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Assessment of radioactive contamination level of environment in case of accident at nuclear power plant

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Abstract. The accidents at nuclear power plants pose a particular threat to the population and the environment. Accidental emissions at nuclear power plants can cause long-term radioactive pollution of the environment, and the elimination of such pollution can take years. For practice, it is very important to predict the intensity and size of radioactive contamination zones for various scenarios of extreme situations at the nuclear power plants. Such a forecast will identify the most vulnerable areas and develop a response strategy to the situation that has arisen. A numerical model has been built that allows to quickly predict the scale of radioactive contamination of the territory during an emergency release at a nuclear power plant. The model is based on the application of implicit difference schemes for the numerical integration of the equation of convective-diffusion transport of impurities in the atmosphere. The developed model is characterized by the calculation speed. The results of the computational experiment are presented.

1. Introduction

Radioactive pollution occurs during the mining and processing of uranium, during the operation of nuclear power plants (NPP), during fuel storage and regeneration. Nuclear crises can be caused by accidents, military actions, terrorist attacks on nuclear facilities, explosion of nuclear devices. Direct damage occurs when radiation interacts with the cells of the human body. There are studies that show that exposure to low levels of radiation does not cause immediate health effects, but may increase the risk of developing cancer over a lifetime [1]. It has been proven that the risk of developing cancer increases when the radiation dose was received in the fetal period or during childhood [2]. It has been shown that in large-scale nuclear accidents, the most important thing is the correct assessment of doses and classification of victims [3]. In this regard, studies on modeling and assessment of contamination zones during radioactive exposure are important [4-9]. In the work [4], pollution modeling was carried out using the European Union nuclear emergency response system RODOS and CALPUFF model, as well as the Weather Research and Forecasting model. The results of calculations of radioactive contamination on a Gaussian scale for the worst accident scenario and the most likely wind speed and metrological conditions show that contamination strongly decreases with distance [5]. An assessment of radiation doses for hypothetical scenarios of the accident of the second research reactor of Egypt [6] and a study of the radiation dose for the expected emergency condition in SAMOP reactor research facility [7] were carried out. Forecasting the level of radioactive contamination of the environment during the emergency emission of radioactive substances at the nuclear power plant is a task of increased importance and necessity for making responsible decisions. The purpose of this work is to develop a numerical model that allows for a quick assessment of the dynamics of the level of atmospheric air and subsoil pollution in the event of an emergency emission of radionuclides at the NPP (figure 1). Quickly obtained areas of potential contamination risk can be useful for developing comprehensive emergency preparedness programs.

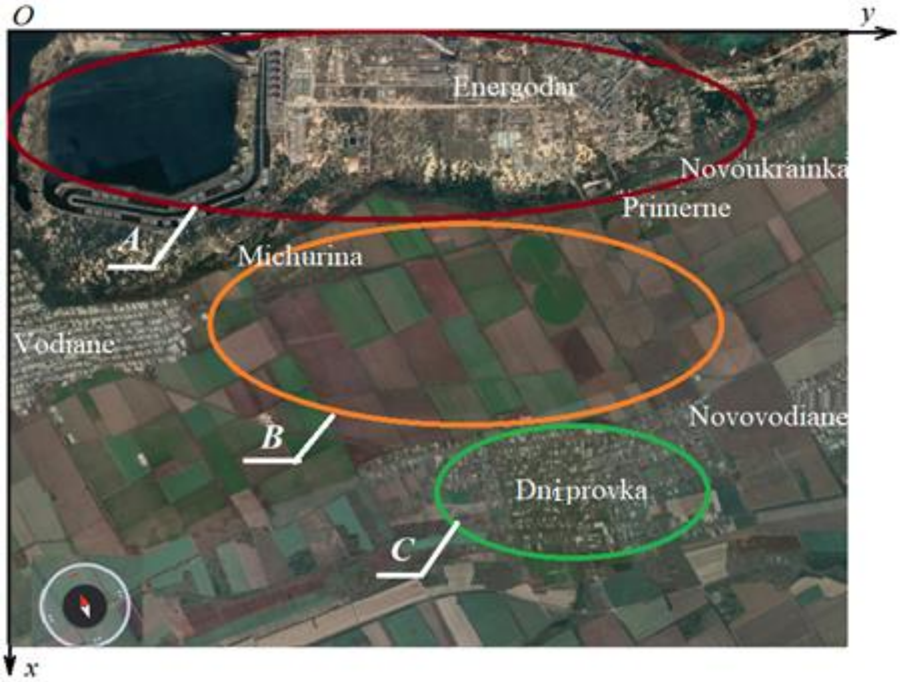

Figure 1. The scheme of the location of ecologically significant zones near NPP: *A* – the territory of NPP, *B* – agricultural land, *C* – territory of Dniprovka village (Google Image, 2022).

2. Methods

The process of dispersion of radioactive emissions into the atmosphere is modeled on the basis of the height-averaged transport equation of the convective turbulent diffusion. The solution of this equation is carried out numerically. To solve the problem, the splitting method is used in conjunction with the implicit alternating-triangular difference scheme.

The following equation for the spread of radioactive emissions in atmospheric air is used to estimate radioactive contamination of the atmosphere in case of emergency radioactive release Q [Ci] at a nuclear power plant [8, 10-12]:

$$\frac{\partial C}{\partial t}+\frac{\partial uC}{\partial x}+\frac{\partial vC}{\partial y}+\lambda C=\frac{\partial}{\partial x}(\mu_x\frac{\partial C}{\partial x})+\frac{\partial}{\partial y}(\mu_y\frac{\partial C}{\partial y})+\sum_{i=1}^{n}Q_i(t)\delta(x-x_i,y-y_i) \qquad (1)$$

where C – deposition along the height of the transfer of the volume activity value, Ci/m^3; u, v – components of the wind speed vector in the projection onto the x and y coordinate axes, respectively, m/s; $\lambda=\frac{0.693}{T_{1/2}}$, 1/s, $T_{1/2}$ – half-life time, s; x_i, y_i – Descartes coordinates of the radioactive emission source at the NPP, m; t – time, s; μ_x, μ_y – coefficients of atmospheric turbulent diffusion, m^2/s; $\delta(x-x_i, y-y_i)$ – Dirac's delta function, with which the location of an emergency radioactive release at a nuclear power plant is specified in the model. In equation (1), it is taken into account that the intensity of the radioactive emission, averaged over the height of the transfer, can change over time $Q_i(t)$, Ci/(s·m). For simulation, this dependence should be set $Q(x,y)=f(t)$. With this approach, within one model, it is possible to simulate different types of emergency release: instantaneous release, semi-continuous release, long-term release, etc.

The boundary conditions for equation (1) are as follows [12–13]:

– on the border of the wind flow entering the study area: $C = C\big|_{\text{entrance}}$ – the background concentration of radioactive pollution in the atmosphere is known (for pilot calculations it is accepted $C = 0$.

– at the boundary of the exit of the wind flow from the research area and the upper boundary: $\frac{\partial C}{\partial n} = 0$, where n – unit vector of the external normal to the boundary.

Initial condition $C\big|_{t=0} = 0$ where $C\big|_{t=0} = C_0$, where C_0 – known background concentration. The value of atmospheric turbulent diffusion coefficients is calculated: $\mu_y = k_0 \cdot u$, $\mu_y = k_0 \cdot v$, where u, v – components of the wind speed vector in the projection onto the x and y coordinate axes, respectively, m/s; $k_0 = 0.1$ [12]. Wind speed and direction are input parameters for the problem and are given to meteorological observation data.

Thus, in order to analyze the formation of zones of radioactive contamination in the atmosphere after an accident at a nuclear power plant, it is necessary to solve the boundary value problem (1) with the corresponding boundary and initial conditions. The finite difference method is used to solve this problem. In practice, it is very important not only to predict the level of radioactive contamination of the atmospheric air in case of a possible accident at a nuclear power plant, but also to determine the level of radioactive contamination of the subsurface, first of all, in ecologically significant zones (villages, fields, etc.). To calculate the intensity of radioactive contamination J [Ci] of the territory the dependence [12] is used:

$$J = \int_0^T dt \int_S w_s C dS\,, \tag{2}$$

where T – time interval from the beginning of pollution, s; S – the area of territory subject to pollution, m^2; w_s – the rate of deposition of radioactive particles in the atmosphere, m/s;. In the computer model, ecologically significant zones are marked [13], for which the level of radioactive contamination is consistently determined over time.

A rectangular difference grid is used for numerical interpolation of equation (1). The components of the air flow velocity vector are set on the sides of the difference cells. The concentration is determined in the centers of the difference cells. To move from derivatives to finite-difference analogs, the following transformations are performed [13]:

$$\frac{\partial uC}{\partial x} = \frac{\partial u^+ C}{\partial x} + \frac{\partial u^- C}{\partial x}, \quad \frac{\partial vC}{\partial y} = \frac{\partial u^+ C}{\partial y} + \frac{\partial u^- C}{\partial y},$$

where $u^+ = \frac{u + |u|}{2}$; $u^- = \frac{u - |u|}{2}$; $v^+ = \frac{v + |v|}{2}$; $v^- = \frac{v - |v|}{2}$.

The first derivatives are approximated [13]:

$$\frac{\partial u^+ C}{\partial x} \approx \frac{u^+_{i+1,j} C^{n+1}_{ij} - u^+_{ij} C^{n+1}_{i-1,j}}{\Delta x} = L^+_x C^{n+1}, \quad \frac{\partial u^- C}{\partial x} \approx \frac{u^-_{i+1,j} C^{n+1}_{i+1,j} - u^-_{ij} C^{n+1}_{ij}}{\Delta x} = L^-_x C^{n+1},$$

$$\frac{\partial v^+ C}{\partial y} \approx \frac{v^+_{i,j+1} C^{n+1}_{ij} - v^+_{il} C^{n+1}_{i,j-1}}{\Delta y} = L^+_y C^{n+1}, \frac{\partial v^- C}{\partial y} \approx \frac{v^-_{i,j+1} C^{n+1}_{i,j+1} - v^-_{ij} C^{n+1}_{ij}}{\Delta y} = L^-_y C^{n+1}.$$

The second derivatives are approximated [13]:

$$\frac{\partial}{\partial x}\left(\mu_x \frac{\partial C}{\partial x}\right) \approx \mu_x \frac{C^{n+1}_{i+1,j} - C^{n+1}_{i\,j}}{\Delta x^2} - \mu_x \frac{C^{n+1}_{i\,j} - C^{n+1}_{i-1,j}}{\Delta x^2} = M^-_{xx} C^{n+1} + M^+_{xx} C^{n+1},$$

$$\frac{\partial}{\partial y}\left(\mu_y \frac{\partial C}{\partial y}\right) \approx \mu_y \frac{C^{n+1}_{i,j+1} - C^{n+1}_{i\,j}}{\Delta x^2} - \mu_y \frac{C^{n+1}_{i\,j} - C^{n+1}_{i,j-1}}{\Delta x^2} = M^-_{yy} C^{n+1} + M^+_{yy} C^{n+1}.$$

Using the given approximation formulas, the difference analog of the original equation (1) is written:

$$\frac{C^{n+1}_{i,j} - C^{n}_{i,j}}{\Delta t} + L^+_x C^{n+1} + L^-_x C^{n+1} + L^+_y C^{n+1} + L^-_y C^{n+1} + \sigma C^{n+1}_{i,j} =$$

$$(M^+_{xx} C^{n+1} + M^-_{xx} C^{n+1} + M^+_{yy} C^{n+1} + M^-_{yy} C^{n+1}) + Q_{i,j}\delta_{i,j}. \qquad (3)$$

The difference equation (3) is split into four steps [13].

The first small step ($k = \frac{1}{4}$):

$$\frac{C^{n+k}_{i,j} - C^{n}_{i,j}}{\Delta t} + \frac{1}{2}(L^+_x C^k + L^+_y C^k) + \frac{\sigma}{4} C^k_{i,j} = \frac{1}{4}(M^+_{xx} C^k + M^-_{xx} C^n + M^+_{yy} C^k + M^-_{yy} C^n). \qquad (4)$$

The second small step ($k = n + \frac{1}{2}$; $c = n + \frac{1}{4}$):

$$\frac{C^{k}_{i,j} - C^{c}_{i,j}}{\Delta t} + \frac{1}{2}(L^-_x C^k + L^-_y C^k) + \frac{\sigma}{4} C^k_{i,j} = \frac{1}{4}(M^-_{xx} C^k + M^+_{xx} C^c + M^-_{yy} C^k + M^+_{yy} C^c). \qquad (5)$$

At the third small step ($k = n + \frac{3}{4}$; $c = n + \frac{1}{2}$) dependence (5) is applied, at the fourth small step ($k = n + 1$; $c = n + \frac{3}{4}$) dependence (4) is applied. In these ratios, $\sigma = \lambda$ is accepted. The software implementation of the constructed numerical model was carried out in the FORTRAN algorithmic language.

3. Results and discussion

Below are the results of solving the problem of assessing the level of radioactive pollution of atmospheric air and the territory near the NPP based on the developed numerical model.

The scenario of an emergency release of radionuclides at Zaporizhzhia NPP, the second unit, is under consideration. The calculation was carried out with the following data: $T_{1/2} = 28.5$ years; wind speed 7 m/s; the wind direction is north-west; the emission is "semi-continuous": the emission occurs with intensity 100 Ci/s during 10 minutes; w_s =0.001 m/s. As ecologically significant zones are considered according to figure 1: the territory of the NPP – zone *A*, agricultural land – zone *B*, the territory of the village of Dniprovka – zone *C*.

Figures 2–4 show how the area of radioactive contamination of atmospheric air in the region develops over time.

Figure 2. Isolines of volume concentration of radioactivity, *t*=17 minutes: 1 – C= 0.07 Ci/m^3; 2 – C= 0.34 Ci/m^3; 3 – C= 0.62 Ci/m^3.

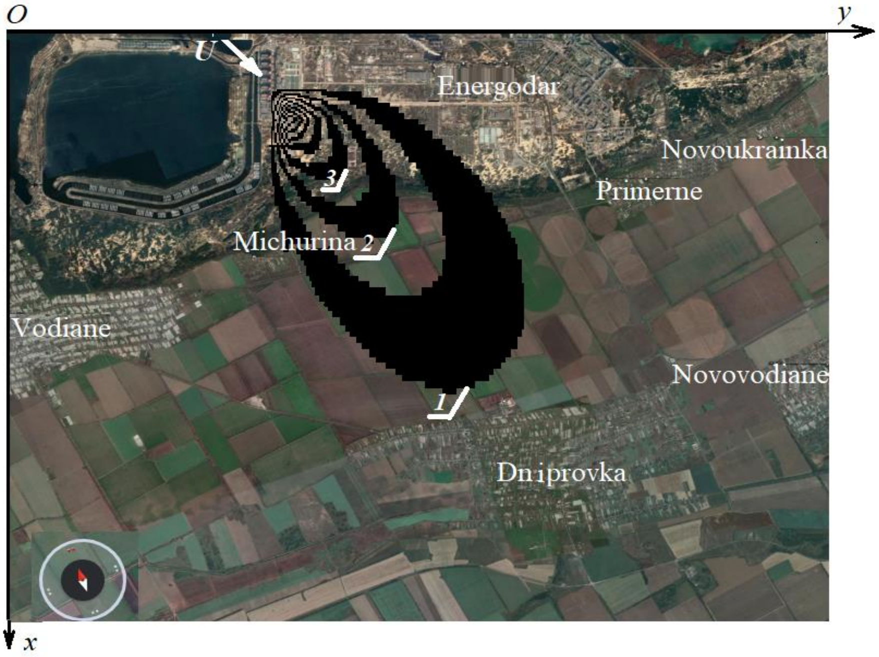

Figure 3. Isolines of volume concentration of radioactivity, *t*=26 minutes: 1 – C= 0.11 Ci/m^3; 2 – C= 0.55 Ci/m^3; 3 – C= 0.99 Ci/m^3.

Figures 2-3 show that the cloud of radioactive pollution increases in the indicated direction of the wind. In the first 15 minutes, it covers only the territory of NPP, and in the next 15 minutes – the agricultural land. The cloud takes the form of an ellipse, which stretches in the direction of air masses movement. The intensive expansion of the radioactive cloud occurs due to atmospheric turbulent diffusion. The zone with a significant gradient of volume concentration of radioactivity is formed near the emission source.

Figure 4. Isolines of volume concentration of radioactivity, t=39 minutes:
1 – C= 0.09 Ci/m^3; 2 – C= 0.47 Ci/m^3; 3 – C= 0.84 Ci/m^3.

As can be seen from the above figures, the area of radioactive contamination very quickly reaches the village of Dniprovka, which is located in the direction of movement of the radioactive cloud. Since the time it takes for the cloud to reach the village is insignificant, there is a real threat to the inhabitants of the village of falling into the zone of radioactive damage. It can be seen from the figures that in 30 minutes, the territory of the NPP and the agricultural lands located near the NPP will be the most polluted.

A pilot assessment of the level of radioactive contamination P [Ci/m^2] of the territory can be carried out according to the ratio:

$$P = \frac{\sum J}{S}, \tag{6}$$

where $\sum J$ – total intensity of radioactive contamination of the surface, Ci; S – surface area affected by contamination.

Table 1 shows forecast data regarding the value of the parameter P and the intensity change equation J.

Table 1. The average value of the level of radioactive radiation in different zones at the time of 40 minutes after the accident.

Zone	P, level of radioactive radiation, Sv/h	Intensity change equation J
the territory of NPP – zone A	$2.3\cdot10^{-3}$	$0.11\ e^{0.35\cdot t}$
agricultural land – zone B	$5.2\cdot10^{-6}$	$6.62e^{0.19\cdot t}$
Dniprovka – zone C	$6.3\cdot10^{-4}$	$0.0013e^{0.29\cdot t}$

where t – the travel time of the pollution wave after the start of the accident, s.

If we take into account that the dangerous level of radioactive radiation is the level of more than 1 mkSv/h, it can be seen from table 1 that in case of an accident at NPP, people will be injured. Note that the calculation time is 2 seconds.

4. Conclusions

As a result of the conducted research, the following results were obtained:

1. A numerical model is proposed for estimating the level of radioactive contamination of air and territory in case of a possible accident at a nuclear power plant. The determination of the fields of volume concentration of radionuclides in the atmospheric air is carried out on the basis of the equation of convective-diffusion transfer of impurities, which takes into account the most significant factors of this process.
2. On the basis of the developed numerical model, a number of computational experiments were carried out, which made it possible to determine the scale of radioactive pollution of the environment in case of an emergency leak of radionuclides on the territory of the Zaporizhzhia NPP.
3. The results of computational experiments show that the emergency emission of radioactive substances at the nuclear power plant can lead to intense pollution of the territory already in the first half hour after the emission begins. The level of radioactive contamination will significantly exceed the permissible limit.

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