MATHEMATICAL MODELING OF ENVIRONMENTAL IMPACTS OF A REACTOR THROUGH THE AIR

by

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This paper presents an algorithm for the calculation of internal and external doses as an integral part of the mathematical model of atmospheric dispersion. The air pollution dispersion model is used on average annual activity concentration in the air, deposition on soil and field of total annual dose to a hypothetical resident contaminated by air in the vicinity of a nuclear reactor. The results of modeling were compared with values from an IAEA publication for a given scenario of radionuclide emission to the atmospheric boundary layer. Due to small differences in the results, compared to the IAEA recommended model, the model presented in the paper can be used as a basis for this type of analysis.

Key words: radionuclide, air, dispersion, air pollution dispersion model, dose, nuclear reactor

INTRODUCTION

Exposure from the normal operation of a nuclear reactor to members of the public in its vicinity can occur from airborne releases. In the analysis of doses from airborne releases through the ventilation of a reactor, air pollution dispersion models play an important role [1]. They could easily include large number of grid points so that outputs from the models are practically continual fields of air pollution.

Data on the hypothetical emission of radionuclides [2], Brookhaven inventory of radionuclide's [3], ventilation parameters, 3-D topography and meteorological data, field of total annual dose received by a resident in the vicinity of a hypothetical reactor (during its routine operation within a one-year period) are used with the air pollution dispersion model (atmospheric dispersion and module for the calculation of radiation doses) [4].

The aim of the research is to find the maximum value of the total annual dose for a hypothetical resident in the vicinity of a nuclear reactor and compare it with the limit value which, in this case, is 10 μSv [5].

MATHEMATICAL MODEL AND INPUT DATA

The straight-line Gaussian plume model is used for modeling input data (meteorological and fields of radionuclides) and for predicting the maximum value of the total annual dose [1]. The Gaussian model is one of the oldest and perhaps the most commonly used model type [6]. It assumes that air pollutant dispersion has a Gaussian distribution, meaning that the pollutant distribution has a normal probability distribution. The primary algorithm used in Gaussian modeling is the generalized dispersion equation for a continuous point-source plume [7]. The complete equation for Gaussian dispersion modeling of continuous, buoyant air pollution plumes [8], is shown below

$$C(x,y,z) \quad \frac{Q}{2\pi\sigma_y\sigma_z U}\exp \quad \frac{1}{2}\frac{y^2}{\sigma_y^2}$$
$$\exp \quad \frac{1}{2}\frac{(z \quad H)^2}{\sigma_z^2} \qquad \exp \quad \frac{1}{2}\frac{(z \quad H)^2}{\sigma_z^2} \tag{1}$$

where, $C(x, y, z)$ is the air pollution concentration at grid point (x, y, z), Q – the source strength, H – the effective height of source emission, σ_y and σ_z – the diffusion coefficients in y- and z-directions, and U – the average wind speed.

The family of Pasquill curves $_{y,z}$ is suitable for practical application in an analytical-graphical form. Atmospheric stability, according to the Pasquill-Gifford classification, shall be determined on the basis of wind speed and solar radiation (mechanic and thermal cause of turbulence in the atmospheric boundary layer), as shown in tab. 1 [9], where A is the very

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Table 1. Pasquill stability classes

Wind speed at 10 m U [ms^{-1}]	Stability class, day, with insolation			Class of stability, night, with cloudiness	
	Strong	Moderate	Slight	Thin overcast or <4/8 low clouds	3/8 cloudiness
$U < 2$	A	A-B	B		
2 $U < 3$	A-B	B	C	E	F
3 $U < 5$	B	B-C	C	D	E
5 $U < 6$	C	C-D	D	D	D
6 U	C	D	D	D	D

unstable, B – the unstable, C – the slightly unstable, D – neutral, E – the slightly stable, and F – the stable.

In this table, stability classes are classified into six categories that are marked by letters A (very unstable) to F (stable). Qualitative descriptions of insolation such as terms strong, moderate and slight, relate to conditions that are typical for England, which is why this scheme should be used with caution in other latitudes. To determine the Pasquill atmospheric stability classes, standard hourly meteorological measurements are used, while the basic parameters for classifying stability are the wind speed at 10 m, qualitative assessment of insolation during the day (strong, moderate, slight) and coverage of the sky with clouds at night. In this scheme of stability classification, the night is defined as the period beginning one hour before sunset and ending one hour after sunrise.

Moderate insolation corresponds to the surface incident solar radiation under a clear sky when the height of the Sun is above the horizon at an angle between 35° and 60°. The terms strong and slight insolation, relate to the height of the Sun greater than 60° and less than 35°, respectively. The height of the Sun can be obtained from astronomical tables for a specific date, time, and latitude. Since clouds reduce insolation, the insolation for a clear sky is adjusted depending on the cloudiness (amount and type of clouds) to give the corresponding Pasquill stability category. Strong insolation can be reduced to moderate if the sky is covered with clouds of medium height and have them 5/8 to 7/8 or to weak insolation if the sky is covered with low clouds.

If there are measurements of insolation, the Sun height limit of 35° and 60° can be replaced by the corresponding values of insolation during a clear day, when the height of the Sun at these altitudes is above the horizon. When the limit values of insolation are obtained by direct measurement of insolation, the effects of insolation weakening due to cloudiness are included. Neutral class D occurs whenever the sky is completely covered by low clouds, day or night.

Diffusion coefficients σ_y and σ_z for situations (A-B), (B-C), and (C-D) are taken as mean values for (A-B), (B-C), and (C-D). Based on the class of stability (a measure of turbulence in the atmospheric boundary layer), standard deviations of concentration activity distribution of σ_y and σ_z are obtained, depending on the distance from the source downwind, as shown in tab. 2 [10].

Table 2. Briggs formula for $\sigma_y(x)$ and $\sigma_z(x)$, $10^2 < x < 10^4$ m

For urban conditions		
Pasquill stability classes	$\sigma_y(x)$	$\sigma_z(x)$
A-B	$0.32x\,(1 + 0.0004x)^{-1/2}$	$0.24x\,(1 + 0.0001x)^{1/2}$
C	$0.22x\,(1 + 0.0004x)^{-1/2}$	0.20x
D	$0.16x\,(1 + 0.0004x)^{-1/2}$	$0.14x\,(1 + 0.0003x)^{-1/2}$
E-F	$0.11x\,(1 + 0.0004x)^{-1/2}$	$0.08x\,(1 + 0.00015x)^{-1/2}$
For rural area		
Pasquill stability classes	$\sigma_y(x)$	$\sigma_z(x)$
A	$0.22x\,(1 + 0.0001x)^{-1/2}$	$0.20x$
B	$0.16x\,(1 + 0.0001x)^{-1/2}$	$0.12x$
C	$0.11x\,(1 + 0.0001x)^{-1/2}$	$0.08x\,(1 + 0.0002x)^{-1/2}$
D	$0.08x\,(1 + 0.0001x)^{-1/2}$	$0.06x\,(1 + 0.0015x)^{-1/2}$
E	$0.06x\,(1 + 0.0001x)^{-1/2}$	$0.03x\,(1 + 0.0003x)^{-1}$
F	$0.04x\,(1 +0.0001x)^{-1/2}$	$0.016x\,(1 + 0.0003x)^{-1}$

To account for the gravitational settling of heavy gases and aerosols, the fixed height of emission H was modified with the term [11]

$$H \quad \frac{v_s x}{u} \tag{2}$$

where v_s is the terminal velocity and x is downwind distance, as shown in fig. 1.

Meteorological data are obtained by measurements at the automatic meteorological station as, at the least, hourly meteorological data collected at a representative location of the source. On the basis of these data, atmospheric stability and σ_y and σ_z are obtained, as well as air pollution distribution on the basis of wind speed and wind direction.

During the routine operation of the nuclear reactor, a part of radionuclide inventory is released via the ventilation stack. It is a conservative assumption that 1% of the total activity inventory will be released in this manner during one year. An upper estimate for total activities and the resulting release rates is shown in tab. 3 [3].

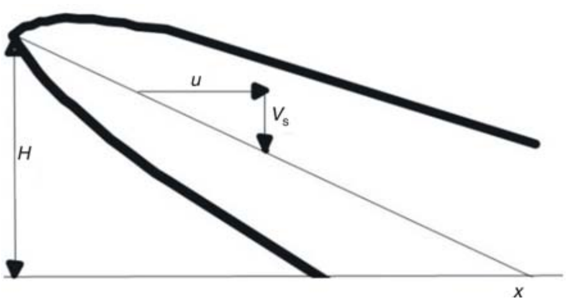

Figure 1. Schematic model of downward sloping plume

In addition to meteorological data (see fig. 2) and to the assumption of the emission of pollutants (radionuclide inventory) shown in tab. 3, the physical characteristics of the sources are expected as input data for the mathematical model.

With the 3-D topography of the hilly terrain (see fig. 3) and with the physical and chemical characteristics of the emitted substances in the atmospheric boundary layer, a minimum set of input data to run the model is completed.

The physical characteristics of the source used in the model are its strength, physical height of the source, diameter at the top/exit of the source-chimney, gas temperature at the exit of the chimney, exit vertical velocity of effluents (W_0), geographical co-ordinates and altitude of the base of the source-chimney(see fig. 4).

The basic subroutines of the model are modules for the effective height of the source (Briggs plume rise concept) [12], module for ground deposition and module for estimation of the dose. The ground depositions of the radionuclides are calculated as follows [13]

$$d \quad (V_{\mathrm{d}} \quad V_{\mathrm{w}})C_{\mathrm{A}} \tag{3}$$

where d [Bqm^{-2}d^{-1}] is the total daily average deposition rate on the ground of a given radionuclide (from both dry and wet processes), including deposition either onto impervious surfaces or onto both vegetation and soil, V_{d} [md^{-1}] – the dry deposition coefficient for a given radionuclide, V_{w} [md^{-1}] – the wet deposition coefficient for a given radionuclide, and C_{A} [Bqm^{-3}] is ground level air concentration at downwind distance x.

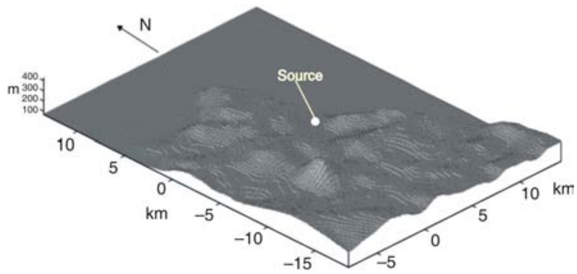

Figure 3. Topography (3-D) of the computational domain and location of the source

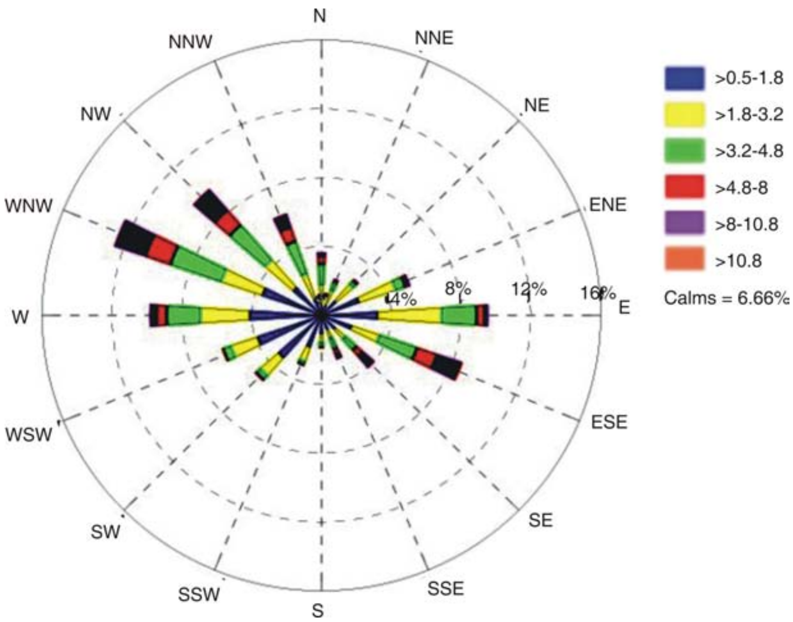

Figure 2. Meteorology, annual wind rose, graphical presentation of wind speed [ms^{-1}] and direction statistics

Table 3. Annual airborne radionuclide releases

Radionuclide	^{41}Ar	^{26}Al	^{76}As	^{128}Ba	^{140}Ba	^{82}Br	^{141}Ce
Released [Bq]	8.2E+13*	4.5E+2	1.7E+7	6.9E+6	5.8E+6	3.2E+8	6.7E+3
Radionuclide	^{144}Ce	^{60}Co	^{59}Fe	^{203}Hg	^{124}I	^{131}I	^{133}I
Released [Bq]	5.3E+4	9.8E+4	1.4E+5	2.2E+6	7.0E+5	1.2E+6	1.3E+7
Radionuclide	^{140}La	^{99}Mo	^{24}Na	^{122}Sb	^{46}Sc	^{75}Se	^{91}Sr
Released [Bq]	3.0E+7	5.7E+3	8.5E+6	1.8E+4	7.9E+2	7.5E+3	1.2E+7
Radionuclide	^{99m}Tc	^{44}Ti	^{133}Xe	^{135}Xe	^{65}Zn	^{69m}Zn	
Released [Bq]	2.2E+6	4.8E+6	3.8E+6	4.0E+7	7.2E+5	5.3E+4	

*8.2E+13 read as 8.2 10^{13}

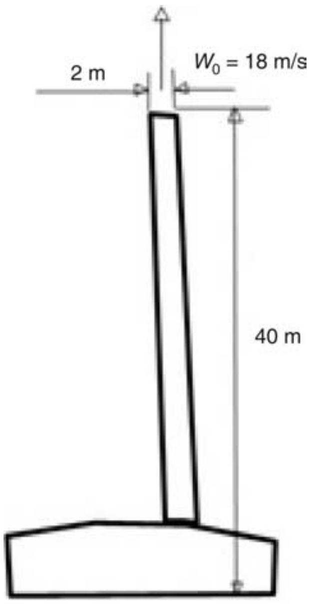

Figure 4. Physical characteristics of the source-chimney

Annual radiation doses for a hypothetical resident are calculated as inhalation, dose of staying in a radioactive cloud (dose of immersion) and the dose of radioactive material deposited on the ground in the form of dry and wet deposition. The total annual dose is calculated as a sum of the doses listed above.

The doses from inhalation are calculated as the product of breathing rate, exposure time, dose inhalation coefficients and radionuclide concentration in the air, using an exposure time of an entire year (8760 h) and the average breathing rate for adults of 1.2 m^3/h [14].

The doses from external irradiation from the activity deposited on the ground are calculated as the product of the ground surface concentration and the dose coefficients for surface deposits. The external radiation dose received by the resident immersed in a cloud of radionuclide's activities for observed annual periods is proportional to the activity concentration in the air near the ground, the exposure time and to the corresponding dose coefficients for the radionuclide in the cloud.

RESULTS AND DISCUSSION

The analysis of radionuclide dispersion through the boundary layer of the atmosphere of the annual routine operation of a reactor and members of the public was done following all described assumptions regarding the source term, meteorological conditions, 3-D terrain topography and physical and chemical characteristics of the emitted substances in the atmospheric boundary layer. A three-step analysis was done:

(1) The described mathematical model in eq. (1) for estimating the dispersion of radionuclides through the atmosphere boundary layer in the vicinity of a nuclear facility, with a module for the evaluation of internal and external doses for the hypothetical adult resident, was tested in computational experiments using the given input data from the publication of IAEA [2].

Results for ground surface concentrations in the air are presented in tab. 4 and those for ground surface concentrations (dry deposition) are presented in tab. 5, for the four radionuclides that were given in order to check the model. Very good agreement was found with the results of the preliminary analysis given in the IAEA document [2].

Table 4. Concentration of activities at 2 m above the ground, per radionuclide

Radionuclide	^{137}Cs	^{90}Sr	^{60}Co	^{154}Eu
Modelled [Bqm^{-3}]	4.8E-04	1.5E-06	3.0E-05	1.5E-05
IAEA document [Bqm^{-3}]	4.8E-04	1.6E-06	3.2E-05	1.6E-05

Table 5. Dry deposition of radionuclide activity per year

Radionuclide	^{137}Cs	^{90}Sr	^{60}Co	^{154}Eu
Modelled [Bqm^{-2}]	154.2	0.49	9.74	4.87
IAEA document [Bqm^{-2}]	174	0.6	12	6

(2) The second step was the simulation of airborne dispersion from the exhaust stack of the reactor facility to the environment in order to obtain the values of ground surface activity concentrations in the air and ground surface concentrations, dry and wet deposition, for the radionuclides of interest.

Fields of the average annual concentration of activities, gained by the presented emission of radionuclides, taking into account the characteristics of sources, weather conditions and soil characteristics, are shown graphically in fig. 5. The maximum value of the average annual activity concentration in the air at 2 m above the ground was 3.9 Bq/m^3.

Dry deposition was calculated from activity concentrations in the air and the deposition rate for the selected terrain and radionuclide emission inventory. The speed of dry deposition is taken from ref. [2], and was based on the recommendations for the deposition rate of 1000 m/d. The field of dry deposition corresponds to the field of concentration of activities, both in shape and by zones with maximum values. The maximum annual value of dry deposition of activities for the selected annual period was 12 kBq/m^2 (see fig. 6).

Wet deposition is calculated as washing with precipitation. The intensity of rainfall was measured by an automatic station for ten minutes. The field of annual activities of wet deposition is calculated from the distribution of activity concentrations with the height and intensity of rainfall. The maximum value of wet deposition was 140 Bq/m^2 (see fig. 7).

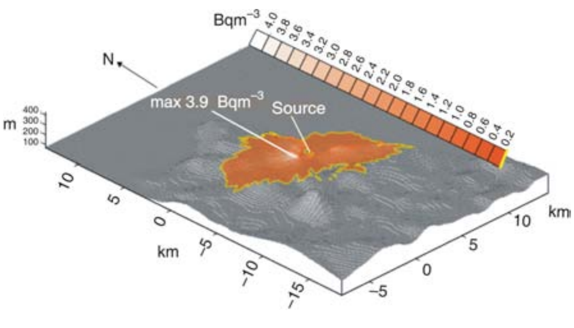

Figure 5. Average annual activity concentration in the air

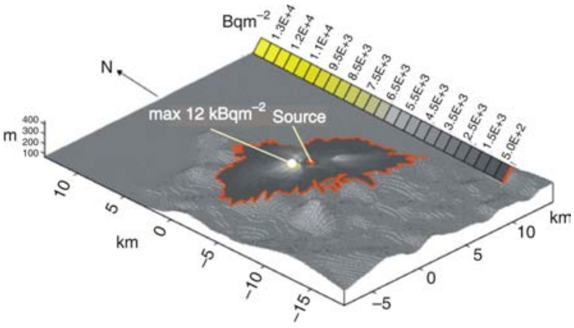

Figure 6. Annual activity of dry deposition

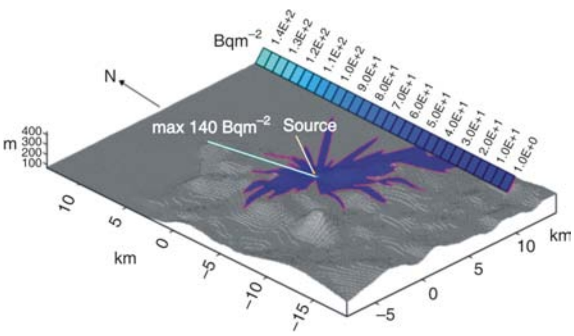

Figure 7. Annual activity of wet deposition

(3) The last step involved the modeling of the exposure of members of the public and the total dose (inhalation and immersion with direct exposure from ground deposition).

As mentioned, the total annual radiation dose for a hypothetical resident in the vicinity of a reactor in operation is modeled as inhalation, the dose of staying in the radioactive cloud (dose of immersion) and the dose of radioactive material deposited on the ground in the form of dry and wet deposition. The total annual dose is calculated as the sum of the doses listed above.

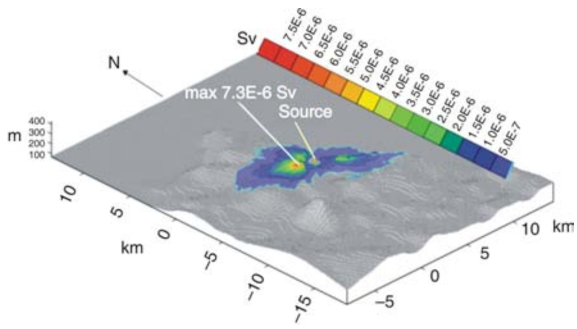

Figure 8. Annual total dose

The maximum value of the total annual dose to a hypothetical resident was 7.3 µSv (see fig. 8).

CONCLUSIONS

The computer code based on the straight-line Gaussian model for atmospheric dispersion used in this analysis, under conservative assumptions on the continuous operation of nuclear reactors and on the preliminary assumed strength of the source based on the 1% inventory of radionuclides continuously emitted into the boundary layer of the atmosphere within a year.

By applying the mathematical model, under the above stated assumptions, the maximum value of the total annual dose for a hypothetical resident was established to equal 7.3 µSv in the vicinity of a nuclear reactor. Based on this result, it can be concluded that a nuclear reactor, under stated conditions of its operation within a year, could not influence the environment above the limit value of 10 µSv.

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AUTHOR CONTRIBUTIONS

Theoretical analysis of the air pollution dispersion model was carried out by D. P. Nikezić and Z. J. Gršić. All authors have analyzed and discussed the results. The manuscript was written by D. P. Nikezić and B. B. Lončar. Figures and tables were prepared by S. D. Dimović and D. P. Nikezić.

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МАТЕМАТИЧКО МОДЕЛОВАЊЕ УТИЦАЈА РЕАКТОРА НА ЖИВОТНУ СРЕДИНУ КРОЗ ВАЗДУХ

У раду је приказан алгоритам за израчунавање унутрашње и спољашње дозе који представља саставни део математичког модела атмосферске дисперзије. Применом дисперзионог модела загађења ваздуха, добијене су просечне годишње концентрације активности у ваздуху, укупна годишња депозиција активности на тлу и укупна доза коју би примио хипотетични становник у околини нуклеарног реактора. Резултати моделовања упоређени су са вредностима из ИАЕА публикације за задати сценарио емисије радионуклида у атмосферском граничном слоју. Захваљујући малим разликама у резултатима, у односу на ИАЕА препоручени модел, модел представљен у раду може се користити као основа за ову врсту анализе.

Кључне речи: радионуклид, ваздух, дисперзија, дисперзиони модел загађења ваздуха, доза, нуклеарни реактор