STUDY ON RADIOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT OF NUCLEAR FUEL CYCLE FACILITIES

by

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The radiological assessment model REIA 1.0 is established to assess the radiological environmental impact of radioactive airborne effluents released from nuclear fuel cycle facilities. It is based on the double Gaussian probability distribution function model and considers the wind pendulum effect of the long-term diffusion factor. The simulation results of the REIA 1.0 model are compared with those of the AERMOD-VIEW model and radiation environmental monitoring results of nuclear fuel cycle facilities. The results are: using the REIA 1.0 and AERMOD-VIEW models, the relative deviations of simulation results are less than 33.33% in 192 subregions. Except for three points, the relative deviations are less than 20%, the simulated results are consistent with the radiation environmental monitoring results in seven sites using the REIA 1.0 model, and the REIA 1.0 model can characterize the incremental contribution of radionuclide concentration in the air caused by the radioactive airborne effluents from nuclear fuel cycle facilities. It can effectively assess the radiological environmental impact of nuclear fuel cycle facilities.

Key words: *radionuclide atmospheric diffusion, nuclear fuel cycle facilities, radioactive airborne effluents, radiological environmental impact assessment*

Introduction

With the rapid development of the nuclear industry, there is a growing interest in the radiological environmental impact caused by radiation exposure. During normal operation of nuclear fuel cycle facilities, radionuclides discharge to the environment through atmospheric discharges as routine releases. Radiological environmental impact assessment models are used to predict the concentration of radionuclides in the atmosphere and their impacts on the general public and the environment released from an operating plant [1]. The actual emissions or designed emissions are the source term from nuclear facilities. The nuclide activity concentrations are calculated using the atmospheric dispersion equations in air. The dose conversion coefficients are used to calculate the individual dose. The radiological environmental impact assessment method is relatively mature, such as the technical report No. 19 in International Atomic Energy Agency (IAEA) [2], the Federal Nuclear Regulatory guidelines [2], and the radiological environmental impact assessment for 30 years of operation of nuclear facilities in China [3].

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Meanwhile, a series of models are developed for the radiological environmental impact assessment abroad, including AIRDOS, CAP88, ARTDOS, MACCS2, and so on [2]. Research institutions have developed radiological environmental impact assessment models under different operating conditions, including the CairDos model [4], the Roulea model [4], the NAREIA model, the NAUMEI model, the UAIR-FINE model [5], *etc*. In general, the CairDos model is used in nuclear fuel cycle facilities. It has certain limitations in dealing with complex terrain and fugitive emission area sources. Besides, the prediction results using the CairDos model are conservative. The AERMOD model is recommended to evaluate the radiological environmental impact assessment of nuclear fuel cycle facilities in China. However, the AERMOD model can not calculate the individual dose and collective dose [6, 7]. The UAIR-FINE system is based on the AERMOD model. It is usually used for uranium mining and associated ore facilities and does not apply to nuclear fuel cycle facilities.

Based on the double Gaussian probability distribution function model in the AERMOD model and the wind pendulum effect of long-term diffusion factor, this study establishes a radiological environmental impact assessment model. This model contains four modules, including a radionuclide atmospheric diffusion and deposition module, an annual effective dose module, and a collective dose calculation module, to achieve a scientifically valid expression of the radiological environmental impact of nuclear fuel cycle facilities.

Radiological environmental impact assessment methods

To overcome the shortcoming of the CairDos model, this model adopts the double Gauss theory to calculate radionuclide concentration in the atmosphere. Besides, it considers the interaction between buoyant plumes and mixed layer tops under convective conditions, the diffusion of pollutant plumes under complex terrain, the wake effect of buildings, and the fugitive emission discharge of pollution from non-point sources.

The annual effective dose and collective dose are calculated using the dose calculation method recommended by NNSA-ZH-0001-2017 [8].

Atmospheric diffusion

– Stable boundary layer diffusion formula

According to User's Guide for the AMS/EPA Regulatory Model (AERMOD), the atmospheric dispersion equations are:

$$\rho(x,y,z)=\frac{Q}{U}F_zF_y \tag{1}$$

$$F_z=\frac{1}{\sqrt{2\pi\sigma_z}}\sum_{n=0}^{\infty}\exp\left[-\frac{(z-h_p-2nh_z)^2}{2\sigma_z^2}\right]+\exp\left[-\frac{(z+h_p+2nh_z)^2}{2\sigma_z^2}\right] \tag{2}$$

$$F_y=\frac{1}{\sqrt{2\pi\sigma_y}}\exp\left[-\frac{y^2}{2\sigma_y^2}\right] \tag{3}$$

where $\rho(y, x, z)$ are the total concentration of the plume, F_z – the dilution of plume, F_y – the plume distribution, h_p – plume height, h_z – the height of vertical mixing layer, σ_z and σ_y – the plume diffusion parameters in the horizontal and vertical directions, respectively.

– Long-term average and the wind pendulum effect

The concentration of a particular wind direction *i* is the cumulative effect of 8760 hours in calculating annual mean diffusion factor. It is observed that the wind direction angle is 22.5° in flat areas. If the wind direction is distributed within the 22.5° (wind swimming) evenly, the concentration factor at *x* downstream of the wind direction *i* is [9]:

$$\overline{\rho/\dot{Q}} = \frac{\int_{-\infty}^{+\infty} (\rho/\dot{Q})\mathrm{d}y}{x\theta} = \frac{2.03}{Ux\sigma_z}\exp\left(\frac{{h_p}^2}{2\sigma_z^2}\right) \tag{4}$$

– Radioactive decay

Radioactive decay is the emission of energy in the form of ionizing radiation [10-13]. The radioactive decay constant is used to calculate the loss of source strength:

$$f_F = \exp\left(-\lambda\frac{x}{U}\right) \tag{5}$$

Individual dose

– Air immersion external irradiation

It can be expressed:

$$D_{\mathrm{EA}} = 8760\left(\sum_i \chi_i DCF_{\mathrm{EA}i} F\right) \tag{6}$$

where D_{EA} [Sv per year] is the annual effective dose of air immersion external irradiation in the polluted semi-infinite smoke cloud at the calculation point, χ_i[Bqm^{-3}] – the concentration of radionuclide *i* in air at the calculation point, $DCF_{\mathrm{EA}i}$ [Sv per hour] [Bqm^{-3}] – the effective dose conversion factor of radionuclide *i* in air immersion external irradiation, and *F* – the shielding factor of the building.

– Surface deposition external exposure

It can be expressed:

$$D_{\mathrm{ES}} = 8760\left\{\sum_i \gamma_i[1-\exp(-\lambda_{\mathrm{G}i}t_{\mathrm{G}})]\lambda_{\mathrm{G}i}^{-1} DCF_{\mathrm{ES}i}\right\} \tag{7}$$

where D_{EG} [Sv per year] is the effective dose of the public staying on the contaminated ground at the calculation point, γ_i [Bqm^{-3} per year] – the surface deposition rate of radionuclide *i* at the calculation point, $\lambda_{\mathrm{G}i}$ [d^{-1}] – the physical removal constant of radionuclide *i* in the terrestrial environment, and DCF_{ESi} [Sv per hour][Bqm^{-2}] – the effective dose conversion factor of radionuclide *i* in surface deposition external exposure.

– Inhalation exposure

It can be expressed:

$$D_{\mathrm{EI}} = 8760\sum_i \chi_i B_{\mathrm{r}} DCF_{\mathrm{E}i} \tag{8}$$

where D_{EI} [Sv per year] is the effective dose caused by the inhalation of polluted air at the calculation point, χ_i [Bqm^{-3}] – the concentration of radionuclide i in air at the calculation point, B_{r} [m^3 per hour] – the respiration rate, and $DCF_{\mathrm{EI}i}$ [SvBq^{-1}] – the effective dose conversion factor of radionuclide *i*.

– Ingestion irradiation

It can be expressed:

$$D_{\mathrm{E}Ei} = \sum_i U_{\mathrm{E}i} DCF_{\mathrm{EF}i} \tag{9}$$

where $DCF_{\mathrm{EE}i}$ [SvBq^{-1}] is the effective dose conversion factor of radionuclide i, and $U_{\mathrm{E}i}$ [Bq per year] – the amount of radionuclide i ingested.

– Collective dose

Collective doses for different age groups are calculated based on individual doses and population data for different age groups, and then obtain 80 km collective doses [8]:

$$D_\mathrm{C} = \sum_{i=1}^{n}\sum_{r=1}^{12}\left\{D_i^{EA}(x_r) + D_i^{ES}(x_r) + \sum_a [D_i^{EI}(x_r) + D_i^{EEi}(x_r)] f_\mathrm{a}(x_r)\right\} N_r \tag{10}$$

where D_C [Sv per year] is the collective effective dose per person, r – the radial number of the evaluation subregion, x_r [m] – the distance from the subregion to the discharge point, f_a – the population share of different age groups, and N_r – the number of population in the subregion.

Radiological environmental impact assessment model

In this study, a radiological environmental impact assessment model is developed using PYTHON and FORTRAN languages. It includes an analysis module of airborne effluents, a concentration calculation module, a deposition concentration calculation module, an analysis module of population and diet data, an individual dose calculation module, a collective dose calculation module, and a nuclide characteristic factor module. The flow chart of the evaluation model is shown in fig. 1.

Comparison with AERMOD view model

The data on radioactive airborne effluents (U-238) from the nuclear fuel cycle facility in Baotou is collected, including 7-point sources and two area sources, as shown in tab. 1. The hourly meteorological data of Baotou weather station from 2016 to 2018 are collected, including time, total cloud cover, low cloud cover, temperature, wind direction, wind speed, station pressure, and rainfall. The topographic data are collected within 100 km around the source item of airborne effluents.

With the same source parameters, meteorological parameters, and terrain data, the concentration calculation results using the AERMOD View model and the REIA1.0 model are compared. The results show that the relative deviations in 192 subregions are less than 33.33% for both REIA1.0 and AERMOD View models. The mean relative deviation is 9.34%. Among 192 subregions, only three simulated calculation points at a distance of 50~80 km have a relatively high relative deviation (greater than 20%). The maximum relative deviation in the subregion within 20 km is 16.29%. The relative deviations meet the deviation requirements of ±67% in the Guide for Selection of Ambient Air Quality Model [10].

Comparison with environmental monitoring data

Nine airborne effluent emission sources (total uranium) of nuclear fuel cycle facilities in 2019 are used to calculate the total uranium concentration in air at seven points of nuclear fuel cycle facilities using the REIA1.0. The simulations superimpose the background level with 1.65 ng/m^3. The results are shown in tab. 2.

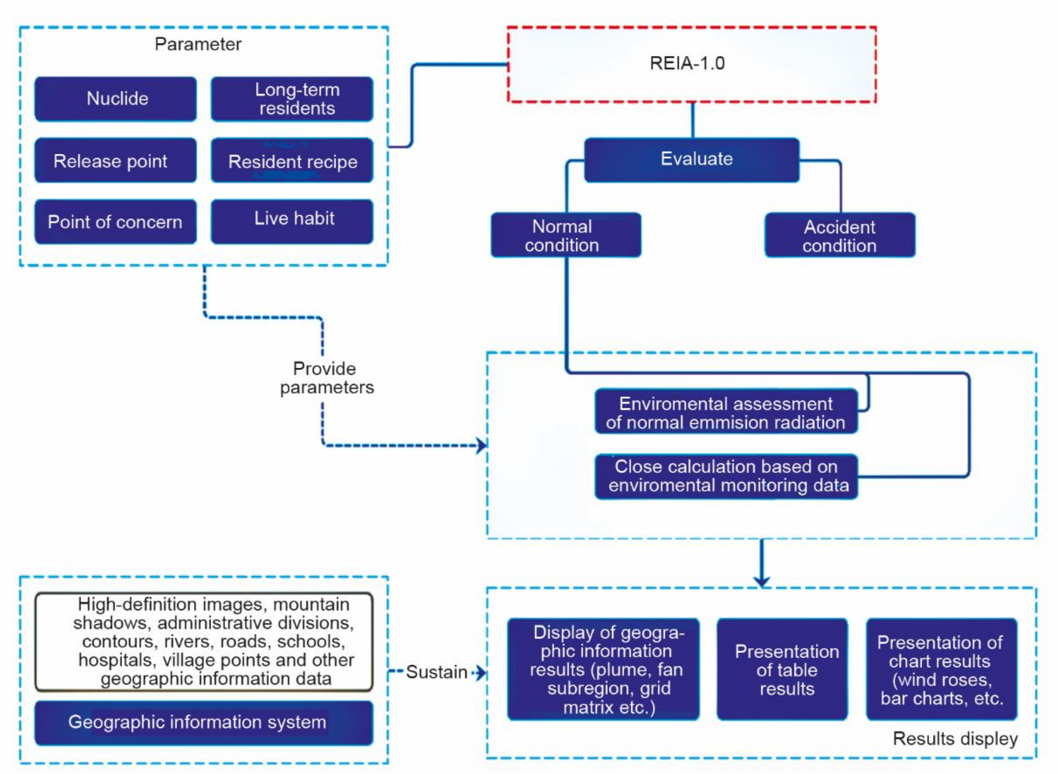

Figure 1. Flow chart of radiation environmental impact assessment model

Table 1. Radioactive airborne effluent of the Baotou nuclear fuel cycle facility

Type	ID	Height [m]	Diam [m]	Exit velocity [ms^{-1}]	Emission rate [Bqs^{-1}]	X [m]	Y [m]
Point	1#	60	2.5	4.17	1	798	–1710
Point	2#	25	1.4	6.14	1	0	0
Point	3#	25	0.9	7.25	1	346	–2447
Point	4#	25	0.3	2.54	1	1352	–421
Point	5#	60	2.5	8.92	1	403	–2552
Point	6#	60	2.5	3.00	1	0	0
Point	7#	30	2.0	6.06	1	–679	–3587
Area	8#	0	1800 m^2	–	1 Bq/m^{2}s	1042	–2127
Area	9#	0	91000 m^2	–	1 Bq/m^{2}s	2736	90

The hourly meteorological data are obtained from the Baotou weather station. The upper-air meteorological data are obtained from the numerical simulation results of the Ministry of Ecology and Environment in China.

The comparison results between the predicted value and radiation environmental monitoring value are shown in tab. 3.

The average level of uranium concentrations is given by the REIA1.0 model in ambient air at 2 hours. The results are within the range of radiation environmental monitoring results. Besides, they are close to the average value.

Table 2. Airborne effluent emissions from the Baotou nuclear fuel cycle facility

Type	ID	Emission rate [gs^{-1}]
Point	1#	$1.16 \cdot 10^{-3}$
Point	2#	$8.11 \cdot 10^{-4}$
Point	3#	$3.64 \cdot 10^{-4}$
Point	4#	$9.94 \cdot 10^{-6}$
Point	5#	$1.27 \cdot 10^{-2}$
Point	6#	$6.36 \cdot 10^{-3}$
Point	7#	–
Area	8#	$1.28 \cdot 10^{-7}$ [gm^{-2}s^{-1}]
Area	9#	$1.51 \cdot 10^{-5}$ [gm^{-2}s^{-1}]

Table 3. Results of radiation environment monitoring and simulation

Monitoring point	Relative position		Environmental monitoring results [ngm^{-3}]			Simulation result [ngm^{-3}]
	Orientation	Distance [km]	Minimum value	Maximum value	Average value	
1	W	2.1	0.38	4.01	1.58	1.81
2	W	1.7	0.27	6.28	1.79	1.89
3	SSW	2.3	0.57	5.39	2.18	2.00
4	WNW	2.2	0.74	3.64	1.95	1.78
5	WSW	7.1	0.28	2.66	1.68	1.70
6	ENE	8.8	0.44	2.16	1.40	1.68
7	NNW	0.8	0.21	5.42	2.44	4.85

Conclusions

Uranium is an important radionuclide for the nuclear fuel cycle facilities. Individual annual effective doses to the public from airborne effluents are more than 95% of all irradiated scenes. Based on this consideration, a radiological environmental impact assessment model REIA1.0 is established. This model is based on the double Gaussian probability distribution function model and considers the wind pendulum effect of the long-term diffusion factor. This model can be used to calculate the individual dose and collective dose in the nuclear fuel cycle facilities. To verify its availability, the simulation results by the REIA1.0 model are compared with the resulted stimulated by the commercial software and radiation environmental monitoring results. It indicates that the REIA1.0 model is effective to identify the contribution of airborne radionuclide concentration from nuclear fuel cycle facilities. This model can effectively assess the radiological environmental impact of nuclear fuel cycle facilities.

The numerical model is an effective tool to simulate radionuclide diffusion and migration. More and more numerical weather prediction models and atmospheric diffusion models have been used to simulate radionuclide diffusion. However, the model accuracy is still relatively low and needed to improve. From the Gaussian model to the Lagrange model and the Euler model, great progress has been made in the application of the model. Not only related to the accuracy of the diffusion model the accurate simulation of radionuclide diffusion is, also closely related to the accuracy of the input parameters, wind field prediction effect, and evaluation parameters. With the increasing demand for the refinement of radiological environmental impact assessment, it is not only essential to focus on the diffusion model but also to pay attention to the accuracy of input parameters.

Atmospheric diffusion of radionuclides is a complex problem, and the fractal diffusion model [14, 15] might be promising for future research.

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