1.0	1.05	1.17	1.21	1.18	1.22	1.25	1.25	1.25	1.17	1.09	1.10	1.11	1.11
	Case 2	1.0	1.0	1.36	1.47	1.49	1.44	1.62	1.84	1.93	1.94	1.82	1.65	1.64	1.62	1.60

Table 2. The Dilution Factor

Distance (km)		1	2	5	7	9	11	13	15
(C/Q)f		2.57E-5	3.10E-6	1.63E-6	4.81E-7	4.15E-7	3.87E-7	2.84E-7	2.05E-7
Case 1	β	1.0	1.17	1.21	1.24	1.25	1.13	1.1	1.1
	C/Q	2.57E-5	2.44E-6	1.11E-6	3.13E-7	2.66E-7	2.97E-7	2.34E-7	1.42E-7
	f	1.0	1.3	1.47	1.54	1.56	1.3	1.21	1.44
Case 2	β	1.0	1.44	1.49	1.75	1.95	1.74	1.63	1.60
	C/Q	2.57E-5	1.51E-6	7.34E-7	1.57E-7	1.09E-7	1.27E-7	1.08E-7	8.0E-8
	f	1.0	2.1	2.2	3.1	3.8	3.0	2.6	2.5

tions. In Table 2, the values of C/Q in flat terrain and in complex terrain are described with dilution factors along the spatial intervals. The dilution factor is defined as

$$f=\frac{C/Q}{(C/Q)_f} \qquad (27)$$

The results indicate that the concentrations over the complex terrain are more dilute by

Table 3. The Field Measurement Data

Location	Height of terrain	Dilution Factor
Huntington Canyon utah	~400m	1 ~4
Garfield utah		2 ~4
Operation Mountain Iron		1.5~3

Table 4. Early Exposure Dose [rem]

Spatial interval	Case 1				Case 2			
	Total MARROW	LUNG	WHOLE BODY	THYROID	Total MARROW	LUNG	WHOLE BODY	THYROID
1 (0.8km)	2.3E0	5.4E0	1.8E0	2.9E1	2.3E0	5.4E0	1.8E0	2.9E1
2 (1.6km)	9.7E-1	1.9E0	8.0E-1	9.1E0	9.7E-1	1.9E0	8.0E-1	9.1E0
3 (2.4km)	5.8E-1	1.0E0	4.8E-1	4.7E0	4.8E-1	8.0E-1	4.0E-1	3.6E0
4 (3.2km)	3.8E-1	6.2E-1	3.2E-1	2.8E0	2.8E-1	4.8E-1	2.4E-1	1.8E0
5 (4. km)	2.7E-1	4.3E-1	2.3E1	1.8E0	2.1E-1	3.0E-1	1.8E-1	1.2E0
6 (4.8km)	2.1E-1	3.1E-1	1.8E-1	1.3E0	1.6E-1	2.3E-1	2.3E-1	8.6E-1
7 (5.6km)	1.7E-1	2.5E-1	1.3E-1	1.0E0	1.3E-1	1.9E-1	1.2E-1	7.1E-1
8 (6.4km)	1.1E-1	1.5E-1	9.4E-2	5.8E-1	8.3E-2	1.1E1	7.2D-2	3.7E1
9 (8. km)	7.5E-2	1.0E-1	6.4E-2	3.6E-1	5.1E-2	6.1E-2	4.4E-2	1.9E1
10 (9.7km)	6.7E-2	9.0E-2	5.7E-2	3.3E-1	4.3E-2	5.2E-2	3.8E-2	1.6E-1
11 (13.7km)	6.1E-2	8.3E-2	5.3E-2	3.0E-1	3.8E-2	4.5E-2	3.3E-2	1.4E-1
12 (16. km)	6.1E-2	8.6E-2	5.3E-2	3.3E-1	3.8E-2	4.7E-2	3.3E-2	1.5E-1
13 (19.3km)	4.6E-2	6.6E-2	3.9E-2	2.5E-1	3.0E-2	3.8E-2	2.6E-2	1.3E-1
14 (24.1km)	2.0E-2	4.1E-2	2.5E-2	1.5E-2	2.1E-2	2.7E-1	1.8E-2	9.1E-2
15 (28.1km)	2.2E-2	3.0E-2	1.8E-1	1.1E-2	1.6E-2	2.0E-2	1.6E-2	6.8E-2
16 (32.2km)	1.7E-2	2.4E-2	1.5E-2	9.3E-2	1.3E-2	1.6E-2	1.1E-2	5.6E-2

a factor of about 1 to 4 than expected over flat terrain using Pasquills curve. These results are coincident with the data of field measurements in complex terrain performed in U.S.A. The brief summary of the measurements are represented in Table 3.

By introducing the compensated C/Q values to the dose calculation model the early exposure doses are calculated for each spatial interval in complex terrain. These doses are shown in Table 4. The chronic exposure doses can be calculated with the same method.

6. Conclusions

1) The compensation of the vertical dispersion coefficient in complex terrain was performed by comparing the Gaussian plume model with numerical model in two dimensional $x—z$ plane for the two cases; one is for a little complex terrain and the other is for more complex terrain.

2) The numerical experiment shows that the vertical dispersion coefficients in complex terrain are a factor of 1 to 1.3 for case 1 and a factor of 1 to 1.9 for case 2, greater than those predicted from the Pasquill curve.

3) The results indicate that the concentrations over complex terrain are a factor of 1 to 2 for case 1 and a factor of 1 to 4 for case 2, more dilute than those expected over flat terrain.

4) By introducing these results into Gaussian plume model, it is possible to apply the CRAC, GASPAR and CHRONIC codes to Korea which has very comple terrain. These codes adopt Gaussian plume model as the transport and dispersion mechanism of gaseous radioactive effluents.

5) In this study the compensation of the vertical dispersion coefficients was performed only for the case of neutral atmospheric condition. For the application of this model to real situation, it is required to compensate the dispersion coefficients for unstable and stable atmospheric conditions over complex terrain.

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