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The Annual Averaged Atmospheric Dispersion Factor and Deposition Factor According to Methods of Atmospheric Stability Classification

Hae Sun Jeong*, Hyo Joon Jeong, Eun Han Kim, Moon Hee Han, Won Tae Hwang

Korea Atomic Energy Research Institute, Daejeon, Korea

ABSTRACT

Background: This study analyzes the differences in the annual averaged atmospheric dispersion factor and ground deposition factor produced using two classification methods of atmospheric stability, which are based on a vertical temperature difference and the standard deviation of horizontal wind direction fluctuation.

Materials and Methods: Daedeok and Wolsong nuclear sites were chosen for an assessment, and the meteorological data at 10 m were applied to the evaluation of atmospheric stability. The XOQDOQ software program was used to calculate atmospheric dispersion factors and ground deposition factors. The calculated distances were chosen at 400 m, 800 m, 1,200 m, 1,600 m, 2,400 m, and 3,200 m away from the radioactive material release points.

Results and Discussion: All of the atmospheric dispersion factors generated using the atmospheric stability based on the vertical temperature difference were shown to be higher than those from the standard deviation of horizontal wind direction fluctuation. On the other hand, the ground deposition factors were shown to be same regardless of the classification method, as they were based on the graph obtained from empirical data presented in the Nuclear Regulatory Commission's Regulatory Guide 1.111, which is unrelated to the atmospheric stability for the ground level release.

Conclusion: These results are based on the meteorological data collected over the course of one year at the specified sites; however, the classification method of atmospheric stability using the vertical temperature difference is expected to be more conservative.

Keywords: Atmospheric dispersion factor, Ground deposition factor, Atmospheric stability, Vertical temperature difference, Standard deviation of horizontal wind direction fluctuation

Original Research

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Corresponding author: Hae Sun Jeong

Korea Atomic Energy Research Institute,
989 Daedeok-daero, Yuseong-gu,
Daejeon 34057, Korea
Tel: +82-42-868-4516
Fax: +82-42-868-2370
E-mail: haesunin@kaeri.re.kr

Introduction

The operation of nuclear power stations is inevitably associated with routine releases of radioactive materials in gaseous effluents. In order to assess the maximum radiological dose to the public, an assessment of atmospheric dispersion and of ground deposition around the nuclear site of concern must be conducted using meteorological data. The U.S. Nuclear Regulatory Commission (NRC) provides a model for the assessment of annual averaged atmospheric dispersion and of annual averaged ground deposition in their Regulatory Guide 1.111. The NRC also provides a computer program (XOQDOQ) that allows analyses to be carried out according to their guidelines [1, 2]. The program uses a joint frequency distribution of atmospheric stability, derived from meteorological data, to calculate projected atmospheric dispersion and ground deposition.

The NRC Regulatory Guide 1.23 presents several methods of classifying atmospheric stability. The vertical temperature difference (ΔT) method and the standard deviation of horizontal wind direction fluctuations (σ_θ) method are the general methods for determining atmospheric stability [3]. The Korean Nuclear Safety and Security Commission Notification No. 2014-25 concerning the assessment standards of the meteorological conditions of nuclear facilities follows and endorses the NRC guidelines for classifying atmospheric stability [4]. Methods of classifying and evaluating atmospheric stability differ among countries; nuclear facilities in Korea principally use the ΔT method to estimate atmospheric stability and the σ_θ method as an ancillary method. In cases where the meteorological data required for assessing ΔT cannot be obtained due to the limited height of meteorological tower, the σ_θ method must be used as an alternative.

Since the calculation of the atmospheric dispersion factor and the ground deposition factor are significantly influenced by atmospheric stability, the choice of classification system for atmospheric stability warrants special attention. In this study, we compared meteorological measurements at the Daedeok and the Wolsong nuclear sites. We compared the annual averaged atmospheric dispersion factors and the ground deposition factors between these two sites, using values derived from estimates of atmospheric stability based on either the ΔT or the σ_θ method.

Materials and Methods

1. Analysis of the meteorological data

The Daedeok site is located in inland Korea. It accommodates a variety of nuclear facilities run by Korea Atomic Energy Research Institute (KAERI), Korea Radioactive Waste Agency (KORAD), and KEPCO Nuclear Fuel (KNF). The Wolsong site is situated in a coastal region. This nuclear power plants operates a total of 6 water reactors, 4 pressurized heavy water reactors, and 2 pressurized water reactors that have been more recently established.

In order to assess atmospheric dispersion and ground deposition at the Daedeok and the Wolsong sites, we compiled meteorological data from each site measured at a 10 meters above the ground between January 2013 and December 2013. Figure 1 illustrates the wind roses of each site corresponding to the period of data collection. The values within the concentric circles represent the probability of calm condition. The data show that the Daedeok site is associated with a relatively higher prevalence of low wind velocities than the Wolsong site. Northwest winds predominated at the Daedeok site, and northwest winds in the direction of the sea predominated at the Wolsong site.

Atmospheric stability is a critical factor for simulations of atmospheric dispersion and ground deposition using Gaussian plume model. Early studies on atmospheric stability were performed by Giblett in 1932 and later by Smith of Brookhaven National Laboratory in 1951 [5, 6]. Additionally,

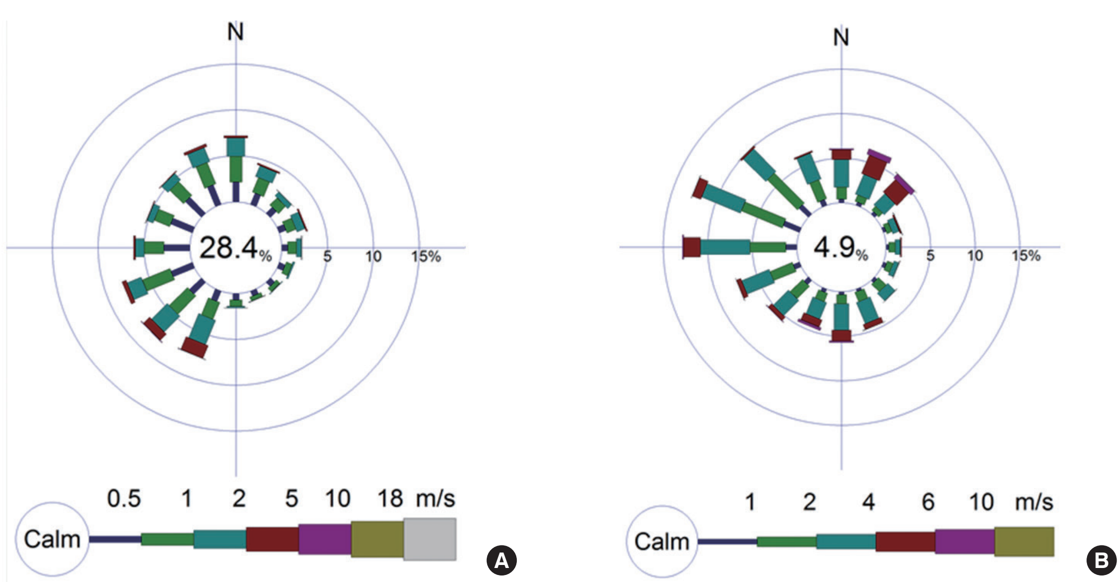

Fig. 1. Wind roses for the height of 10 m above ground level at (A) the Daedeok site and (B) the Wolsong site in 2013.

other fundamental concepts were established by Pasquill in 1961, which have since been further developed [7]. Numerous methods of estimating atmospheric stability have been proposed, and the basic meteorological parameters used in the estimation include the vertical temperature difference (ΔT), standard deviation of horizontal wind direction fluctuation (σ_θ), solar radiation, and cloud cover [8].

The NRC Regulatory Guide 1.23 presents Pasquill stability categories for atmospheric stability that are based on either ΔT or σ_θ (Table 1). The Pasquill system is a fairly reliable reflection of synoptic atmospheric stability under steady-state conditions, and because the routine collection of meteorological elements is useful for other purposes, this classification system is widely used. Our assessment used 7 subclasses of stability, with category A representing extremely unstable conditions and category G representing extremely stable conditions. The ΔT method of classification of atmospheric stability uses the difference in temperature between two atmospheric levels, and takes into account vertical mixing in the atmosphere and the vertical dispersal induced by wind velocity. The meteorological measurements involved in the ΔT method are useful and straightforward for estimating atmospheric stability, but require an observatory tower of a certain height. Cramer proposed the σ_θ method for estimating atmospheric stability, which is based on the hypothesis that the dispersion of atmospheric pollutants induced by strong wind conditions at a given altitude is similar to the dispersion caused during conditions of atmospheric instability [9]. Similarly to the ΔTmeasurements, because the σ_θ data have been shown to be useful in other ways and the σ_θ has indeed been shown to be closely correlated to atmospheric stability, its use is widespread.

In this study, we used ΔT and σ_θ to determine Pasquill stability classes at the Daedeok site and the Wolsong site. To calculate ΔT, the temperatures were measured at 10 and 67 meters above ground level at the Daedeok site and at 10 and 58 meters above ground level at the Wolsong site, while σ_θ was calculated from measurements made 10 meters above ground level. The resulting parameters were used to estimate and classify atmospheric stability.

Table 1. Two Methods of Classifying Atmospheric Stability

Stability classification	Pasquill category	Temperature change with height [°C per 100 m]	σ_θ* [degrees]
Extremely unstable	A	$\Delta T/\Delta z \le -1.9$	$\sigma_\theta \ge 22.5$
Moderately unstable	B	$-1.9 < \Delta T/\Delta z \le -1.7$	$22.5 > \sigma_\theta \ge 17.5$
Slightly unstable	C	$-1.7 < \Delta T/\Delta z \le -1.5$	$17.5 > \sigma_\theta \ge 12.5$
Neutral	D	$-1.5 < \Delta T/\Delta z \le -0.5$	$12.5 > \sigma_\theta \ge 7.5$
Slightly stable	E	$-0.5 < \Delta T/\Delta z \le 1.5$	$7.5 > \sigma_\theta \ge 3.8$
Moderately stable	F	$1.5 < \Delta T/\Delta z \le 4.0$	$3.8 > \sigma_\theta \ge 2.1$
Extremely stable	G	$4.0 < \Delta T/\Delta z$	$2.1 > \sigma_\theta$

*σ_θ: Standard deviation of horizontal wind direction fluctuation over a period of 15 minutes to 1 hour.

2. Annual averaged atmospheric dispersion and ground deposition

The gaseous effluents from nuclear facilities is dispersed into the atmosphere and deposited onto the ground according to meteorological and geographical conditions. The extent to which radioactive material disperses into the atmosphere and is deposited onto the ground can be denoted as the atmospheric dispersion factor (χ/Q) and the ground deposition factor (D/Q), respectively. In accordance to the NRC Regulatory Guide 1.111, a straight-line Gaussian plume model using a statistical data that is compiled into the annual joint frequency distributions according to atmospheric stability class can be used to simulate dispersion. With regard to ground-level release, the higher of the atmospheric dispersion factors derived from equations (1) and (2) is used.

$$\frac{\chi}{Q}(x,k)=\frac{2.032}{x}RF(x,k)\sum_{ij}DP_{ij}(x,k)DC_i(x)f_{ij}(x,k)[u_i(\sigma_{zj}^2(x)+CD_Z^2/\pi)^{1/2}]^{-1} \quad (1)$$

$$\frac{\chi}{Q}(x,k)=\frac{2.032}{x}RF(x,k)\sum_{ij}DP_{ij}(x,k)DC_i(x)f_{ij}(k)[\sqrt{3}u_i\sigma_{zj}(x)]^{-1} \quad (2)$$

χ/Q: annual averaged atmospheric dispersion factor (sec·m^{-3})
x: downward wind distance (m)
i: index of wind speed
j: index of atmospheric stability classes
k: index of wind direction
u: wind velocity along the plume centerline (m·sec^{-1})
σ_{zj}: vertical diffusion coefficient (m)
f: probability of meteorological occurrence
RF: correction factor for air recirculation and stagnation
DP: correction factor for plume depletion
DC: correction factor for radioactive decay
C: constant for building wake effect (=0.5)
D_z: structure height [m]
$2.032=\frac{2n}{(2\pi)^{3/2}}$ (n: number of wind-direction sectors)

The ground deposition factor, which represents the degree of deposition of gaseous effluents, considers only dry process.

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$$\frac{D}{Q}(x,k)=\frac{RF(x,k)\sum_{ij}D_{ij}f_{ij}(k)}{(2\pi/n)x} \quad (3)$$

Here,
D/Q: annual averaged ground deposition factor (m^{-2})
D: relative deposition rate (m^{-1})

Results and Discussion

We used the joint frequency distribution according to atmospheric stability class to calculate annual averaged dispersion factor and annual averaged deposition. After estimating atmospheric stability on the basis of ΔT or σ_θ, we performed a comparative analysis of the meteorological characteristics derived from these two methods of classifying stability. Assuming a ground level release, we used meteorological data obtained 10 meters above ground level. For the assessment of ΔT, measurements were taken at 10 and 67 meters above ground level at Daedeok and at 10 and 58 meters above ground level at Wolsong. Other meteorological characteristics, such as the building wake effect and the recirculation and stagnation of building turbulence that are specifications of each nuclear facility were not considered. Rather, in this study, we chose only to investigate the effects of meteorological characteristics on atmospheric stability. In accordance with the NRC Regulatory Guide 1.23, we subdivided wind speed into 11 categories.

Figures 2 and 3 show the occurrence probability according to the classification method (ΔT or σ_θ) at the Daedeok site and at the Wolsong site. For the Daedeok site, the distribution of atmospheric stability results based on ΔT was generally homogeneous, showing a slight peak at category E (slightly stable atmospheric conditions). In contrast, the distribution of atmospheric stability results based on σ_θ showed a highly skewed distribution; the occurrence of category A (extremely unstable) atmospheric conditions had a probability over 90%. For the Wolsong site, ΔT-based atmospheric stability was most strongly associated with category E (slightly stable) atmospheric conditions and σ_θ-based atmospheric stability was most strongly associated with category A (extremely unstable) atmospheric conditions. However, these associations were not as strong as those observed for the Daedeok site.

Joint frequency distribution based on these two classification methods was input into the XOQDOQ program to calculate the atmospheric dispersion factor and the ground deposition factor. Radioactive decay and plume depletion were not taken into account. A total of 7 distances from a release point were chosen for comparison and discussion of the results: 400 m, 800 m, 1,200 m, 1,600 m, 2,400 m, 3,200 m, and 4,000 m. Figures 4 and 5 illustrate the atmospheric dispersion factors at each calculation distance according to the classification method for the Daedeok site. The maximum value of atmospheric dispersion factor based on ΔT was 1.46×10^{-4} $sec\cdot m^{-3}$ in the east direction, and that based on σ_θ was 2.25×10^{1} $sec\cdot m^{-3}$ in the east-northeast direction. Likewise, Figures 6 and 7 illustrate the atmospheric dispersion factors according to the classification method at various calculation distances of the Wolsong site. The maximum atmospheric dispersion factor based on ΔT was 6.62×10^{-5} $sec\cdot m^{-3}$ in the east-southeast direction and the maximum atmospheric dispersion factor based on σ_θ was 1.50×10^{-5} $sec\cdot m^{-3}$

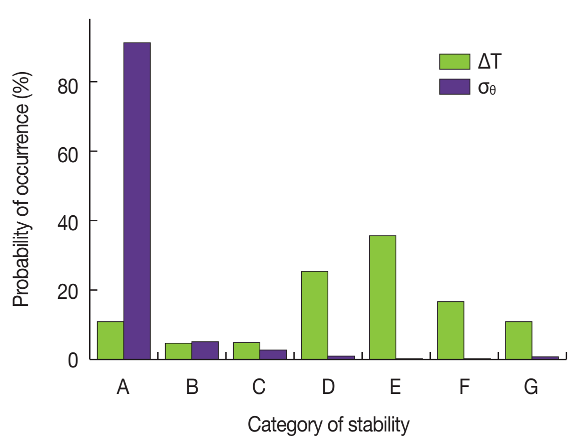

Fig. 2. Joint frequency distributions according to stability category at the Daedeok site.

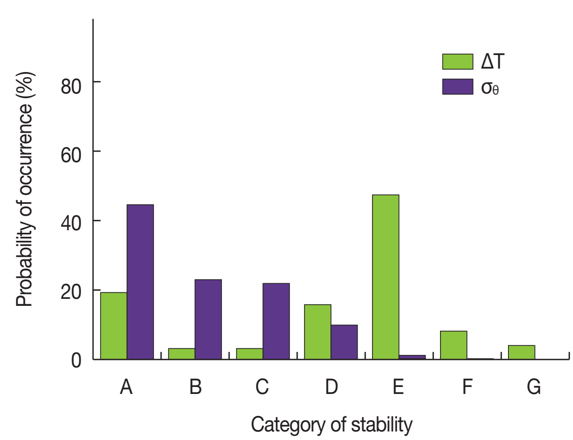

Fig. 3. Joint frequency distributions according to stability category at the Wolsong site.

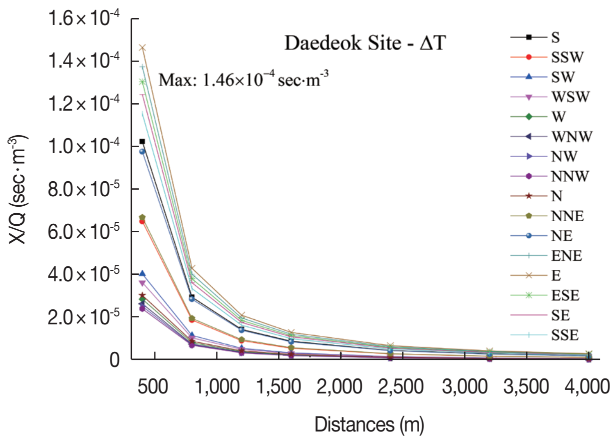

Fig. 4. Annual averaged atmospheric dispersion factors (χ/Q) evaluated using atmospheric stability based on temperature differences at the Daedeok site.

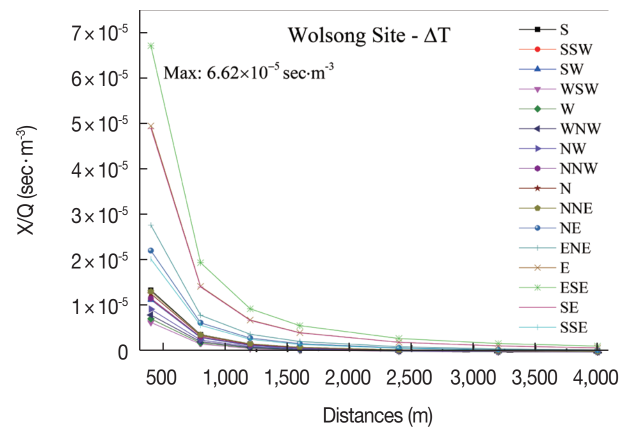

Fig. 6. Annual averaged atmospheric dispersion factors (χ/Q) evaluated using atmospheric stability based on temperature differences at the Wolsong site.

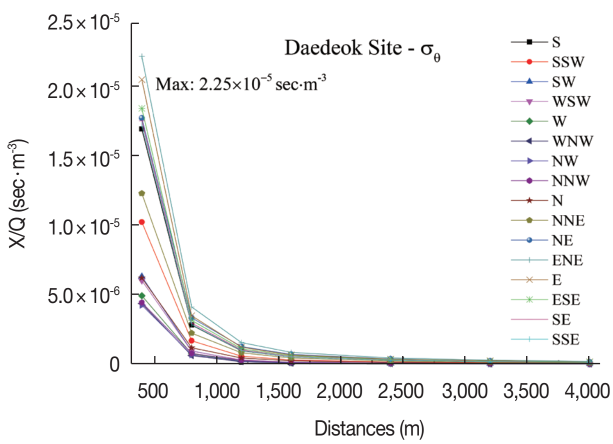

Fig. 5. Annual averaged atmospheric dispersion factors (χ/Q) evaluated using atmospheric stability based on the standard deviation of horizontal wind direction fluctuation at the Daedeok site.

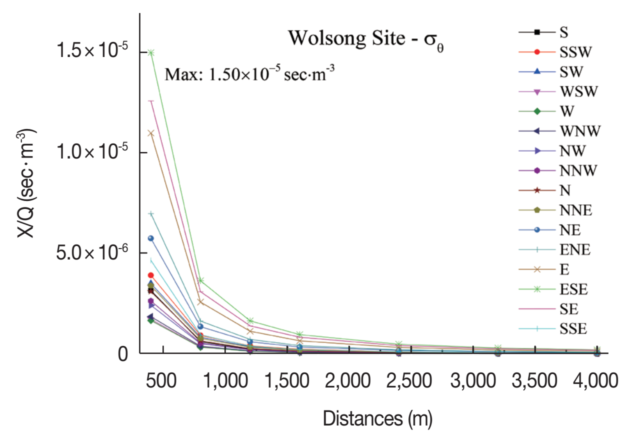

Fig. 7. Annual averaged atmospheric dispersion factors (χ/Q) evaluated using atmospheric stability based on the standard deviation of horizontal wind direction fluctuation at the Wolsong site.

in the east-southeast direction. The maximum values of the ground deposition factor, regardless of the classification method used, were found in the east-northeast direction at the Daedeok site (Figures 8, 9) and in the east-southeast direction at the Wolsong site (Figures 10, 11). The maximum values of the ground deposition factor were as follows: at the Daedeok site, 6.24×10^{-8} m^{-3} (ΔT method) and 6.28×10^{-8} m^{-3} (σ_θ method); and at the Wolsong site, 7.92×10^{-8} m^{-3} (ΔT method) and 7.76×10^{-8} m^{-3} (σ_θ method). Our results suggest that atmospheric stability based on ΔT is the more conservative in calculating the annual averaged atmospheric dispersion factor and the ground deposition factor, with the exception of the ground deposition factor at the Daedeok site.

To protect radiation-induced health detriment of the public, the atmospheric dispersion factor and the ground deposition factor should be evaluated based on their maximum values when determining acceptability within the limits of legal standards. Therefore, we compared the maximum values of these factors according to methods of classifying atmospheric stability. Table 2 shows the highest atmospheric dispersion factor evaluated by each classification method at varying distances from the nuclear facilities in Daedeok and in Wolsong sites. At both sites, the atmospheric dispersion factor based on ΔT was higher than that based on σ_θ. The difference between the two atmospheric dispersion factors by different classification systems appears to be correlated to the distance from the nuclear power station: the greater the distance from the nuclear facilities, the larger the difference between the factors. The atmospheric dispersion factor based on ΔT was 6.5 to 14.5 times higher than the atmo-

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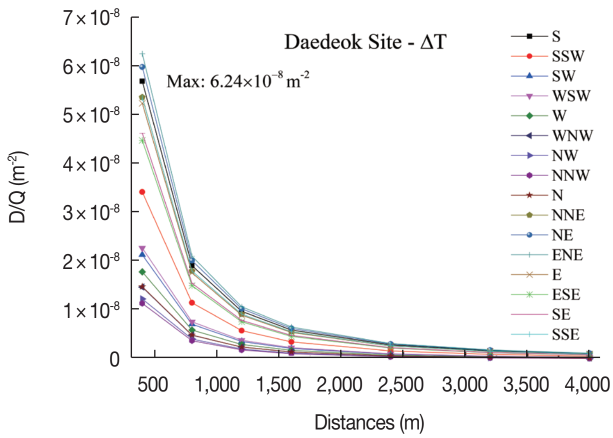

Fig. 8. Annual averaged ground deposition factors (D/Q) evaluated using atmospheric stability based on temperature differences at the Daedeok site.

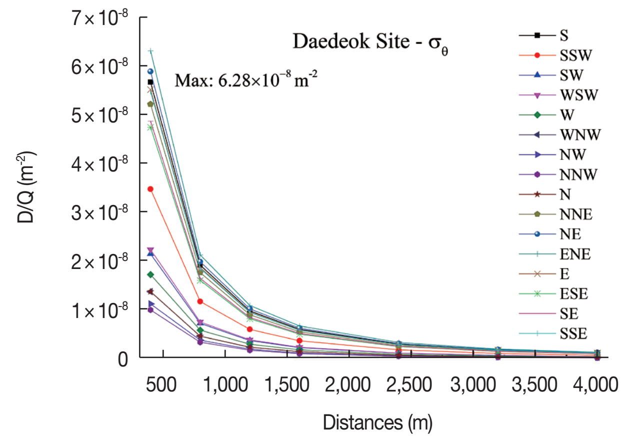

Fig. 9. Annual averaged ground deposition factors (D/Q) evaluated using atmospheric stability based on the standard deviation of horizontal wind direction fluctuation at the Daedeok site.

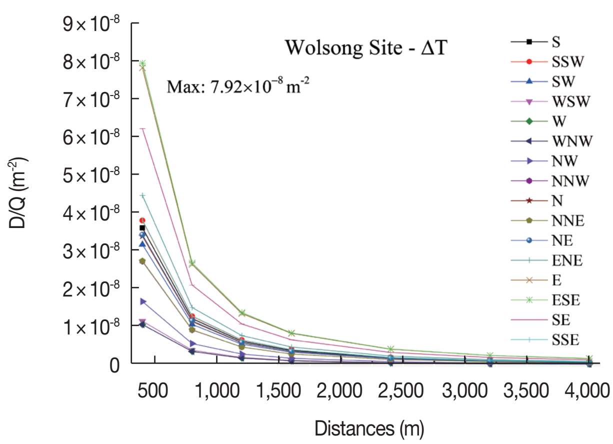

Fig. 10. Annual averaged ground deposition factors (D/Q) evaluated using atmospheric stability based on temperature differences at the Wolsong site.

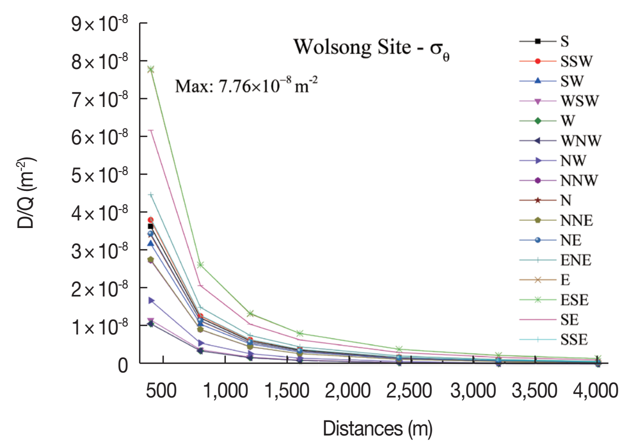

Fig. 11. Annual averaged ground deposition factors (D/Q) evaluated using atmospheric stability based on the standard deviation of horizontal wind direction fluctuation at the Wolsong site.

Table 2. Maximum Values of Annual Averaged Atmospheric Dispersion Factors (χ/Q) Evaluated Using Two Methods of Atmospheric Stability Classification

[m]	Daedeok			Wolsong		
	ΔT [sec·m^{-3}]	$\sigma\theta$ [sec·m^{-3}]	$\Delta T/\sigma\theta$	ΔT [sec·m^{-3}]	$\sigma\theta$ [sec·m^{-3}]	$\Delta T/\sigma\theta$
400	1.46×10^{-4}	2.25×10^{-5}	6.51	6.62×10^{-5}	1.50×10^{-5}	4.43
800	4.29×10^{-5}	4.21×10^{-6}	10.20	1.94×10^{-5}	3.65×10^{-6}	5.31
1,200	2.10×10^{-5}	1.61×10^{-6}	13.07	9.49×10^{-6}	1.65×10^{-6}	5.76
1,600	1.30×10^{-5}	8.95×10^{-7}	14.48	5.86×10^{-6}	9.68×10^{-7}	6.05
2,400	6.79×10^{-6}	4.87×10^{-7}	13.94	3.08×10^{-6}	4.85×10^{-7}	6.34
3,200	4.37×10^{-6}	3.23×10^{-7}	13.52	1.98×10^{-6}	3.01×10^{-7}	6.59
4,000	3.13×10^{-6}	2.38×10^{-7}	13.17	1.42×10^{-6}	2.09×10^{-7}	6.80

spheric dispersion factor based on σ_θ at the Daedeok site and 4.4 to 6.8 times higher at the Wolsong site.

The maximum values of the annual averaged ground deposition factor according to the atmospheric stability classification at varying distances from the nuclear facilities are presented in Table 3. For both sites, we found that the ratio of the ground deposition factors determined using the different methodologies (ground deposition factor based on ΔT to

Table 3. Maximum Values of the Annual Averaged Ground Deposition Factors (D/Q) Evaluated Using Two Methods of Atmospheric Stability Classification

[m]	Daedeok			Wolsong		
	ΔT [sec·m^{-2}]	$\sigma\theta$ [sec·m^{-2}]	$\Delta T/\sigma\theta$	ΔT [sec·m^{-2}]	$\sigma\theta$ [sec·m^{-2}]	$\Delta T/\sigma\theta$
400	6.24×10^{-8}	6.24×10^{-8}	0.99	7.92×10^{-8}	7.76×10^{-8}	1.02
800	2.11×10^{-8}	2.11×10^{-8}	0.99	2.68×10^{-8}	2.62×10^{-8}	1.02
1,200	1.08×10^{-8}	1.08×10^{-8}	0.99	1.38×10^{-8}	1.35×10^{-8}	1.02
1,600	6.66×10^{-9}	6.66×10^{-9}	0.99	8.44×10^{-9}	8.27×10^{-9}	1.02
2,400	3.32×10^{-9}	3.32×10^{-9}	0.99	4.21×10^{-9}	4.12×10^{-9}	1.02
3,200	2.01×10^{-9}	2.01×10^{-9}	0.99	2.55×10^{-9}	2.50×10^{-9}	1.02
4,000	1.36×10^{-9}	1.36×101	0.99	1.73×10^{-9}	1.69×10^{-9}	1.02

ground deposition factor based on σ_θ) was not influenced by distance. The corresponding ratios were almost same for the Daedeok and Wolsong sites. The reason that the impact of the classification method on the atmospheric dispersion factor was found to be sensitive to the distance from the nuclear site, whereas no distance dependency was observed for the ground deposition factor, may be because the ground deposition factor is evaluated through the relative deposition rate, which takes distance into account, and because ground-level release is calculated independently of atmospheric stability.

Conclusion

Using atmospheric stability classified on the basis of either ΔT or σ_θ, we analyzed the atmospheric dispersion factor and the ground deposition factor at the Daedeok site and the Wolsong site. For both sites, we found that the atmospheric dispersion factor derived from the atmospheric stability class obtained using ΔT was higher than that derived from the atmospheric stability class obtained using σ_θ. For the ground deposition factor, since the ground-level release, which is estimated through empirical graphs presented in the NRC Regulatory Guide 1.111, is assessed independently of atmospheric stability, the results of the two methods were the same. Since our study was an investigation for selecting sites in a specific year, it is difficult to say that the findings of our study have strong implications for different cases. However, our findings suggest that in general, ΔT is the more conservative method for offsite dose calculations for nuclear facilities. If at the time of preliminary study for the determination of site distance, no local meteorological tower is tall enough to measure ΔT, σ_θ may have to be measured. In this case, the margin for site distance should be considered to meet the national standards to protect radiation-induced health detriment to the public.

Acknowledgments

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