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To cite this article: A I Ksenofontov *et al* 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **487** 012009

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# Application of simulation modelling approaches for analyzing $\gamma$ -radiation characteristics of a plume induced by a Nuclear Accident at NPP

A I Ksenofontov, A P Elokhin and E A Alalem

National Research Nuclear University-Moscow Engineering Physics Institute (NRNU-MEPHI), Moscow, Russia

E-mail: [issaalem2@yahoo.com](mailto:issaalem2@yahoo.com)

**Abstract.** Method Monte Carlo is applied to assess the radiological impacts to the environment. As such cases, determining the dose rates due to external radiation source is considered, that is induced by radioactive inert gases when they are released from a nuclear power plant; also to estimate the volumetric concentrations of the released radioactive inert gases, and other characteristics associated with the use of gamma detectors of the automated radiation monitoring systems of the environment and unmanned aircraft radiometric system. In order to assure the reliability and the accuracy of the calculations by Monte Carlo method for the dose rates estimations, the results are compared with the results that obtained by the integral method, which showed satisfactory agreement.

## 1. Introduction

The calculated values of the radiation characteristics of radioactive pollutant, which is propagating in the atmosphere as a result of radiation accidents at nuclear power plants or other nuclear facilities are requiring both the meteorological parameters of the atmosphere that characterizing its stability state, functional dependence of volumetric activity on these parameters, and the radiation characteristics of the pollutant itself, determined by the radionuclide composition, the total activity and the  $\gamma$ -radiation energy.

In work [1] to determine the functional dependence of the volumetric activity of the radioactive pollutant on the coordinates  $q(x, y, z)$  and the meteorological parameters of the atmosphere in the framework of the near surface layer model [2, 3], the meteorological characteristics of the specified atmospheric layer were measured, Including (surface wind velocity  $u(z)$ , the turbulent diffusion coefficient  $k(z)$ , and the turbulent pulsation energy  $b(z)$  as functions of height  $z$ ) based on the readings of meteorological monitors measuring the temperature and surface wind speed at several levels (heights), including the temperature of the earth level, using the method of gradient observations.

**Table 1.** Averaged values of meteorological parameters [1].

Season/time	$\bar{u}$ , m/s	$\bar{k}$ , m <sup>2</sup> /s	$\bar{b}$ , m <sup>2</sup> /s <sup>2</sup>	$L$ , m	$v_*$
winter, 20:00	3,057	0,684	0,041	17	0,139
spring, 20:00	3,836	11,743	1,129	-5	0,232

$L$  – the scale of the surface layer of the atmosphere (the Monin-Obukhov scale).

$v_*$  – the dynamic velocity.



In order to obtain the simplest solution of the turbulent diffusion equation that describes the transport of the pollutant in the atmosphere in the framework of its surface layer, the functional dependences of these meteorological parameters were averaged over the height, and their mean values were used in the equation as constant coefficients [4, 5], given in table 1. Finally, the volumetric activity of the gas-aerosol radioactive pollutant propagating in the atmosphere were calculated in formula (1), in which the  $\exp(-y^2/2\sigma_y^2(x))/\sqrt{2\pi\sigma_y(x)}$ , describes the Gaussian (transverse) dispersion, determined by formula (2), in which  $\sigma_y(x)$  – is its dispersion;  $S(x, z)$  is the two-dimensional distribution function of the pollutant [2], determined by formula (3) [4, 5].

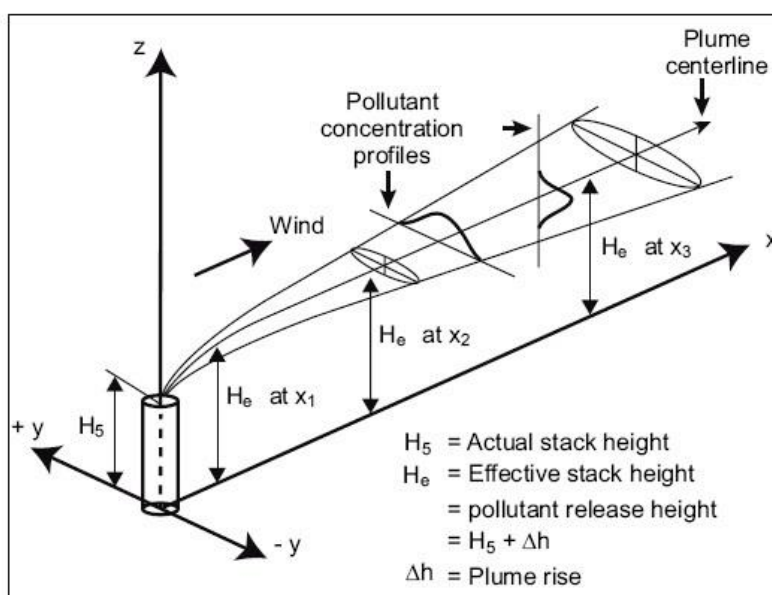
$$q(x, y, z) = \frac{S(x, z)}{\sqrt{2\pi\sigma_y(x)}} \exp(-y^2/2\sigma_y^2); \quad (1)$$

$$\sigma_y^2(x) = \bar{b}x^2/\bar{u}^2(1 + ax\bar{b}/\bar{k}\bar{u}), \quad (2)$$

where  $a = 0,015$ ;

$$S(x, z) = \frac{M}{2} \exp\left(-\left[\frac{\sigma_0 x}{\bar{u}} + \frac{w^2 x}{4\bar{k}\bar{u}} + \frac{w(z-h_{eff})}{2\bar{k}}\right]\right) \left\{ \frac{\exp\left(-[z+h_{eff}]^2 \bar{u}/4\bar{k}x\right) + \exp\left(-[z-h_{eff}]^2 \bar{u}/4\bar{k}x\right)}{\sqrt{\pi\bar{k}\bar{u}x}} - \frac{(2\beta-w)}{\bar{k}\bar{u}} \exp\left[-\frac{(2\beta-w)(z+h_{eff})}{2\bar{k}} + \left(\frac{2\beta-w}{2\bar{k}}\right)^2 \frac{\bar{k}x}{\bar{u}}\right] \times \right. \\ \left. \times \operatorname{erfc}\left[\left(\frac{2\beta-w}{2\bar{k}}\right)\sqrt{\bar{k}x/\bar{u}} + \frac{(z+h_{eff})}{2\sqrt{\bar{k}x/\bar{u}}}\right] \right\}, \quad (3)$$

where  $M$  – the value of the release rate (Bq /s);  $w$  – is the gravitational velocity of deposition of the radioactive pollutant (m/s);  $\sigma_0$  – is the constant of washing out of the pollutant from the atmosphere ( $s^{-1}$ );  $\beta$  – is the rate of dry precipitation of the pollutant (m /s);  $h_{eff}$  – is the emission effective height (m) (figure 1).



**Figure.1.** Schematic of the plume (Schulze and Turner, 1996).

## 2. Methods

### 2.1. Integral method

The calculation of dose characteristics by the integral method [6], in which the volume of the radioactive pollutant that is propagating in the atmosphere is represented as a set of elementary sources with the corresponding coordinates, in each of which the pollutant distribution is assumed uniform. The distance  $r$  between the detection point and the corresponding elementary source is determined by formula (4), and the value of the dose rate is calculated as an integral of the set of point sources by the formula (5).

$$r = \sqrt{(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2}, \quad (4)$$

where  $x, y, z$  – coordinates of the point source;  $x_0, y_0, z_0$  – coordinates of the detection point.

$$D'(x_0, y_0, z_0) = \frac{E \cdot \eta \cdot \mu_a}{4\pi} \cdot \int_V B(E, r) \cdot q(x, y, z) \cdot \frac{e^{-\mu \cdot r}}{r^2} dV, \quad (5)$$

where  $E$  – energy of photons;  $\eta$  – yield;  $B(E, r)$  – build up factor [7];  $\mu_a, \mu$  – linear absorption coefficient and linear attenuation coefficient respectively;  $V$  – volume of the source.

### 2.2. Monte Carlo Method

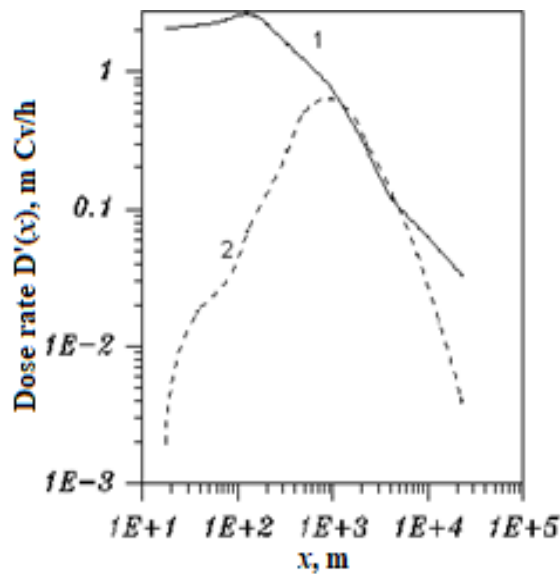
At present, the basic methods for calculating the dose rates from radioactive pollutant of the underlying surface, which are used to estimate the dose rates from external radiation source, are based either on the concept of beam equilibrium [8] or on integral methods, taking into account the buildup factor [6]. It is advisable to estimate the dose rate for radioactive pollutant of air – within the framework of the concept of beam equilibrium – at distances from the emission source of more than 700 m, and at shorter distances – by an integral method [4]. In this case, the main error source that can be accrued is from distribution function of the radioactive pollutant determined by the formulas (1) – (3), since it contains a number of meteorological parameters measured with a certain error, and the error in calculating the buildup factor.

Monte-Carlo method (MC) is a numerical simulation of the physical process of photon interaction with matter based on the randomness of the photon scattering event, independent of its prehistory [9–12]. MC is free from the shortcomings typical of the integral method, but, unfortunately, it takes much more run time, to reduce the calculation error it needs more statistics, which is provided by a large number of stories, which consider random selection of elementary sources, forming volumetric radioactive pollutant. However, the technical capabilities of the current computer technology make it possible to use this method without any limitations [13–15].

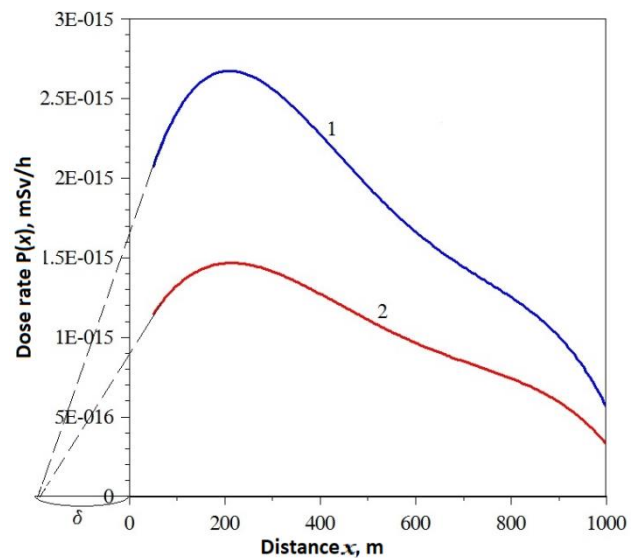
## 3. Results

When calculating the dose rate of external irradiation from a volume source - plume of a radioactive pollutant - attention should be given for improving the distributions of this functional in the area of small (NPP site) distances from the source. The interest in this range of distances is due to the fact that a high gradient is observed in it in the distribution of the surface concentration of the radioactive pollutant, in connection with which the conditions of radiation equilibrium are violated [4] (see figure 2), which, in turn, can result to a significant error in estimating the dose rate. The greatest agreement of dose rate calculations is observed at distances from 0.7 to ~ 10 km from the source. At distances less than 0.7 km, the condition of the beam equilibrium is not fulfilled, and therefore the preference should be given to calculations by the Monte Carlo method and the integral method. Figure 3 shows the dose rate distributions from the volume source on its axis under the emission of  $^{85}\text{Kr}$  under a steady state of the atmosphere (winter), (curve 1) and unsteady state (spring), (curve 2). The calculations were carried out using the integral method. The region of the maximum on the curves

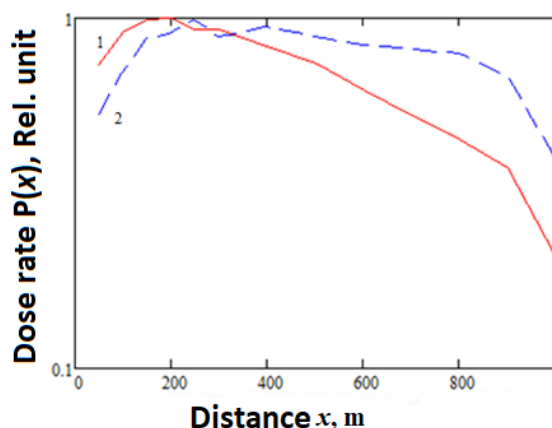
corresponds to the high density of the radioactive pollutant that appears in the atmosphere at small distances from the source. As the pollutant diffuses, the dose rate decreases, as curves 1 and 2 show. As for the shown nature of the distribution of dose rate for various states of atmospheric stability, this fact is explained by the significantly different distribution of the radioactive pollutant in the atmosphere, i.e. character of the distribution of the function  $q(x, y, z)$ , determined by the expression (1), for various states of stability of the atmosphere. Figs. 4 and 5 show the results of calculating the dose rate for the steady (Figure 4) and unsteady (Figure 5) states of the atmosphere by the integral method (curves 1) and MC (curves 2) in these figures.



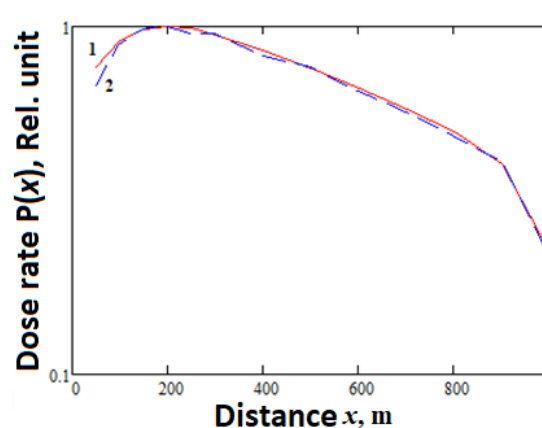
**Figure 2.** The dose rate distribution as a function of distance from the source during a hypothetical accident [4]: 1 – integral method; 2 – concept of radiation equilibrium.



**Figure 3.** Dose rate distribution  $P(x)$  as a function of distance  $x$  from the source (during a hypothetical accident) using the integral method for steady (winter), curve (1) and non-steady (spring), curve (2) states of the atmosphere.



**Figure 4.** Dose rate distribution  $P(x)$  as a function of the distance  $x$  from the source (at a hypothetical accident) for the steady state of the atmosphere (winter) using the integral method, curve (1) and the Monte Carlo method, curve (2).



**Figure 5.** Dose rate distribution  $P(x)$  as a function of the distance  $x$  from the source (at a hypothetical accident) for the unsteady state of the atmosphere (spring) using the integral method, curve (1) and the Monte Carlo method, curve (2).

When forming the curves, there are two exclusive effects: the accumulation of volumetric activity in the atmosphere and its dispersion both due to the airflow and due to the transverse Gaussian broadening of the emission, as noted above.

In general, the results of calculations carried out by both methods agree satisfactorily, but much better with an increase in distances of  $\sim 700$  m. The decrease in dose rate with increasing distances is due to a decrease in the volume activity of the radioactive pollutant that arises from its Gaussian broadening, which increases with increasing distance at source, and due to its decrease as a result of wind transfer. Scattering of the radioactive pollutant with increasing distance leads to its more even distribution in the atmosphere, and when calculating by the Monte Carlo method, in this case, a large number of histories are not required.

At such distances, an estimate of the dose rate can be obtained within the framework of the concept of beam equilibrium, as demonstrate Figure 2. On the contrary, at small distances from the source of emissions, the distribution density of volumetric activity is much higher than on large ones, and its volume is much less. As a result, in this area, much more histories are required to evaluate the dose rate than at large distances from the source. This is indicated by the fact that in both the steady and unsteady states of the atmosphere in the region of small  $x$ , for example, in the region of the maximum of the curves, the difference in the calculation results is 30-40%, and at large distances, the discrepancy is insignificant.

Comparing the results of calculations near the source, it should be noted that calculations of the dose rate in this region should indeed not be carried out, based on the concept of radiation equilibrium. One should also give attention to the value of the dose rate in the region of negative values of  $x$  in Figure 3-5, i.e. in the region  $\delta$  behind the vent tube. The absence of a radioactive pollutant in this region, as it blows the wind into the region of large  $x$ , only indicates that the inhalation dose in this region is zero, but the dose rate of external exposure, strictly speaking, in it will be nonzero at the expense of the scattered and non-scattered gamma radiation of a radioactive pollutant, since it is isotropic. An estimate of the dose rate values of the region  $\delta$  can be different from zero, and it is easy to obtain by linear extrapolation of the dose rate values given in figure 3 with the corresponding state of atmospheric stability.

One of the main characteristics of radioactive emissions is the magnitude of the emission power  $M$  (Ci/s), that is used in the solution of the turbulent diffusion equation (3). Indeed, this quantity plays the role of a normalization factor, since in all functions of the form (5) it will be simply a constant that is derived from the sign of the integral. It is enough to represent the volume activity  $q(x, y, z)$  in (3) in the form of (1), in which the function  $S(x, z)$  will be represented by formula (3). The significance of this parameter cannot be overestimated, given that all characteristics of radioactive pollution in the form of an air basin and the underlying surface or dose exposure on personnel and population will depend on the volume activity  $q(x, y, z)$ .

Given these features, an estimate of this value can be obtained by comparing the measured dose rate and its calculated value, determined by the formula (5). This can be done most simply if the detector is located in an area in which the distribution of volumetric activity can be considered uniform. Indeed, by measuring the value of the dose rate, in this case, with the coordinates  $(x_0, y_0, z_0)$ , the number of which obeys the rule of the necessary number, and placing them on the territory of the site in a large distance from the center and a uniform distribution along the azimuth, for example, along the Archimedes spiral [1], the desired parameter  $M$  can be found in the form of:

$$M = \frac{4\pi D'(x_0, y_0, z_0)}{E \cdot \eta(E) \cdot \mu_a(E) \cdot q_0 \cdot \int_V B(E, r) [\exp(-\mu(E)r)/r^2] dV}, \quad (6)$$

where the distribution  $q(x, y, z)$  can be considered uniformly distributed and equal to  $q_0$ . In this formula, in addition to  $D'(x_0, y_0, z_0)$  the measured parameters are the energy of  $\gamma$ -photons  $E$  and the volume activity  $q_0$ . When determining the parameter  $M$ , all other characteristics of radioactive

pollutants of the environment and dose exposure on the population can be carried out at a one emission rate  $M$ .

Another possibility for estimating the volumetric activity  $q_0$  (Ci/m<sup>3</sup>) with its known radio nuclide composition is the direct use of the vent tube, from which the inert gases emission. In this case, when estimating the dose rate  $D'$  from the cylindrical gaseous uniformly distributed source, which is the internal area of the vent tubes, and comparing it with the analogous calculated, calculated, for example, in the last-mentioned parameter, the desired parameter  $q_0$  can be given as a ratio

$$q_0 = \frac{4\pi D'(x_0, y_0, z_0)}{E \cdot \eta(E) \cdot \mu_a(E) \int_{V_C} [\exp(-\mu(E)R)/R^2] dV}, \quad (7)$$

where  $R = \sqrt{(h_{\text{eff}} - h)^2 + r^2}$ ,  $dV = 2\pi r dr dh$ , volume  $V_C$  is characterized by the range:

$0 \leq h \leq h_{\text{eff}}$ ;  $0 \leq r \leq r_0$ ,  $r_0$  – is the internal radius of the vent tube. In this case, the buildup factor, according to [4], can be equal to 1. If the discharge rate  $G$  (m<sup>3</sup>/s) of radioactive pollutant through the vent tube is known, (for example, it can be measured with the help of a flow and ionization chambers placed at the top of the vent tubes [16]), then  $M$  can be found as the product  $G \times q_0$  (Ci/s), and multiplying the product by the emission time  $\tau_b$ , the total activity of radionuclides released into the atmosphere can be found:

$$Q_0 = G \times q_0 \times \tau_b, \quad (8)$$

The advantage of the above methods for estimating the radioactive characteristics considered above is that they allow us to determine these parameters in the on-line Mode.

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