On-Line Atmospheric Transport Model for Estimation and Prediction of Consequences of Radiation Accident

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1 Introduction

In case of radiation accident radioactive gas-aerosol releases to the atmosphere are among major sources of environmental contamination. This paper presents an on-line model accounting for transport and dispersion of radioactive material within 100 km in the atmospheric boundary layer (ABL) in case of accidental release at nuclear facilities. The model makes possible estimating distribution of pollutant in the ABL and its integral characteristics, as well as pollutant deposition density on the underlying surface under different accident scenarios with allowance for specific meteorological conditions.

2 Modeling transport and dispersion of pollutant in the atmosphere

Description of transport and dispersion of pollutant in the atmosphere is naturally divided into modeling radionuclides transport and dispersion and modeling characteristics of the environment in which dispersion occurs. The concept underlying the method for calculating environmental contamination with radioactive material entering the atmosphere as a result of an accident at a nuclear facility consists in modeling of 1) the release according to the accident scenario by a series of sequential plumes 2) transport, dispersion and deposition of radionuclides in a separate plume with allowance for local values of meteorological parameters 3) concentration and deposition density of pollutant in the ABL as a sum of contributions from a series of plumes.

This approach lets us taking into account changes in meteorological conditions of transport and dispersion in space and time. The radionuclide concentrations $q(x,y,z,t)$ and deposition density $D(x,y,t)$ occurring as a result of an atmospheric release during an accident are found as

$$q(x,y,z,t) = \sum_{k=1}^{K} q_0(x,y,z,t;t_k),\; D(x,y,t) = \sum_{k=1}^{K} D_0(x,y,t;t_k) \tag{1}$$

where t_1 is the time of beginning of accidental release, $t_k = t_1 + (k-1)\cdot \Delta t$ are time moments when separate plumes enter the atmosphere which model a release of finite action time t_s $q_0(x,y,z,t;t_k)$ and $D_0(x,y,t;\, t_k)$ is concentration and deposition density of radionuclides from the k-th plume ($k = 1,...K$, $K = [t_s/\Delta t]$).

The method for calculation of transport and dispersion of radioactive material in a separate plume is based on analytical solution of the semi-empirical non-stationary 3-D turbulent diffusion equation for an instantaneous point source located in a mixing layer. Using the analytical solution of the diffusion equation makes it possible to perform calculations fairly quickly and ensures that there are no errors due to numerical solution. Yet, deriving analytical solutions of the non-stationary semi-empirical equation of turbulent diffusion will inevitably involve its simplification, in which, however, the main specific features of transport and dispersion can still be taken into account. The simplification consists in the fact that the coefficients of the semi-empirical diffusion equation are taken as time functions in the centroid of a pollutant plume, which makes possible allowing for not only temporal but also approximately for spatial heterogeneity of meteorological elements.

The concentration of pollutant due to a separate k-th plume from an instantaneous point source is written as

$$q_0(x,y,z,t;t_k) = \begin{cases} 0, & \text{at } t < t_k, \\ Q(t_k)\cdot q_1(x,y,t;t_k)\cdot q_2(z,t;t_k), & \text{at } t \geq t_k. \end{cases} \qquad (2)$$

where $Q(t_k)$ is the release activity from the k-th plume. The function $q_1(x,y,z,t;t_k)$ accounts for horizontal transport and dispersion of pollutant, its radioactive decay and wash-out with precipitation. The function $q_2(z,t;t_k)$ determines dispersion and sedimentation of pollutant in the vertical and its interaction with the upper boundary of the atmospheric boundary layer and underlying surface. For q_1 and q_2 analytical expressions have been derived.

The concentration of pollutant in the atmosphere is strongly dependent on pollutant pathway to the atmosphere (determined by the scenario of an accident) and dispersing properties of the atmosphere (turbulence of the atmosphere).

If an accidental release occurred in the form of explosion, the plume rise is estimated by expert judgment or by modeling the explosion, or either by solving the inverse problem based on matching results of model calculation of area contamination with radiological measurement data. If an accidental release occurs through a stack, additional elevation due to pollutant stack exit velocity and its overheating with respect to the environment in the moving turbulent air flow for different weather conditions is estimated using the modified Nattervill formulae /1/.

The dispersion of pollutant in the atmosphere due to turbulence is determined in the diffusion model through variance characteristics of a pollutant plume as represented by the so-called σ-curves (σ_x^2, σ_y^2, σ_z^2 are plume variances lengthwise of transport and transverse to it and in the vertical). Approximation formulae for variances of a pollutant plume based on environmental characteristics are written as /2/

$$\begin{cases} \sigma_x(t_D) = \sigma_u \cdot t_D \cdot f_{xy}(t_D/\tau_{xy}), \\ \sigma_y(t_D) = \sigma_v \cdot t_D \cdot f_{xy}(t_D/\tau_{xy}), \\ \sigma_z(t_D) = \sigma_w \cdot t_D \cdot f_z(t_D/\tau_z), \end{cases} \qquad (3)$$

where t_D is the diffusion time, σ_u, σ_v, σ_w are standard deviations of wind velocity in the longitudinal, transverse and vertical directions, respectively, τ_{xy}, τ_z are the time Lagrangian scales. The type of the functions f_{xy} and f_z used in different publications varies, but lately the most frequently used universal representation is the following /3/:

$$f_{xy}(t_D/\tau_{xy}) = \frac{1}{\sqrt{1+\dfrac{t_D}{2\cdot\tau_{xy}}}}, \quad f_z(t_D/\tau_z) = \frac{1}{\sqrt{1+\dfrac{t_D}{2\cdot\tau_z}}} \qquad (4)$$

for calculation of σ_u, σ_v, σ_w and τ_{xy}, τ_z the approximation formulae derived from works /3-7/ are used:

To account for the initial size of a pollutant plume released to the atmosphere during an accident from a ventilation stack the so-called «virtual source method» is applied. This method essentially consists in the following. The initial plume size is characterized by variance which is calculated over the virtual diffusion time Δt_s . During this time the calculation concentration from the virtual point source in the plume centroid becomes equal to the true concentration in the stack exit. «The virtual diffusion time» is written as:

$$\Delta t_s = \left(\frac{w_s}{(2\pi)^{3/2} \cdot \sigma_u \cdot \sigma_v \cdot \sigma_w} \right)^{1/2}, \qquad (5)$$

where w_s is the stack pollutant exit volumetric velocity. Then the pollutant concentration in the ABL is calculated using the formulae for a point source by increasing diffusion time by Δt_s.

Transport of a separate plume is characterized by movement of its centroid, the coordinates of which $\{x_c, y_c, z_c\}$ are determined by the ratio of the first (M_1) to zero (M_0) moments of the function of pollutant distribution in plume, i.e.

$$x_c = \frac{\int x q_0 d\vec{x}}{\int q_0 d\vec{x}},\ y_c = \frac{\int y q_0 d\vec{x}}{\int q_0 d\vec{x}},\ z_c = \frac{\int z q_0 d\vec{x}}{\int q_0 d\vec{x}}. \tag{6}$$

Naturally, since there is no influence of side boundaries of calculation domain on pollutant transport, the coordinates of the plume centroid in the horizontal will be written as

$$x_c = x_s + \int_{t_k}^{t} u(\tau)d\tau,\ y_c = y_s + \int_{t_k}^{t} v(\tau)d\tau, \tag{7}$$

where u and v are components of the wind velocity in the plume centroid.

Because the function $q_0(x,y,z,t)$ is multiplicative with respect to spatial variables, determination of the plume centroid coordinates in the vertical is reduced to the following:

$$z_c = \frac{M_{1z}}{M_{0z}}, \tag{8}$$

where $M_{0z} = \int_0^H q_2(z,t;t_k)dz$, $M_{1z} = \int_0^H z q_2(z,t;t_k)dz$.

Note that the expressions for M_{0z} and M_{1z} are rather bulky due to allowance for the influence of the boundaries. Analytical solutions were derived for them as a function of the sedimetation velocity V_R and the deposition velocity V_d, the height of the boundary layer H and the effective height h.

The meteorological preprocessor using standard surface measurements at meteorological stations provides parameterization of the ABL by specifying vertical profiles of meteorological parameters (velocity and temperature), the ABL height and parameters of the surface atmospheric layer in the form of interpolation formulas based on experimental data, and using the Monin-Obukhov similarity theory and the estimate of surface energy balance.

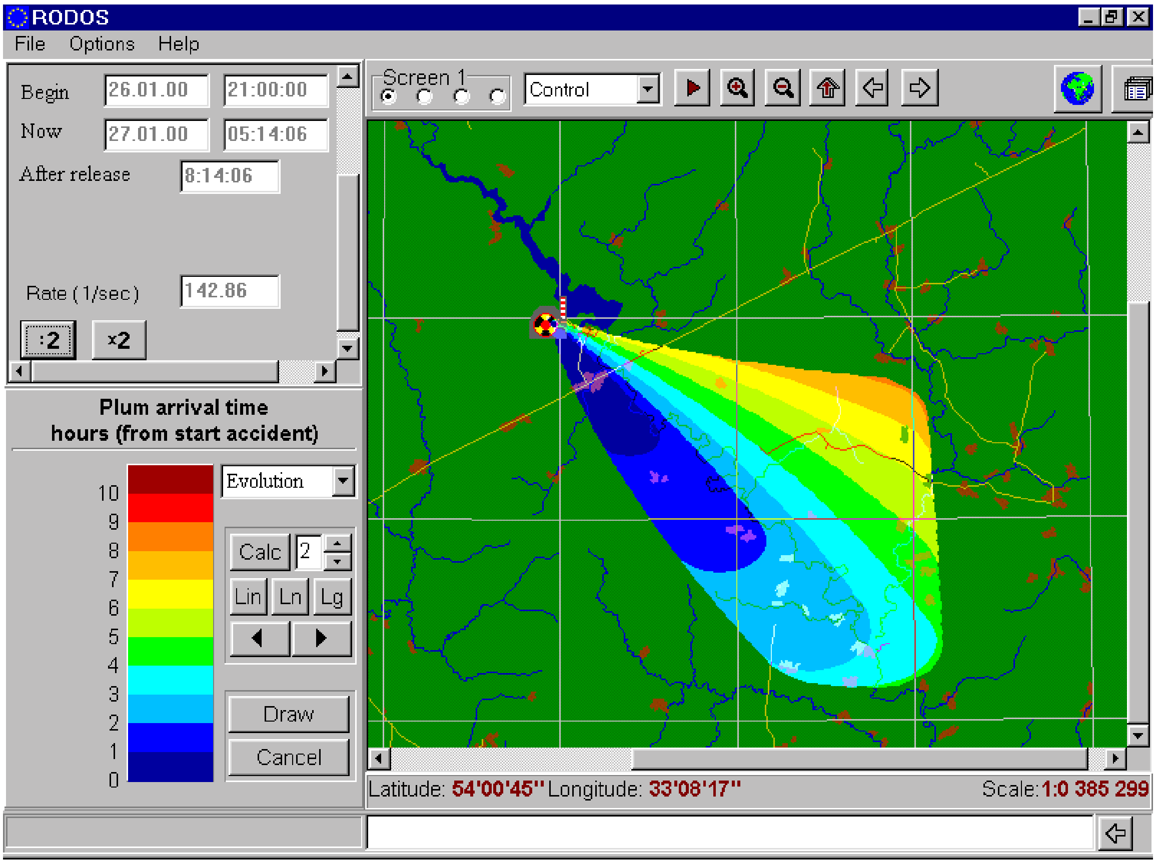
3 Modeling calculations

The on-line model was used to calculate a hypothetical accident situation at the Smolensk NPP with coordinates 33°14′ E and 54°10′ N. The hypothetical situation was modeled for specific meteorological conditions under the assumption that the release from the NPP stack occurred at 21 o'clock GMT on 26 January 2000 and lasted for 6 hours at a constant rate. The total volume of the ^{137}Cs release was taken to be 1 Bq.

The time of calculating the movement of a radioactive plume was about 3 seconds using the computer *Digital Alpha* (533 MHz, 256 MB RAM), the time of calculating total depositions and concentrations in the air (every hour during 24 hours) was about 20 seconds.

Fig. 1 is a map showing occurrence of radioactive pollutants every hour after the release. During the accident the wind was changing from north-west to west and as a result the contamination area is rather extensive. Fig.2 presents the spatial distribution of ^{137}Cs concentration 3 hours after the beginning of the accident. Fig. 3 shows the ^{137}Cs deposition field which was finally formed in the 50 km zone 9 hours after the beginning of the accident.

So, the on-line model for the early phase of an accident is capable of calculating pollutant plume trajectories up to 100 km from the source, the pollutant concentrations $q(x,y,z,t)$ in the ABL, the concentration in specified points integrated over time, the pollutant deposition density $D(x,y,z)$ on the underlying surface by time t. The model is applicable to the conditions of transport and dispersion over heterogeneous underlying surface at non-stationary meteorological conditions.



Begin 26.01.00 21:00:00
Now 27.01.00 05:14:06
After release 8:14:06
Rate (1/sec) 142.86

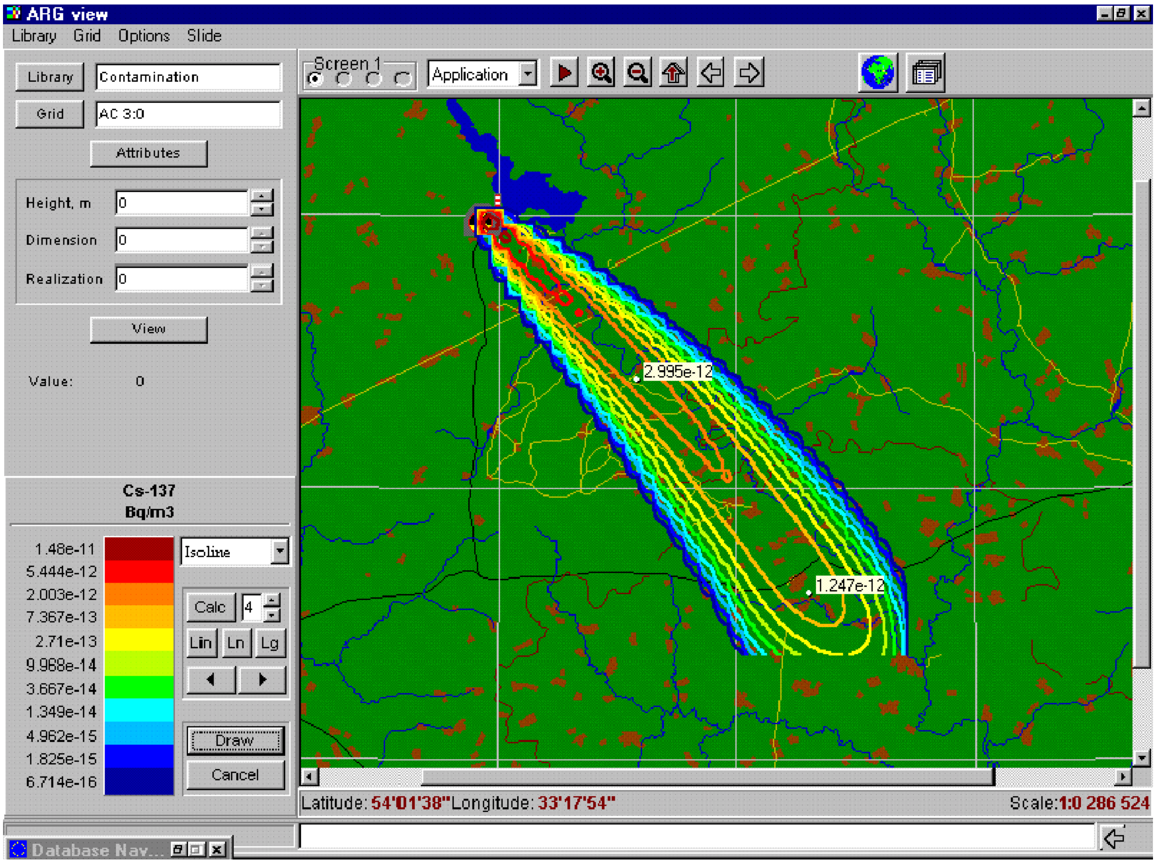
Plum arrival time
hours (from start accident)

10
9
8
7
6
5
4
3
2
1
0

Calc 2

Latitude: 54'00'45" Longitude: 33'08'17" Scale: 1:0 385 299

Figure 1 Dynamics of radioactive contamination.



Library Contamination
Grid AC 3:0
Height, m 0
Dimension 0
Realization 0
Value: 0

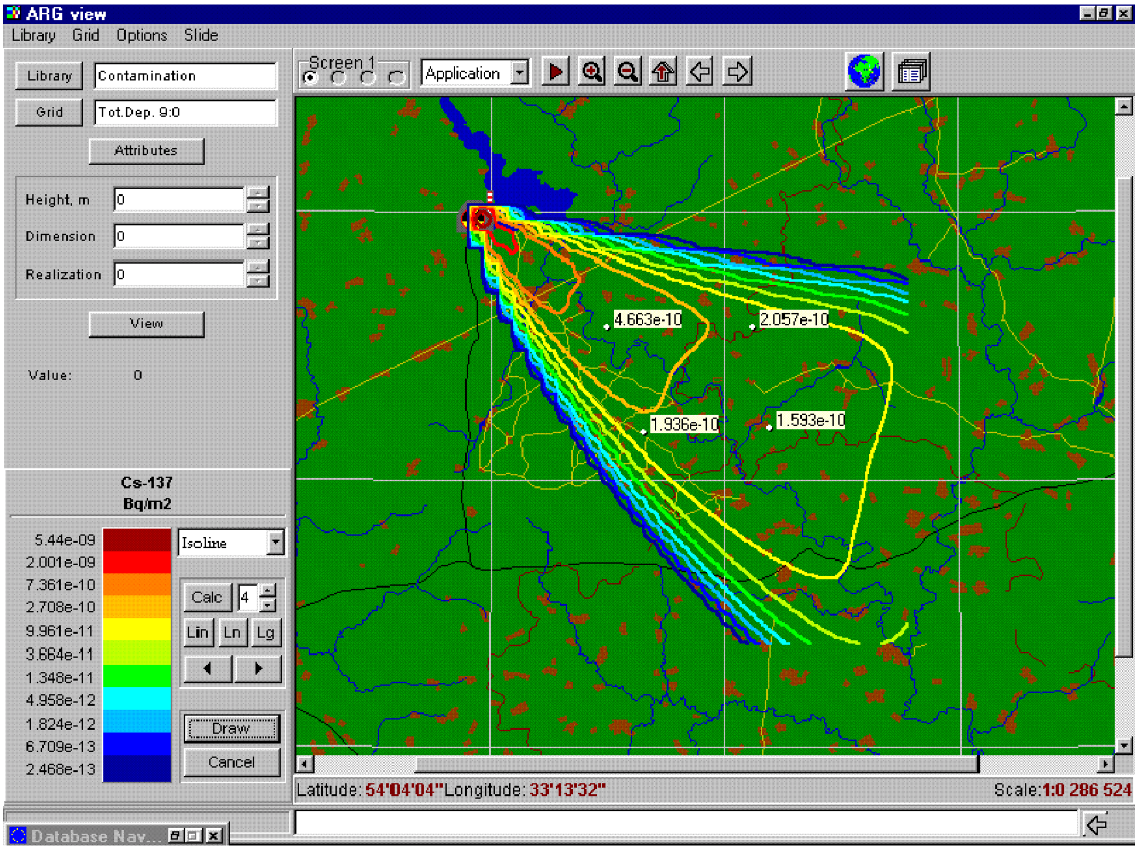
Cs-137
Bq/m3

1.48e-11
5.444e-12
2.003e-12
7.367e-13
2.71e-13
9.968e-14
3.667e-14
1.349e-14
4.962e-15
1.825e-15
6.714e-16

Calc 4

Latitude: 54'01'38" Longitude: 33'17'54" Scale: 1:0 286 524

Figure 2 Surface concentration of ^{137}Cs 3 hours after the beginning of a hypothetical accident.



Library: Contamination

Grid: Tot.Dep. 9:0

Height, m: 0

Dimension: 0

Realization: 0

Value: 0

Cs-137
Bq/m2

5.44e-09
2.001e-09
7.361e-10
2.708e-10
9.961e-11
3.664e-11
1.348e-11
4.958e-12
1.824e-12
6.709e-13
2.468e-13

Isoline

4

Latitude: 54'04'04" Longitude: 33'13'32"

Scale: 1:0 286 524

Figure 3 ^{137}Cs deposition density.

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