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Numerical analysis of aerosol radionuclide fall-outs from accident outbursts into the atmosphere*

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1. Introduction

The problem of the assessment of the quantitative characteristics of radioactive pollutions in the environment in response to accidents at atomic stations and enterprises of the nuclear technological cycle is a pressing task. Application of methods of the direct simulation of pollution transport makes it basically possible to correctly describe the concentration fields. However in the case under consideration such an approach runs into obstacles when providing models with an appropriate input information. To such difficulties one can refer the indefiniteness of the height and intensity of a source of the radionuclide outburst into the Atmosphere, distribution in the original cloud of aerosol particles by size and velocity of settling-outs, determination of the current meteorological conditions, etc., resulting in the necessity to use in the numerical modeling a supplementary experimental information about the pollution fields and development of suitable reconstruction models [1–3].

It should also be noted that when using statements of inverse problems, it is undesirable to describe in considerable detail the radionuclide transport processes, as this can bring about difficulties of their substantiation and numerical implementation. A required stage of solving these problems is the analysis the information content of experimental data involved, planning and optimization of the monitoring systems [4, 5].

2. A model of reconstructing the atmospheric fall-outs of polydisperse impurities

A previous analysis of the obtained experimental data of observation of aerosol radionuclide fall-outs reveals that a change in their concentrations farther and farther away from the location of an accident outburst can appear to be quite considerable. This suggests that they contain both large and rather small aerosol fractions. For a priori description of distribution of an impurity substance by velocities of settling-out w in the atmosphere, let us make use of the following two-parameter function [6, 7]:

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$$N(w) = \frac{a^{m+1}}{\Gamma(m+1)} w^m e^{-aw}, \quad m \geq -1, \quad a = \frac{m}{w_m}, \tag{1}$$

where the parameter w_m characterizes the velocity of the impurity fraction, having the greater amount of particles, m is the degree of homogeneity of distribution of impurity particles by the velocities w_m, $\Gamma(m)$ is the Euler gamma-function.

The initial instant for calculating the field of fall-outs of a poly-disperse impurity from a point source is the relation [6]:

$$p = \int_0^\infty w q_w N(w)\, dw, \tag{2}$$

where q_w is the concentration field of a mono-disperse impurity with the settling-out velocity w.

When calculating the mean impurity concentration in the surface atmospheric layer, of primary importance are encountered meteorological conditions. To them we refer the so-called normal meteorological modes, for which we use the power approximation of the wind speed and that of the coefficient of the vertical turbulent exchange [8]:

$$u(z) = u_1 \cdot \left(\frac{z}{z_1}\right)^n, \quad K_z = k_1 \frac{z}{z_1}, \tag{3}$$

where u_1 and k_1 are values of u and K_z for $z = z_1$.

Using relation (3) and analytical solutions to the turbulent diffusion equation for relatively low sources, the concentration field q_ω near to the ground can be represented as [9]:

$$q_\omega(x, y) = \frac{M c^\omega}{2(1+n)\sqrt{\pi k_0}\Gamma(1+\omega) x^{1.5+\omega}} \exp\Big(-\frac{c}{x} - \frac{y^2}{4k_0 x}\Big). \tag{4}$$

Here the axis x is aligned with the direction of wind, the axis y is directed across the wind direction, M is the impurity source intensity, k_0 is a turbulent exchange parameter aligned with the axis y,

$$c = \frac{u_1 H^{1+n}}{(1+n)^2 k_1}, \qquad \omega = \frac{w}{k_1(1+n)}. \tag{5}$$

With allowance for relations (1), (4), formula (2) can be written down as

$$p(x, y) = \frac{M a^{m+1}}{2(1+n)\sqrt{\pi k_0}\Gamma(1+m) x^{1.5}} \exp\Big(-\frac{c}{x} - \frac{y^2}{4k_0 x}\Big) \times \\ \int_0^\infty \frac{\omega^{m+1} \exp(-a\omega)}{\Gamma(1+\omega)} \Big(\frac{c}{x}\Big)^\omega d\omega$$

$$= \frac{Ma^{m+1}(1+n)^{m+1}k_1^{m+2}}{2\sqrt{\pi k_0}\Gamma(1+m)x^{1.5}} \exp\Big(-\frac{c}{x} - \frac{y^2}{4k_0 x}\Big) \times$$
$$\int_0^\infty \frac{\omega^{m+1}\exp(-ak_1(1+n)\omega)}{\Gamma(1+\omega)} \Big(\frac{c}{x}\Big)^\omega d\omega. \tag{6}$$

In particular, for the axial concentration ($y = 0$), relation (6) is represented in the form

$$p(x) = \frac{\theta_1}{x^{1.5}} \exp\Big(-\frac{c}{x}\Big) \int_0^\infty \frac{\omega^{\theta_2}\exp(-\theta_3\omega)}{\Gamma(1+\omega)} \Big(\frac{c}{x}\Big)^\omega d\omega, \tag{7}$$
$$\theta_1 = \frac{Ma^{m+1}(1+n)^{m+1}k_1^{m+2}}{2\sqrt{\pi k_0}\Gamma(1+m)x^{1.5}}, \quad \theta_2 = m+1, \quad \theta_3 = ak_1(1+n).$$

Investigation of properties of function (7) reveals that within the interval $x \in (0, \infty)$ it attains its maximum at a certain point x_0, monotonously increases within $x \in (0, x_0)$ and, respectively monotonously decreases with $x \in (x_0, \infty)$ and tends to zero for $x \to 0$, $x \to \infty$. The unknown parameters $\theta_1, \theta_2, \theta_3$ being a part of relation (7), are estimated by the method of least squares with the measurements data of radiation levels at locality points. It should also be noted that the value c corresponds to that of a distance at which a maximum surface concentration of a light impurity is attained [9].

Remark. The parameters θ_1, θ_2 depend on characteristics of the dispersive content of an aerosol impurity and meteorological conditions. This circumstance makes possible to essentially decrease the number of reference points of measurements when carrying out repeat evaluations of the axial contamination at other time instants. In this case, it is sufficient to re-evaluate the parameter θ_1 only, which according to (7) is proportional to the intensity of a source, whose change will occur only as consequence of radioactive disintegration of precipitated nuclides.

3. Numerical reconstructions of the axial part of a trace resulted from the accident at Siberian Chemical Industrial Complex (SCIC) in 1993

On April 6, 1993, there occurred a failure with a reservoir filled-in with a radioactive solution. This happened at the radio-chemical industrial complex in the city of Tomsk. The accident was accompanied by a short-term salvo outburst of radioactive substances into the environment through the ventilation system, i.e., an outlet pipe 150 m high, and through a disintegrated part of a wall of the building at the height of 15 m. The outburst was formed with a stable wind and moved to the north-East. Distribution of a radioactive contamination of the area was investigated with aero-gamma survey and with the help of surface route observations of the snow and soil cover contamination. The initial length of the trace with a level exceeding 15 μR/h made up 28 km, the largest width being 6 km, the square of the contaminated area exceeding 100 km^2 [10]. Further observations in May–June revealed a sufficiently rapid decrease of contamination levels due to the decay of the short-term radionuclides: ^{103}Ru, ^{95}Nb, ^{95}Zr, ^{106}Ru. That were dominant in the outburst content [10–12].

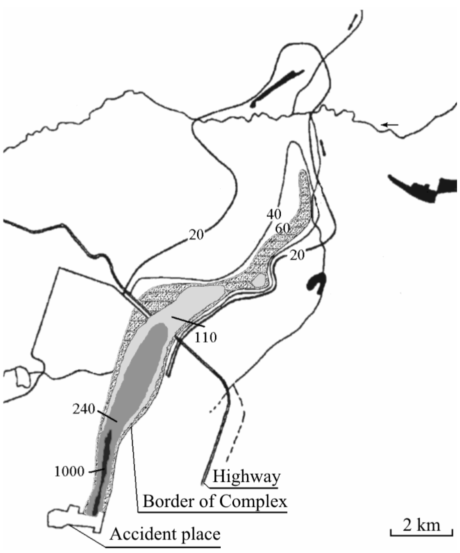

Figure 1

Figure 1 represents a map of the radioactive situation in the vicinity of the accident on May 13, 1993, that was obtained from the data of the surface measurements of the gamma-field at the height of 1 m [11, 12]. By that time, the snow cover was already absent, which essentially simplified making observations and analyzing the experimental results obtained. Using the data from Figure 1 and the model dependence (7), the axial part of the trace was reconstructed. In order to evaluate the unknown parameters θ_1, θ_2, θ_3 the following levels were used as reference measurement levels: 110, 240, 1,000 μR/h.

The results of numerical reconstruction of the axial radio-nuclides fall-outs by the three reference measurement levels are presented in Figure 2a. Using one reference point on the axis of the trace and assessments of the parameters θ_2, θ_3, taken from the previous calculation, the fields of radioactive contamination caused by the accident at the SCE as of April 12 and June 13, 1993, were numerically analyzed. Figures 2b–2d demonstrate the results of reconstructing the nuclide fall-outs in the axial directions according to the data obtained by the aero-gamma and surface snow and soil surveys.

The analysis of results of modeling has revealed a fairly satisfactory fit between the measured and calculated values of the activity at the control measurements points. In spite of a considerable height of the source, the contamination levels were rapidly decreasing with distance, which indicates to an essential heterogeneity of disperse fall-outs of the radio-nuclides mixture. Nevertheless, the initial length of the trace was no less than 40 km. From comparison of the values of the calculated estimations of the parameters θ_1 for the aero- and surface gamma-surveys it follows that in the case of the accident in question, the aero-survey yielded, on the average, 40 % lower as for the values of intensity of a dose. Analysis of Figures 2a and 2b shows

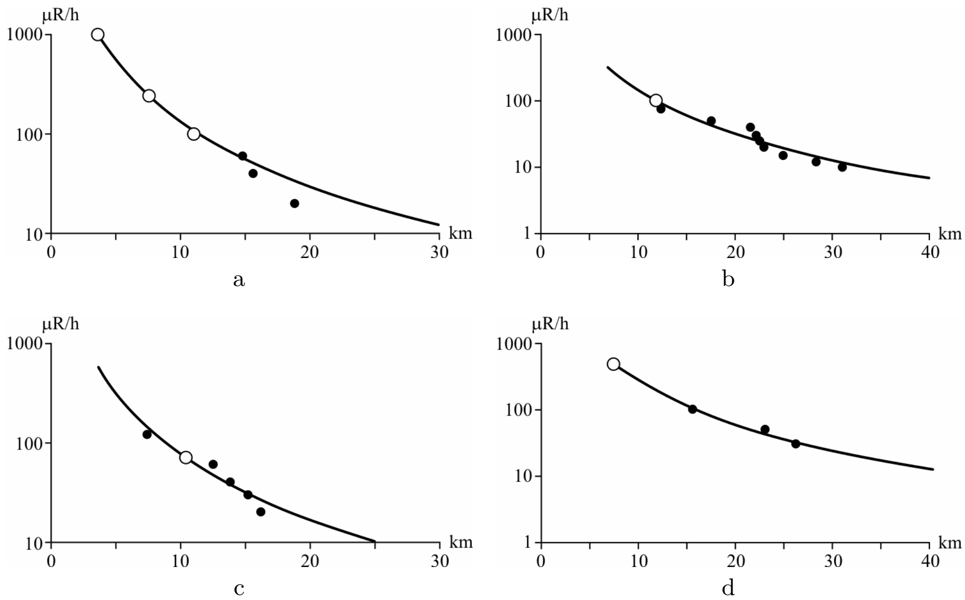

Figure 2. Levels of radioactive contamination of soil and snow cover resulted from the accident at the SCIC in 1993, that were numerically reconstructed from the observational data along the axis of the trace: a) May 13, b) April 12 (aero-gamma survey), c) June 13, d) April 12 (surface observations); — the result of numerical modeling; •, ∘ reference and control measurements points

a distinct decrease of the level of the soil contamination during one month, which, in the first place, is associated with processes of the radioactive decay.

4. Analysis of observational data of radioactive soil cover contamination in the vicinity of the AES "Fukusima-1"

A strong earthquake of March 11, 2011 at the coasts of Japan was a reason of switching-off the central electric supply at the AES "Fukusima-1", followed by a catastrophic tsunami that knocked out the reserve diesel-generators thus prevailing from the effective cooling of active zones of the stopped reactors. Finally, this brought about a series of powerful explosions at the station, accompanied by the outburst into the atmosphere of a radio-nuclides mixture, including radioactive iodine and caesium isotopes. In particular, a trace of fall-outs with a high level of radioactive contamination was formed in the north-west from the AES (the prefecture of Fukusima).

In the Fukusima prefecture, a daily automobile radiation survey of the contaminated area outside of the 20km zone around the AES takes place. The monitoring data are daily available at the site of the Ministry of Education, Culture, Sports, Science and Technology of Japan. In the initial period of the contamination (March, 15–18), a maximum intensity of a dose was about 150–170 µSv/h at a distance of 30 km to north-west from AES. Hereinafter, the dose intensity on the trace was rapidly decreasing, which indicated to the presence in the outburst content of an essential portion of the short-living radio-nuclides. The quantitative information about the radio-nuclide content of the outburst has not been published yet.

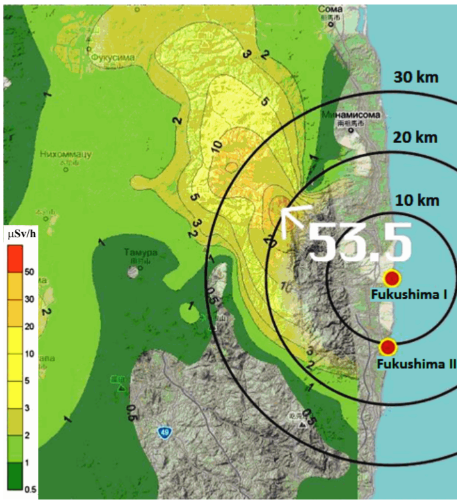

Figure 3

Figure 3 represents a map of intensity of doses µSv/h as of April 12, 2011, constructed based on the data of mobile monitoring. A maximum dose on the radioactive trace was already 58.8 µSv/h at a distance of 20 km from the AES. In order to numerically reconstruct the contamination along the axis of the trace, the points with values of doses 3, 5 and 10 µSv/h were used as reference points. Figure 4a presents the results of reconstruction of the axial part of the trace, obtained with relation (7) using the above reference values of intensities of doses.

The analysis of the numerical modeling results shows that the recovered curve quite satisfactorily describes the contamination along the axis of the trace and that dependence (1) fairly adequately reproduces by the sedimentation velocities the spectrum of the distribution of particles thrown by explosions at the AES. A rapid growth of the intensity of doses in the direction to the AES indicates to the fact that such a tendency should also be expected inside the 20 km zone. Dependence (7) makes possible to assess the levels of the axial radioactive contamination inside the area in question

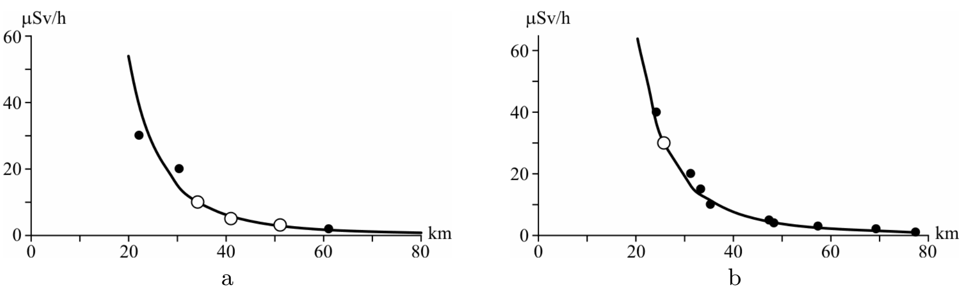

Figure 4. Numerical reconstruction of the axial part of the trace of radioactive fallouts resulted from the accident at the AES "Fukusima-1": a) April 12, b) April 24

up to distances of 5–10 km from the AES. For increasing the accuracy of description of the contamination levels in the nearest zone, a detailed account of distribution of activity in vertical at the time instant of the radionuclide mixture outburst is needed.

The use of the obtained assessments of the parameters θ_2, θ_3 as of April 12, 2011, allowed the analysis of the axial contamination, also, for other observational periods based on a more limited information. In particular, Figure 4b represents the results of reconstructing the axial contamination from one value of the intensity level of doses as of April 24, 2011. A good fit of the data of the radiation monitoring and the numerical reconstruction within 20–80 km confirms both the reliability of the measurements and a certain universality of the obtained assessments of the parameters θ_2, θ_3 as applied to the accident contamination of the area under consideration.

5. Conclusion

The developed small-parameter model of reconstructing fall-outs of a polydisperse impurity makes possible to numerically analyze observational data essentially over the whole axis of a trace. For obtaining assessments of unknown parameters in dependence (7), one needs relatively a small volume of measurements data. According to the numerical analysis of the radiation monitoring data, the separation of a group of parameters, dependent on characteristics of the disperse content, appeared to be a useful technique that has allowed us to additionally diminish the number of the used measurements levels when reconstructing the fields of axial concentrations at other time instants. Highly efficient is the information about the quantitative content of a radionuclide mixture thrown into the atmosphere. After carrying out the numerical reconstruction of the field of nuclides fall-outs, its presence makes possible to predict the radiation situation for subsequent time instants.

For analyzing the monitoring data of the accident contamination in the nearest zone, one needs a more detailed account of the vertical distribution of relative activity in the cloud of explosion. In this connection, it is useful to attract additional a priori information about its character and intensity.

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