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Environment Assessing for Airborne Radioactive Particulate Release-introduction of Methods in IAEA Safety Report Series No.19

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ABSTRACT

Background: Airborne radioactive particulate in many important nuclear facilities (particularly nuclear power plants) will have a strong impact on the relative public dose if they are released into the corresponding environment traversing the stack or vents. The radiation protection researchers have regarded the relative environment assessing and estimation of public doses. And the model of assessing impact of discharges radioactive substance to the environment have been recommended by many international organizations (e.g. IAEA) with the nuclear energy safety and radiation protection.

Materials and Methods: This paper introduced the generic models that were suggested by International Atomic Energy Agency (IAEA), for use in assessing the impact of discharges of radioactive substances to the environment (e.g. IAEA Safety Report Series No.19).

Results and Discussion: The writers of this paper, based on the recommend methods, assessed the discharge limits in some airborne radioactive substances discharging standards. The reasons that IAEA method are introduced are mainly the following considerations: IAEA is one of international organizations with some authorities in the nuclear energy safety and radiation protection; and, more important, the recommend modes are operational methods rather than the methods having little operations such as that have used by some researchers.

Conclusion: It is wish that the introduced methods in this paper can be referenced in draft or revise of the standards related to discharges of radioactive substances to the environment.

Keywords: Airborne radionuclides, External irradiation, Inhalation, Ingestion, Estimation of doses, Discharge limits

Introduction

There are a number of methods (models) for the dose assessing of populations once the airborne radioactive substance are discharged to the environment through the stacks and (or) ducts. This paper will mainly present the models that have been recommended by International Atomic Energy Agency (IAEA) [1, 2]. The assessing results obtained by these models will be given for some discharging limits required in corresponding standards. This paper only referred to atmospheric discharge, and will be presented in the other papers for the assessing of surface water discharge.

The many steps must be considered for the evaluations of the dose harms for populations. These approaches (chain models) may be illustrated as Figure 1. The basic

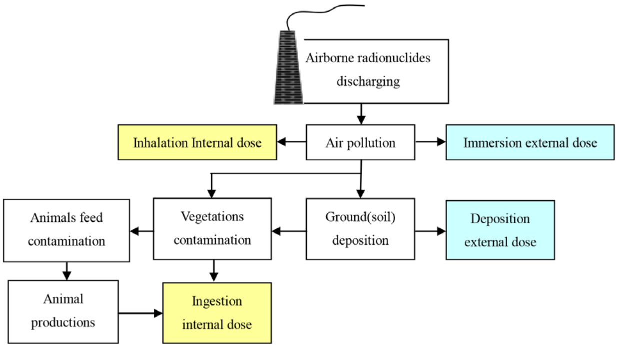

Fig. 1. Potential exposure pathways of public dose due to atmospheric discharge.

conception and relative procedures to be considered in assessing will be described as Figure 1.

Materials and Methods

1. Atmospheric dispersion and deposition

Airborne radioactive particulates discharged from the stacks and vents will have air contaminations in environment due to atmospheric dispersion features. And ground deposition would be possible due to the setting characterization of aerosol particles in air.

1) Pollution concentration in air

Basing on the discharging height (*H*) of the stack or duct and the height (H_B) and the projected cross-sectional area (A_B) of the adjacent building, the ground level air concentration at downwind distance (*x*) may be calculated.

(1) when H ≥2.5H_B

$$C_{A,i} = Q_i \cdot \frac{P_P}{u_d} \cdot F \qquad (1)$$

$$F = \frac{12}{\sqrt{2\pi^3}} \cdot \frac{1}{x\sigma_Z} \exp\left(-\frac{H^2}{2\sigma_Z^2}\right) = \frac{1.524}{x\sigma_Z} \cdot \exp\left(-\frac{H^2}{2\sigma_Z^2}\right) \qquad (2)$$

Where, $C_{A,i}$ refers to the ground level air concentration for a certain radionuclide (i) at the calculation point or the receive point of public (Bq·m^{-3}). *x* refers to the distance between the receive point and discharging point (m). P_P refers to is the fraction of the time during the year that the wind blows towards the receptor of interest in sector *p* (dimensionless), usually P_P = 0.25. u_a refers to the geometric mean of the wind speed at the height of release representative of one year (m·s^{-1}). *F* refers to the Gaussian diffusion factor (m^{-2}) appropriate for the height of release *H* and the downwind distance (x) being considered. Q_i refers to the annual average discharging rate for a certain radionuclide (Bq·s^{-1}). H refers to the discharging height (m). σ_Z refers to the vertical diffusion parameter (m), its calculation method is following:

for $H \le 45$ m: $\sigma_z = 0.006x/\sqrt{1+0.0015x}$
for $H > 45$-80 m: $\sigma_z = Ex^G$
(if *H* = 46-80 m, *E* = 0.215, *G* = 0.885; if *H* > 80 m, *E* = 0.265, *G* = 0.818)

(2) when $H \le 2.5\,H_B$

In this case, the calculate model are performed by two type.

Type 1) $x > 2.5\sqrt{A_B}$

$$C_{A,i} = Q_i \cdot \frac{P_P}{u_d} \cdot B \qquad (3)$$

$$B = \frac{12}{\sqrt{2\pi^3}}\,\frac{1}{x\Sigma_Z} \qquad (4)$$

$$\Sigma_Z = \left(\sigma_Z^2 + \frac{A_B}{\pi}\right)^{1/2} \quad (x \ge 2.5\sqrt{A_B}) \qquad (5)$$

Where, *B* refers to the diffusion factor with building wake correction for neutral atmospheric stratification (m^{-2}). AB refers to the surface area of the appropriate wall of the building of concern (m^2).[1)]

Type 2) $x \le 2.5\sqrt{A_B}$

(a) If the calculation points (receipt points) and the release points are on same building surface, the air concentrations is given by following Equations:

$$C_{A,i} = Q_i \cdot \frac{P_P}{V} \quad (x \le 3D_y) \qquad (6)$$

$$C_{A,i} = Q_i \cdot \frac{B_0}{u_a x^2} \quad (x > 3D_y) \qquad (7)$$

Where, $C_{A,i}$ refers to the ground level air concentration (Bq·m^{-3}) at downwind distance *x*. Q_i refers to the average discharge rate for radionuclide (i) (Bq·s^{-1}). V refers to the volumetric air flow rate of the stack or vent at the point of release (m^3·s^{-1}). P_P refers to the fraction of the time of the wind blows towards the receptor of interest (dimensionless). B_0 refers to the unit-less constant to accounts for potential increases in

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[1)] The recommended values above F and B have been given by IAEA [1, 2].

the concentration in air along a vertical wall owing to the presence of zones of air stagnation created by building wakes, usually $B_0 = 30$.[2)]

For $x \leq 3D_y$, from Equation 6, the air concentration ($C_{A,i}$) in ground level is really the exit concentration of the stack (or vent). That is, the radionuclide concentration at the point of interest (often referred to as the receptor location) is equal to the atmospheric radionuclide concentration at the release point of release.

(b) If the calculation points (receipt points) and the release points are not on same building surface, the empirical formulation about the air concentration would be

$$C_{A,i} = Q_i \cdot \frac{P_P}{\pi u_a \cdot H_B \cdot K} \tag{8}$$

Where, K is a constant of value 1 m. In this situation of the wake zone and $x \leq 2.5(A_B)^{1/2}$, the air concentration ($C_{A,i}$) is not related to the distance (x) of receipt point.

2. Ground deposition

The airborne radioactive substance may be deposited on the ground surfaces due to wet and dry deposition effects.

1) Deposition rate

The deposited radioactivity per unit time and area is called as the deposition rate, and be calculated by following Equation:

$$d_{G,i} = \left(V_d + V_w\right) \cdot C_{A,i} = V_t \cdot C_{A,i} \tag{9}$$

Where, d_{Gi} refers to the total daily average deposition rate on the ground of a given radionuclide ($Bq \cdot m^{-2} \cdot d^{-1}$), at calculation point (x). V_d refers to the dry deposition coefficient for a given radionuclide ($m \cdot d^{-1}$). V_W refers to the wet (rainout etc.) deposition coefficient for a given radionuclide ($m \cdot d^{-1}$). V_t refers to the total deposition coefficient, that is, $V_t = V_d + V_W$, usually $V_t = 1000\ m \cdot d^{-1}$.

For the usual ground deposition, it is not considered that the radionuclides on the ground may be re-suspended into the air by the action of wind and other disturbances, particularly for continuous discharging.

2) Deposition density

Deposition density is obtained from the ground deposition rate dGi according to the Equation 9

$$C_{gr,i} = \frac{d_{G,i}[1 - \exp(-\lambda_{is} t_b)]}{\lambda_{is}} \tag{10}$$

Where, $C_{gr,i}$ refers to the deposition density of radionuclide (i) ($Bq \cdot m^{-2}$). d_{Gi} refers to the total ground deposition rate ($Bq \cdot m^{-2} \cdot d^{-1}$). λ_{is} refers to the effective rate constant for reduction of the activity in the top 10 to 20 cm of soil (d^{-1}), where $\lambda_{is} = \lambda_i + \lambda_s$. λ_i refers to the rate constant for radioactive decay of radionuclide (i) (d^{-1}). λs refers to the rate constant for reduction of soil activity owing to the physics processes other than radioactive decay (d^{-1}), the value of λs see following Equation 12. t_b refers to the duration of the discharge of radioactive material (d), usually $t_b = 30(a) = 1.1 \times 10^4$ d.

2. Transport of radionuclide

The air concentration and ground deposition of airborne radioactive matters will lead to the external and internal doses of populations. On the other hand, the radioactive nuclides in air and on ground may be retained in the vegetations due to transport of radionuclide. The vegetations (and food) retained radionuclide are eaten by people and animals, and the public doses may be from the foods of vegetations and animals.

1) Concentrations in vegetations

The vegetations are divided into two groups: the vegetation consumed by grazing animals and the vegetation consumed by humans. They are called as 'forage' group and 'crops' group respectively.

(1) Direction contamination

The radionuclide concentration on and in the vegetations from direct contamination of radionuclide may be estimated by:

$$C_{v,i,1} = \frac{d_{G,i}\alpha[1 - \exp(-\lambda_{iw} t_e)]}{\lambda_{iw}} \tag{11}$$

Where, $C_{v,i,1}$ refers to the concentrations ($Bq \cdot kg^{-1}$) in the vegetations including dry matter for vegetation consumed by grazing animals, and fresh matter for vegetation consumed by humans. d_{Gi} refers to the deposition rate (wet and dry processes) of radionuclide on the ground ($Bq \cdot m^{-2} \cdot d^{-1}$), calculated from Equation 9. α refers to the mass interception factor ($m^2 \cdot kg^{-1}$), i.e. the fraction of deposited activity intercepted by the edible portion of vegetation per unit mass as the result of both wet and dry deposition processes. For pasture forage the unit of mass is conventionally given in terms of dry weight, and for fresh vegetables the unit is in wet weight.

[2)] D_y is the diameter of the stack or vent from which the radionuclide is emitted.

Table 1. The Default Values of Effective Surface Soil Densities ρ (kg·m^{-2})

Rooting zone depth	P (kg·m^{-2}, dry soil)	
	Peat soils	Other soils
Pasture: 0 to 10 cm	50	100
All other crops: 0 to 20 cm	130	260

Table 2. The Values of λ_s

Nuclide	λ_s (d^{-1})
Anions such as TcO_4^- , Cl^- and I^-	0.0014
Sr and Cs	0.00014
All other nuclides (including non-anionic forms of Tc and I)	0

Usually, $\alpha_1 = 3$ m^2·kg^{-1} for pasture forage (dry weight); $\alpha_2 = 0.3$ m^2·kg^{-1} for fresh vegetables (wet weight). t_e refers to the time period that crops are exposed to contamination during the growing season (d), usually $t_e = 30$ d (for fresh vegetables), $t_e = 60$ d (for pasture forage). $\lambda_{i,w}$ refers to the effective rate constant for reduction of the activity concentration of radionuclide from crops (d^{-1}), where $\lambda_{i,w} = \lambda_i + \lambda_w$. λ_i refers to the rate constant for radioactive decay of radionuclide (d^{-1}). λ_w refers to the rate constant for reduction of the concentration of material deposited on the plant surfaces owing to the physics processes other than radioactive decay (d^{-1}), for any the plant, usually $\lambda_w = 0.05$ d^{-1}.

(2) Indirection contamination

The radionuclide concentration in vegetation arising from indirect processes i.e. from uptake from the soil and from soil adhering to the vegetation is estimated by:

$$C_{v,i,2} = F_v \cdot C_{s,i} = \frac{F_v}{\rho} C_{gr,i} = \frac{F_v}{\rho} \cdot \frac{d_{G,i}[1-\exp(-\lambda_{is} t_b)]}{\lambda_{is}} \qquad (12)$$

Where, $C_{v,i,2}$ refers to the concentrations (Bq·kg^{-1}) in the vegetations including dry matter for vegetation consumed by grazing animals and fresh matter for vegetation consumed by humans. $C_{s,i}$ refers to the concentration of radionuclide in dry soil (Bq·kg^{-1}). $C_{gr,i}$ refers to the deposition density of radionuclide (Bq·m^{-2}), see Equation 10. F_V refers to the concentration factor for uptake of the radionuclide from soil by edible parts of crops (Bq·kg$^{-1}_{(plant)}$/Bq·kg$^{-1}_{(soil)}$). It is conservatively assumed that all activity removed from the atmosphere becomes available for uptake from the soil. In addition, the implicitly of the selected values must be taken account of the adhesion of soil to the vegetation. Again, for pasture forage the unit of mass is for dry matter; for vegetation consumed by humans the unit of mass is for fresh weight. The selection methods of F_v values have been given by IAEA [1, 2]. t_b refers to the duration of the discharge of radioactive material (d), usually $t_b = 30(a) = 1.1 \times 10^4$ d. ρ refers to a standardized surface density for the effective root zone in soil (kg·m^{-2}, dry soil). For generic calculations, the default values of effective surface soil densities ρ (kg·m^{-2}) are given as Table 1. λ_{is} refers to the effective rate constant for reduction of the activity concentration in the root zone of soils (d^{-1}), $\lambda_{is} = \lambda_i + \lambda_s$. λi—the rate constant for radioactive decay of radionuclide (d^{-1}). λ_s refers to the rate constant for reduction of the concentration of material deposited in the root zone of soils owing to processes other than radioactive decay (d^{-1}). In practice, the value λ_s is highly dependent on climate, agricultural management practices, soil type, vegetative cover and the chemical form of the radionuclide. For the purpose of generic assessment, the values λ_s are given as Table 2.

(3) Total concentration in vegetation

The total concentration of the radioactive nuclide in the vegetation would be from to direct and indirect processes. Thus,

$$C_{v,i} = (C_{v,i,1} + C_{v,i,2})\exp(-\lambda_i t_h) \qquad (13)$$

Where, $C_{v,i}$ refers to the total concentration (Bq·kg^{-1}) in the vegetation matter including dry matter for vegetation consumed by grazing animals and fresh matter for vegetation consumed by humans. λ_i refers to the rate constant for radioactive decay of radionuclide (i) (d^{-1}). t_h refers to a delay (hold-up) time (d) that represents the time interval between harvest and consumption of the food (d). Usually, $t_h = 0$ d for forage consumed by animals. $t_h = 14$ d for food crops consumed by humans. $t_h = 90$ d for stored feed consumed by animals.

2. Concentrations in animal feed

The feed consumed by animals is from to fresh forage feeds and stored feeds. The concentration in feed consumed by animals is calculated by

$$C_{a,i} = f_p C_{v,i} + (1 - f_p) C_{p.i} \qquad (14)$$

Where, $C_{a,i}$ refers to the concentration of radionuclide (i) in the animal feed (Bq·kg^{-1}, dry matter). $C_{v,i}$ refers to the concentration (Bq·kg^{-1}, dry matter) of radionuclide for fresh pasture, calculated using Equation 13 with $t_h = 0$ d. $C_{p,i}$ refers to the concentration (Bq·kg^{-1}, dry weight) of radionuclide in stored feeds, calculated using the Equation 13 with $t_h = 90$ d. f_p refers to the fraction of the year that animals consume fresh pasture vegetation (dimensionless), $f_p = 0.7$.

3. Concentrations in animal productions

The animal productions (milk and meat) may be containing the radioactive nuclide due to the feed retained radionuclide is consumed by the animals. Therefore, to estimate irradiation dose from ingestion of animal productions, the radionuclide concentrations in the animal productions must be estimated.

1) Concentration in milk

The concentration of radionuclide in milk is estimated as

$$C_{m,i} = F_m\left(C_{a,i}Q_m + C_{w,i}Q_w\right)\exp\left(-\lambda_i t_m\right) \quad (15)$$

Where, $C_{m,i}$ refers to the concentration in milk of radionuclide (i) ($Bq \cdot L^{-1}$). F_m refers to the fraction of the animal's daily intake of the radionuclide that appears in each liter of milk at equilibrium ($d \cdot L^{-1}$); The selection methods of F_v values have been given by IAEA [1, 2]. $C_{a,i}$ refers to the concentration of radionuclide in the animal feed ($Bq \cdot kg^{-1}$, dry matter). Q_m refers to the amount of feed (in dry matter) consumed by the animal per day ($kg \cdot d^{-1}$), usually $Q_m = 16$ $kg \cdot d^{-1}$ (milk, large animal). $C_{w,i}$ refers to the concentration of radionuclide in water ($Bq \cdot m^{-3}$). Q_w refers to the amount of water consumed by the animal per day ($m^3 \cdot d^{-1}$), usually $Q_w = 0.06$ $m^3 \cdot d^{-1}$ (milk, large animal). λ_i refers to the rate constant for radioactive decay of radionuclide (d^{-1}). t_m refers to the average time between collection and human consumption of milk, usually $t_m = 1$ d (for fresh milk).

(1) Concentration in meat

The concentration of radionuclide in meat is estimated as

$$C_{f,i} = F_f\left(C_{a,i}Q_f + C_{w,i}Q_w\right)\exp\left(-\lambda_i t_f\right) \quad (16)$$

Where, $C_{f,i}$ refers to the concentration of radionuclide (i) in animal flesh ($Bq \cdot kg^{-1}$). Ff refers to the fraction of the animal's daily intake of a radionuclide that appears in each kg of flesh at equilibrium or at the time of slaughter ($d \cdot kg^{-1}$); The selection methods of F_f values have been given by IAEA [1, 2]. $C_{a,i}$ refers to the concentration of radionuclide (i) in the animal's feed ($Bq \cdot kg^{-1}$, dry matter). $C_{w,i}$ refers to the concentration of radionuclide(i) in water ($Bq \cdot m^{-3}$). Q_f refers to the amount of feed (in dry matter) consumed by the animal per day ($kg \cdot d^{-1}$), usually $Q_f = 12$ $kg \cdot d^{-1}$ (meat, large animal). Q_w refers to the amount of water consumed by the animal per day ($m^3 \cdot d^{-1}$), usually $Q_w = 0.04$ $m^3 \cdot d^{-1}$ (meat, large animal). λ_i refers to the rate constant for radioactive decay of radionuclide (d^{-1}). t_f refers to the average time between slaughter and human consumption of meat, usually $t_f = 20$ d (for fresh meat).

3. Dose estimation method

The populations exposed in the environment with radioactive source will receipt the external and internal irradiation exposure doses. The external exposure doses are mainly as result of the radioactivity from the air contamination and ground deposition of airborne radionuclide. The internal exposure doses are due to inhale radionuclide in air and due to ingest radioactivity in the productions of the vegetation and animal.

1) Calculation for external irradiation dose

The external irradiation dose is from the immersion external irradiation and the ground deposition external irradiation.

(1) Immersion external irradiation

① γ *radionuclide*

For evaluation of the effective dose from external exposure, γ radiation from airborne radionuclides is the main exposure pathway. Based on semi-infinite cloud model, the annual effective dose from immersion in the atmospheric discharge plume is given by

$$E_{mi,\gamma} = C_{A,i} \cdot DF_{mi} \cdot O_f \quad (17)$$

Where, E_{mi} refers to the annual effective dose ($Sv \cdot a^{-1}$). $C_{A,i}$ refers to the annual average concentration of γ nuclide (i) in air ($Bq \cdot m^{-3}$). DF_{mi} refers to the effective dose coefficient for immersion ($Sv \cdot a^{-1}/Bq \cdot m^{-3}$); The selection methods of DF_{mi} values have been recommended by IAEA [1,2]. O_f refers to the fraction of the year for which the hypothetical critical group member is exposed to this particular pathway, usually $O_f = 1$.

The gross dose from all possible γ nuclide will be

$$E_{m,\gamma} = \sum_i E_{mi,\gamma} \quad (18)$$

② *β radionuclide*

Some β radiation radionuclides can lead to exposure to the skin. From the annual average concentration of a given radionuclide in air, the equivalent dose to skin can be calculated by

$$E_{mi,s} = C_{A,i} \cdot DF_{si} \cdot O_f \tag{19}$$

Where, $E_{mi,s}$ refers to the annual skin dose from β irradiation (Sv·a^{-1}). $C_{A,i}$ refers to the annual average concentration of β nuclide in air (Bq·m^{-3}). D_{si} refers to the skin dose owing to β irradiation per unit air concentration (Sv·a^{-1}/Bq·m^{-3}); The selection methods of D_{si} values have been recommended by IAEA [1, 2]. O_f refers to the fraction of the year exposed to this particular pathway, usually $O_f = 1$.

The gross dose from all possible β nuclide will be

$$E_{m,s} = \sum_i E_{mi,s} \tag{20}$$

(2) Ground external irradiation

The annual effective dose due to external exposure $E_{gr,i}$ from ground sediment is given by

$$E_{gr,i} = C_{gr,i} \cdot DF_{gri} \cdot O_f \tag{21}$$

Where, $E_{gr,i}$ refers to the annual effective dose from ground sediment (Sv·a^{-1}). $C_{gr,i}$ refers to the surface activity concentration in sediments (Bq·m^{-2}), as described in Equation (10). $DF_{gr,i}$ refers to the dose coefficient for exposure to ground deposits (Sv·a^{-1}/Bq·m^{-2}); The selection methods of $DF_{gr,i}$ values have been recommended by IAEA [1, 2]. Of refers to the fraction of the year exposed to this particular pathway, usually $O_f = 1$.

The gross dose from all possible nuclide of ground deposition will be:

$$E_{gr} = \sum_i E_{gr,i} \tag{22}$$

2) Calculation for internal irradiation dose

The internal dose following an intake of radioactive material into the body by inhalation or ingestion is important contents. The basic assessment approach is as following.

(1) Internal irradiation dose from inhalation

The annual effective dose from inhalation of airborne radioactive substance is estimated by

$$E_{inh,i} = C_{A,i} \cdot R_{inh} \cdot DF_{inh,i} \tag{23}$$

Where, $E_{inh,i}$ refers to the annual effective dose (Sv·a^{-1}) due to inhalation of radionuclide (i) in air. $C_{A,i}$ refers to the radionuclide (i) concentration in air (Bq·m^{-3}). R_{inh} refers to the inhalation rate (m^{3}·a^{-1}), e.g. $R_{inh} = 8{,}400$ m^{3}·a^{-1}. $DF_{inh,i}$ refers to the inhalation dose coefficient (Sv·Bq^{-1}); The selections of $DF_{inh,i}$ values may be from the literatures [3, 4].

The gross inhalation dose from all possible nuclide in air will be:

$$E_{inh} = \sum_i E_{inh,i} \tag{24}$$

(2) Internal irradiation dose from ingestion

The annual effective dose from ingestion of the food stuff retained radionuclides is calculated by

$$E_{ing,i} = C_{F,i} \cdot H_F \cdot DF_{ing,i} = \left(C_{v,i} \cdot H_v + C_{m,i} \cdot H_m + C_{f,i} \cdot H_f\right) \cdot DF_{ing,i} \tag{25}$$

Where, $E_{ing,i}$ refers to the annual effective dose from consumption of nuclide (i) in foodstuff (Sv·a^{-1}). $C_{F,i}$ refers to the concentration (Bq·kg^{-1}) of radionuclide (i) in foodstuff (vegetables-grain, milk, meat) at the time of consumption. The individual corresponding $C_{v,i}$ (vegetables), $C_{m,i}$ (milk) and $C_{f,i}$ (meat) may be calculated by Equations 13 to 15. H_F refers to the consumption rate for foodstuff (kg·a^{-1}). The individual is corresponding to H_v (vegetables and grain), H_m (milk) and H_f (meat). The default consumption rates are given based on the food habits, locations and characteristics of populations, e.g. $H_v = 410$ kg·a^{-1}, $H_m = 250$ L·a^{-1}, $H_f = 100$ kg·a^{-1}. $D_{Fing,i}$ refers to the dose coefficient (Sv·Bq^{-1}) for ingestion of radionuclide (i); The selections of $D_{Fing,i}$ values may be from the literatures [3, 4].

The gross ingestion dose from all possible nuclide in foodstuff will be

$$E_{ing} = \sum_i E_{ing,i} \tag{26}$$

3) Total irradiation dose

The total annual effective doses at calculated point (x) from the airborne radionuclides are consisted of the gross external irradiation doses ($E_{m,\gamma}$, $E_{m,\beta,}$ and $E_{g\gamma}$) and gross internal irradiation doses (E_{inh} and E_{ing}), that is:

$$E_G = \left(E_{m,\gamma} + E_{m,s} + E_{gr}\right) + E_{inh} + E_{ing} \tag{27}$$

4) Collective dose

The collective dose here may be considered as the product of the number of individuals exposed to a source and their average radiation dose in a designed region (rather than extending over large regions, or even globally).

(1) Local collective dose

The collective dose of a specific local component (critical group) in the localization is the product of the individual average radiation dose (critical group) and the number of population in this local component. That is:

$$E_{Gpn} = E_{Gp} \cdot p_n \tag{28}$$

Where, E_{Gpn} refers to the collective dose in n^{th} local component ($\mathrm{Bq \cdot man \cdot a^{-1}}$). E_{Gp} refers to the individual average dose in n_{th} local component ($\mathrm{Bq \cdot a^{-1}}$). P_n refers to the number of population in n_{th} local component (man).

(2) Regional collective dose

For the designed assessing region (including many local component), the collective dose within this region would be

$$E_{collec} = \sum_n \sum_k E_{Gpn}(k) \cdot p_{nk} \tag{29}$$

Where, E_{collec} refers to the collective dose in the designed assessing region ($\mathrm{Bq \cdot man \cdot a^{-1}}$). k refers to the number of local component in a localization. n refers to the number of localization.

4. Applications of assessment model

The models presented above if these methods have been understood may estimate the dose harms for the public wing to the discharging of the airborne radioactive substance. The dose evaluation for a critical people group is performed by an iterative approach based on the recommendations of IAEA.

1) Screening method

The simplest and most pessimistic evaluation approach is 'no-dilution' screening technique. The 'no-dilution model' is to assume that the radionuclide concentration at the point of interest (often referred to as the receptor location) is equal to the atmospheric radionuclide concentration at the point of release. The annual effective dose including external and internal doses may be calculated when the discharging concentration at the release point is 1.0 $\mathrm{Bq \cdot m^{-3}}$. The maximum annual dose per unit discharge concentration (1 $\mathrm{Bq \cdot m^{-3}}$) is called as 'screening dose calculation factor', DF_{ser} ($\mathrm{Sv \cdot a^{-1}/Bq \cdot m^{-3}}$). The exposure conditions of the critical group for the calculation of DF_{ser}, that is the annual effective dose including external dose from irradiations and internal doses from inhalation and ingestion, are as following (see Equations 6 and 9),

$$C_A = 1\ \mathrm{Bq \cdot m^{-3}} \times 0.25 = 0.25\ \mathrm{Bq \cdot m^{-3}}$$

$$d_G = 0.25\ \mathrm{Bq \cdot m^{-3}} \times 1000\ \mathrm{m \cdot d^{-1}} = 250\ \mathrm{Bq \cdot m^{-2} \cdot d^{-1}}$$

The above C_A and d_G are respectively the air concentration and the ground deposition rate when the discharging concentration is 1.0 $\mathrm{Bq \cdot m^{-3}}$ at the point of release (or per unit concentration). The values of DF_{ser} for some radionuclides are reported by IAEA.

It is obvious that the public dose obtained by such 'no-dilution' method may be overestimation, even very much overestimation. The dose evaluation must be iterated by the other approaches if the annual dose exceeds the relevant dose criterion, e.g. 0.25 $\mathrm{mSv \cdot a^{-1}}$, based on such 'no-dilution model'.

2) Generic environmental model

The generic environmental model is also called as 'dilution' model. The 'dilution' model assumed that the public dose is resulted to a greater distance from the discharging source. Based on this model, the annual effective dose including external and internal doses may be calculated when the discharging rate at the release point is 1.0 $\mathrm{Bq \cdot s^{-1}}$. The annual effective dose per unit discharge rate (1 $\mathrm{Bq \cdot s^{-1}}$) is called as 'generic model dose calculation factor' PF_{gen} ($\mathrm{Sv \cdot a^{-1}/Bq \cdot s^{-1}}$). The exposure conditions for the calculation of PF_{gen} in the 'generic environmental model' or the 'dilution model' are, see Equations 3 and 9, as Table 3.

The values of PF_{gen} ($\mathrm{Sva^{-1}/Bqs^{-1}}$) that were given by IAEA for some radionuclides are listed by IAEA [1, 2]. In general, the annual effective dose that is calculated based on the 'generic

Table 3. The Conditions of the 'Dilution' Model

Dose type		Distance from source	Exposure condition
External dose	from immersion from deposition from inhalation	20 m	$C_A = 2 \times 10^{-3}$ ($\mathrm{Bq \cdot m^{-3}}$) $d_G = 2$ ($\mathrm{Bq \cdot m^{-2} \cdot d^{-1}}$)
Internal dose	from ingestion of crops	100 m	$C_A = 1.25 \times 10^{-4}$ ($\mathrm{Bq \cdot m^{-3}}$) $d_G = 0.125$ ($\mathrm{Bq \cdot m^{-2} \cdot d^{-1}}$)
	from ingestion of milk and meat	800 m	$C_A = 7.5 \times 10^{-6}$ ($\mathrm{Bq \cdot m^{-3}}$) $d_G = 7.5 \times 10^{-3}$ ($\mathrm{Bq \cdot m^{-2} \cdot d^{-1}}$)

The relating values (such as F, B etc.) in calculation are taken by the ways: $H \le 2.5H_B$, $H_B = (A_B)^{1/2} = (500\ \mathrm{m^2})^{1/2}$. For details, see Annex I of reference [1].

dose calculation factor' (PF_{gen}) from the generic environmental model may still be overestimated for public doses. The dose evaluation methods that are in accord with the realistic discharging characteristic of nuclear facilities would be need if the annual dose based on the generic environmental model ('dilution model') exceeds the relevant dose criterion.

3) Realistic model

For realistic model, the exposure conditions of how the estimation of dose would be performed are not recommended (could not be recommended) in IAEA reports. The determination of the exposure conditions is dependent to the realistic discharging characteristic of the nuclear facilities tried to performed environmental evaluation. These characteristic parameters are including (for example):

(1) The distance between the critical group and the discharging source.
(2) The conditions of members of hypothetical critical group and of food productions, etc.
(3) Annual average wind speed and direction.
(4) Dietary habits of residence time of the critical group.

The writers of this paper designed a realistic model and assessed relevant annual effective dose based on this model. This model is called as '800 m model' for the moment. It is assumed that the receive point of the public is at a distance of 800 m from the discharging point. That is, for the critical group, the exposure conditions including the external and internal irradiation dose are at the point of 800 m from the discharging point.

For this model, the calculation is performed in two cases.

(1) When $H \leq 2.5 H_B$ and $x > 2.5(A_B)^{1/2}$, for the discharging rate of 1.0 ($Bq \cdot s^{-1}$), the exposure conditions will be ($u_a = 2$ $m \cdot s^{-1}$, $p_p = 0.25$), $CA = 7.5 \times 10^{-6}$ ($Bq \cdot m^{-3}$); $d_G = 7.5 \times 10^{-3}$ $Bq \cdot m^{-2} \cdot d^{-1}$. Thus, the annual effective dose per unit discharge rate (1 $Bq \cdot s^{-1}$) may be calculated, and is called as 'realistic model dose calculation factor' $PF_{800\text{-}1}$ ($Sv \cdot a^{-1}/Bq \cdot s^{-1}$).

(2) When $H > 2.5\ H_B$ and $x > 2.5(A_B)^{1/2}$, for the discharging rate of 1.0 $Bq \cdot s^{-1}$, the exposure conditions will be ($u_a = 2$ $m \cdot s^{-1}$, $p_p = 0.25$), $C_A = 2.5 \times 10^{-6}$ $Bq \cdot m^{-3}$; $dG = 2.5 \times 10^{-3}$ $Bq \cdot m^{-2} \cdot d^{-1}$. Thus, the annual effective dose per unit discharge rate (1 $Bq \cdot s^{-1}$) may be calculated, and is called as 'realistic model dose calculation factor' $PF_{800\text{-}2}$ ($Sv \cdot a^{-1}/Bq \cdot s^{-1}$). The writers calculated $PF_{800\text{-}1}$ ($Sv \cdot a^{-1}/Bq \cdot s^{-1}$) and $PF_{800\text{-}2}$ ($Sv \cdot a^{-1}/Bq \cdot s^{-1}$) for some radionuclides (Table 4).

Results and Discussion

Based on the applications of the assessment models, the writers calculated the possible annual doses for the discharging limits required in some the discharge standards related to airborne radioactive nuclides. The Table 1 listed the corre-

Table 4. Evaluation for Some Annual Discharging Limits with the Different Assessing Models

Discharging Nuclide		Discharging rate Qi [$Bq \cdot a^{-1}$]	Evaluation results with different model								
			Screening model			Generic mode		Realistic model-800-1		Realistic model-800-2	
			$C_{A,i}$ [$Bq \cdot m^{-3}$]	DF_{scr} [$Sv \cdot a^{-1}/Bq \cdot m^{-3}$]	Annual dose [$mSv \cdot a^{-1}$]	PF_{gen} [$Sv \cdot a^{-1}/Bq \cdot a^{-1}$]	Annual dose [$mSv \cdot a^{-1}$]	$PF_{800\text{-}1}$ [$Sv \cdot a^{-1}/Bq \cdot s^{-1}$]	Annual dose [$mSv \cdot a^{-1}$]	$PF_{800\text{-}2}$ [$Sv \cdot a^{-1}/Bq \cdot s^{-1}$]	Annual dose [$mSv \cdot a^{-1}$]
1	^{238}U	1.5×10^{9}	0.68	2.2×10^{-1}	150	4.8×10^{-11}	72	2.0×10^{-13}	0.30	6.7×10^{-14}	0.10
2	^{131}I	1.5×10^{10}	6.8	3.7×10^{-2}	250	1.2×10^{-13}	1.8	3.5×10^{-14}	0.52	1.2×10^{-14}	0.18
	^{137}Cs	4.5×10^{9}	2.0	4.6×10^{-2}	92	5.1×10^{-12}	23	4.1×10^{-14}	0.19	1.4×10^{-14}	0.06
	^{90}Sr			1.7×10^{-1}	340	1.6×10^{-12}	7.2	1.6×10^{-13}	0.72	5.4×10^{-14}	0.24
3	^{90}sr	8×10^{10}	36	1.7×10^{-1}	6,120	1.6×10^{-12}	128	1.6×10^{-13}	12.8	5.4×10^{-14}	4.3
	^{129}I	5.0×10^{9}	2.3	2.3×10^{-1}	530	1.2×10^{-12}	6	2.3×10^{-13}	1.15	7.6×10^{-14}	0.38
	^{137}Cs	4.0×10^{10}	18	4.6×10^{-2}	828	5.1×10^{-12}	204	4.4×10^{-14}	1.76	1.4×10^{-14}	0.56
	^{239}Pu	6.0×10^{9}	2.7	2.5×10^{-1}	675	2.9×10^{-11}	174	2.5×10^{-13}	1.50	8.2×10^{-14}	0.50
4	^{131}I	2.0×10^{10}	9	3.7×10^{-2}	33	1.2×10^{-13}	2.4	3.5×10^{-14}	0.70	1.2×10^{-14}	0.24
	^{137}Cs	5.0×10^{10}	23	4.6×10^{-2}	1,060	5.1×10^{-12}	255	4.4×10^{-14}	2.2	1.4×10^{-14}	0.7
	^{90}Sr			1.7×10^{-1}	3,910	1.6×10^{-12}	81	1.6×10^{-13}	8.0	5.4×10^{-14}	2.7
	^{60}Co			1.1×10^{-1}	2,530	1.3×10^{-11}	650	1.0×10^{-13}	5.0	3.5×10^{-14}	1.7

(1) The mean of 1,2,3,4 grouping of first column refer to the type of nuclear facilities, e.g. nuclear power plants;
(2) "Q_i" of second column are from to the average discharge rate regulated by these nuclear facilities;
(3) It is assumed that the annual average volumetric air flow rate of the stack is $V = 70$ (m^3/s) $= 2.5 \times 10^5$ (m^3/h) $= 2.2 \times 10^9$ (m^3/a), $C_{Ai} = Q_i/V$ (Qi–the average discharge rate of a radionuclide).

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sponding results given by the different assessment models. The huge difference of assessing results in Table 1 shown the important of the selection and design for the assessing model (including input data).

Accurately assessing doses that could be received by members of the public may be a complex and time consuming process. The basic formulations presented in the paper (that is calculation formulations given by IAEA) would be useful. The iterative screening approaches suggested by IAEA have reference significance for assessing critical group doses resulting from radioactive discharges to the environment.

However, the main problems of the assessing models may be the selections of the default values that must be used in the evaluation calculations, particularly for a realistic nuclear facility and its corresponding critical group. The following considerations should be included for the selections of the default parameters:

(1) The relationship between the height at which the effluent is released and the heights of the buildings that affect airflow near the release point;

(2) The location of members of the hypothetical critical group (that is the distance from the discharging source), and the designs of food productions, etc.;

(3) Dietary habits and residence times of members of the hypothetical critical group;

(4) The climate conditions including annual average wind speed and direction, etc.;

(5) Specific exposure pathways, for example, if external doses are important, it may be necessary to consider migration of radionuclides in soil;

(6) The uncertainty of the discharge amount—these are relative to the sampling and monitoring techniques of the airborne radionuclides discharge, for example, as recommended by some standards [5, 6].

Conclusion

The main purpose of this paper is to provide simple methods recommended by IAEA [1, 2] for calculating public doses arising from airborne radioactive discharges into the environment. These methods may be useful for the evaluating suitable discharge limits (as done in Table 1), and to allow comparison with the relevant dose limiting criteria specified by the relevant regulatory authority.

The calculation results in table 1 shown that the models for use in assessing the impact of discharges of radioactive substances to the environment are operational and practical. It is important how the assessing models are applied reasonably to in the realistic discharging situations.

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