# Information systems modeling

UDC 519:62 **doi:** https://doi.org/10.20998/2522-9052.2024.2.03

Viktoriia Biliaieva[1], Larysa Levchenko[2], Iryna Myshchenko[3], Oksana Tykhenko[4], Vitalii Kozachyna[1]

[1] Ukrainian State University of Science and Technologies, Dnipro, Ukraine
[2] National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine
[3] Wroclaw University of Science and Technology, Wroclaw, Poland
[4] National Aviation University, Kyiv, Ukraine

## MODELING THE DISTRIBUTION OF EMERGENCY RELEASE PRODUCTS AT A NUCLEAR POWER PLANT UNIT

\

**Abstract.** Despite the fact that much attention is paid to the safe operation of nuclear power plants, there is a possibility of an accident with the release of radionuclides. This is especially true in Ukraine, where there is a threat of the damage to nuclear reactors as a result of military operations. It is impossible to research the distribution of products emergency releases radioactive substances in laboratory conditions. Therefore, the only tool for the development predicting of an accident is the modeling the spread of a radionuclides cloud. **The purpose of the research** is a modeling the distribution of emergency release products in a nuclear power plant unit, suitable for the operative assessment of a development an accident. **Results of the research**: The mathematical model of the distribution emission products of a nuclear power plant has been developed, which takes into account the value of the initial activity of emission products, the rate of the settling radioactive particles, the wind speed components, the intensity changes radionuclide emission over time. The technique for solving the boundary value problem of modeling in conditions of a complex shape of the computational domain, taking into account the presence of obstacles to the spread of emission products has been developed. The use of the velocity potential equation in evolutionary form allows us to speed up the calculation process. The chosen splitting scheme of an alternating-triangular method allows to find the speed potential according to the explicit form at each splitting step. This allowed software implementation of the CFD model. The visualized models of the emission cloud distribution allow to determine the radiation situation in any place of the emission product distribution zone. The developed model makes it possible to quickly predict the development of an accident in space and time, which makes it possible to take measures to protect people from exposure in the shortest possible time. **Conclusions:** The obtained emission cloud propagation models and their visualization make it possible to determine the state of environmental pollution under various initial conditions during the development of the accident.

**Keywords:** modeling; nuclear accident; radionuclides; forecasting.

### Introduction

Despite the implementation of strict safety measures at nuclear power plants, in particular, increasing the reliability of nuclear reactors, the possibility of an emergency release of radioactive substances exists. Despite the implementation of strict safety measures at nuclear power plants, in particular, an increasing the reliability of nuclear reactors, the probability of an emergency release radioactive substances exists. This is especially relevant for Ukraine, where as a result of hostilities it is possible the damage of the reactors power units' nuclear plants. The peculiarity of the modeling the process the spread radioactive substances from the emergency release of the power unit is that it is impossible to verify the results of the modeling in laboratory conditions and on real object. A lot of attention is paid to the modeling of the spread clouds emissions substances dangerous to humans. The disadvantage of most of them is the long time it takes to take into account individual options depending on the initial conditions and their changes in the process of propagation of the emission cloud. This complicates the decision-making process for the protecting people from the dangerous exposure. But in such a situation, the speed of the response to the danger is the main factor in the minimizing of the impact harmful substances on people. That is, the actual task is to develop a model that allows you to calculate the spread of the cloud in the shortest possible time, taking into account all critical factors in the conditions of their complex dynamics. This requires the selection of an adequate mathematical model, the development of a methodology for the solving the relevant equations, and the development of appropriate software. This will allow to model of the spread of the radioactive emission cloud in almost real time with the visualization of the simulation results on the monitor screen with the reference to the terrain.

**Analysis of research and publications.** Most of the studies and publications on the spread of clouds of hazardous substances in the event of an emergency release at enterprises concern the chemical industry [1, 2]. This is due to a large number of enterprises of the chemical industry. But the consequences of such accidents are less harmful to people due to the rapid dissolution of chemicals in the air. In addition, the specific weights of chemical substances differ from those of radioactive materials, which causes different patterns of their distribution in the space under the same conditions. Most research on nuclear accidents is aimed at the preventing them. Works [3, 4] present the modern principles of the forming a complex of nuclear safety measures and a personnel training system for responding to possible emergency situations at nuclear plants during operation. The study [5] concerns the assessment of the possible contamination the territory with radioactive substances. These semi-empirical models operate on the data on the pollution of the territory from the point of view the prevailing factors of the influence (the wind, the temperature, precipitation) in a specific territory. In the work [6], CFD modeling of the possible development of the accident is used, which is very effective, but a moving object is considered, which is not relevant for most active power plants. In the study [7], a model of changes in territory pollution after sedimentation of emission products was developed. The paper [8] defines the risks of emission at a nuclear power plant with recommendations for decision-making in the event of accidents. At the same time, the dynamics of the development of accidents is not taken into account. The study [9] laid the methodological foundations for modeling the spread of a cloud radioactive substances, which is formed in the event of an emergency release of a reactor. The application of the velocity potential equation to build the emission propagation model allows you to speed up the calculation process. Therefore, the use of such an approach is appropriate for obtaining a model of the distribution emission products a nuclear power plant.

**Purpose and tasks of the research.** The purpose of the study is to model the distribution of emergency release products at the power unit of a nuclear power plant, suitable for the operational assessment the development an accident.

To achieve the goal, the following tasks are defined:

- the development of a mathematical model the distribution power unit emission products;

- the development of a methodology for solving a boundary value problem in the conditions of a complex shape the calculation area;

- an obtaining and a visualization of the model showing the development the accident at the power unit.

## Mathematical model of the distribution products the emergency release of the power unit

Modeling of the distribution products the emergency release radionuclides is carried out on the example of the Zaporizhzhia nuclear power plant (Ukraine).

Forecasting of the radiological situation is carried out on the basis of the developed CFD model [11, 12].

The task is to assess the level of radiological air pollution on the territory of the Zaporizhia Nuclear Power Plant (NPP) in the area where the power units are located. The calculation area is shown in Fig. 1.

To estimate the level of radioactive air pollution in the event of an emergency radioactive release Q [Ci] at the NPP, the following equation for the distribution of radioactive emissions in an atmospheric air is used:

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


**Fig. 1.** Calculation area (Google Image, 2023)

where C is the volume activity value, Ci/m³; $u$, $v$, $w$ – components of the wind speed vector in the projection on the coordinate axis $x$, $y$, $z$, respectively, m/s; $w_s$– rate of deposition of radioactive particles in the atmosphere; $\lambda = 0,693/T_{1/2}$, 1/s, $T_{1/2}$ – half-life, years; $x_i$ $y_i$ $z_i$ – Cartesian coordinates of the $i$-th source of radioactive emission at the NPP, $m$; $t$ – time, s; $\mu_x,\mu_y,\mu_z$ – coefficients of atmospheric turbulent diffusion, $m^2/s$; $\delta\left(x_i,y_i,z_i\right)$ – the Dirac delta function, with the help of which the location of the emergency radioactive release at the NPP is specified in the model [12, 13]. The emission intensity of radionuclides is equal to $Q$.

This model takes into account changes in the intensity of the radionuclide releases over time. To carry out the modeling, a dependency must be specified $Q\left(x_i,y_i,z_i\right)=f\left(t\right)$, i.e. specify how the intensity of radionuclide release changes over time. With this approach, within the framework of the modeling an equation (1), it is possible to model different types of an emergency release: semi-continuous release, long-term release, instantaneous release.

Boundary conditions for the modeling equation (1) are as follows:

- at the entrance of the air flow to the study area $C = C|_{entrance}$: the background concentration of the radioactive pollution in an atmosphere is known (for pilot calculations is accepted $C = 0$);

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

The initial condition $C|_{t=0}=0$ or $C|_{t=0}=C_0$, where $C_0$ is the known the background concentration of radionuclides.

The wind speed profile and atmospheric diffusion coefficients are calculated as follows:

$$u=u_1\left(\frac{z}{z_1}\right)^p,\ \mu_z=k_1\left(\frac{z}{z_1}\right)^m,\ \in\mu_x=\mu_y=k_0u,$$

where $p$=0,15; $m$=1; $k_1$=0,2; $z_1$=1 m; $k_0$=0,1; $u_1$ is the wind speed at a height of $z_1$=1m.

The wind speed and the direction are input parameters for the problem and are given by meteorological observation data.

Since the process of the distribution radionuclides within the limits of the industrial site is considered, then it is necessary to take into account the influence of buildings (power units) on the formation areas the radioactive contamination. That is, it is necessary to solve the problem of an aerodynamics - to calculate the air flow velocity field on an industrial site under construction conditions. The potential motion model is used to solve this problem. In this case, the modeling equation of an aerodynamics has the form:

the equation for the velocity potential:

$$\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}=0, \tag{2}$$

where $P$ is the speed potential.

Boundary conditions for the modeling equation (2) are as follows:

1. $\frac{\partial P}{\partial n}=0$ on impermeable boundaries.
2. $\frac{\partial P}{\partial n}=0$ on the upper limit.
3. $\frac{\partial P}{\partial n}=V_n$ at the boundary where the flow flows into the calculation area, ($V_n$ – the air flow velocity).
4. P=const at the border of the flow "exit" from the calculation area.

Projections of an air flow velocity vector on axis of the Cartesian coordinate system are defined as follows:

$$u=\frac{\partial P}{\partial x}; \quad v=\frac{\partial P}{\partial y}; \quad w=\frac{\partial P}{\partial z}, \tag{3}$$

Thus, in order to analyze the formation of zones the radioactive contamination in an atmosphere on the territory of the industrial site during an emergency emission at the power unit, it is necessary to solve the boundary value problem (2) and calculate the components of the air flow speed at the industrial site based on dependencies (3). Next, using the data on the air flow velocity field, calculate equation (1) and obtain the volume activity distribution at an industrial site for a certain time after the start of the emergency emission radionuclides on the territory of the NPP.

## The method of the solving the boundary value problem in the conditions of the complex shape the calculation area

Finite-difference methods of the numerical integration are used to solve the boundary value problem (1), (2) in the conditions of the complex shape the calculation domain, which is an industrial site with power unit buildings. The alternating triangular method is used for the numerical integration of equation (2). To construct the finite-difference scheme of this method, it is necessary to reduce the equation for the speed potential to the "evolutionary" form:

$$\frac{\partial P}{\partial t}=\frac{\partial^2 P}{\partial x^2}+\frac{\partial^2 P}{\partial y^2}+\frac{\partial^2 P}{\partial z^2}, \tag{4}$$

where $t$ is a fictitious time.

Next, the following splitting scheme of the alternating triangular method is used. This numerical model is developed to solve the evolution equation (4) based on the difference splitting scheme:

- the first step of the splitting:

$$\begin{aligned}\frac{P^{n+1/2}_{i,j,k}-P^{n}_{i,j,k}}{0,5\Delta t}&=\frac{P^{n}_{i+1,j,k}-P^{n}_{i,j,k}}{\Delta x^2}+\frac{-P^{n+1/2}_{i,j,k}+P^{n+1/2}_{i-1,j}}{\Delta x^2}\\&+\frac{P^{n}_{i,j+1,k}-P^{n}_{i,j,k}}{\Delta y^2}+\frac{-P^{n+1/2}_{i,j}+P^{n+1/2}_{i,j-1}}{\Delta y^2}+\\&+\frac{P^{n}_{i,j,k+1}-P^{n}_{i,j,k}}{\Delta z^2}+\frac{-P^{n+1/2}_{i,j,k}+P^{n+1/2}_{i,j,k-1}}{\Delta z^2},\end{aligned} \tag{5}$$

- the second step of splitting:

$$\begin{aligned}\frac{P^{n+1}_{i,j,k}-P^{n+1/2}_{i,j,k}}{0,5\Delta t}&=\frac{P^{n+1}_{i+1,j,k}-P^{n+1}_{i,j,k}}{\Delta x^2}+\frac{-P^{n+1/2}_{i,j,k}+P^{n+1/2}_{i-1,j,k}}{\Delta x^2}\\&+\frac{P^{n+1}_{i,j+1,k}-P^{n+1}_{i,j,k}}{\Delta y^2}+\frac{-P^{n+1/2}_{i,j,k}+P^{n+1/2}_{i,j-1,k}}{\Delta y^2}+\\&+\frac{P^{n+1}_{i,j,k+1}-P^{n+1}_{i,j,k}}{\Delta z^2}+\frac{-P^{n+1/2}_{i,j,k}+P^{n+1/2}_{i,j,k-1}}{\Delta z^2}.\end{aligned} \tag{6}$$

At each splitting step, the velocity potential is found using an explicit formula. This allows for easy software implementation of the developed CFD model.

The components of the air flow velocity vector at the industrial site are calculated on the sides of the difference cells on the basis of dependencies (7):

$$\begin{aligned}u_{i,j,k}&=\frac{P_{i,j,k}-P_{i-1,j,k}}{\Delta x},\\ v_{i,j,k}&=\frac{P_{i,j,k}-P_{i,j-1,k}}{\Delta y},\ \mathrm{w}_{i,j,k}=\frac{P_{i,j,k}-P_{i,j,k-1}}{\Delta z}.\end{aligned} \tag{7}$$

For the numerical integration of equation (1), a number of transformations are carried out, namely:

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

$$\frac{\partial vC}{\partial y}=\frac{\partial v^+C}{\partial y}+\frac{\partial v^-C}{\partial y},$$

$$\frac{\partial wC}{\partial z}=\frac{\partial w^+C}{\partial z}+\frac{\partial w^-C}{\partial z},$$

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

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

Next, the following approximation of the derivatives is performed:

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

$$-\mu_x\frac{C^{n+1}_{i,j,k}-C^{n+1}_{i-1,j,k}}{\Delta x^2}=M^-_{xx}C^{n+1}+M^+_{xx}C^{n+1},$$

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

$$\frac{\partial}{\partial z}\left(\mu_z \frac{\partial C}{\partial z}\right) \approx \mu_z \frac{C^{n+1}_{i,j,k+1} - C^{n+1}_{i,j,k}}{\Delta z^2} - \mu_z \frac{C^{n+1}_{i,j,k} - C^{n+1}_{i,j,k-1}}{\Delta z^2} = M^-_{zz}C^{n+1} + M^+_{zz}C^{n+1}.$$

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

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

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

$$\frac{\partial w^+ C}{\partial z} \approx \frac{w^+_{i,j,k+1}C^{n+1}_{i,j,k} - w^+_{i,j,k}C^{n+1}_{i,j,k-1}}{\Delta z} = L^+_z C^{n+1},$$

$$\frac{\partial w^- C}{\partial z} \approx \frac{w^-_{i,j,k+1}C^{n+1}_{i,j,k+1} - w^-_{i,j,k}C^{n+1}_{i,j,k}}{\Delta z} = L^-_z C^{n+1}.$$

Further, for the numerical integration of equation (1), the following splitting scheme is used:

1) the first splitting step ( $k$= 1/2):

$$\frac{C^{n+k}_{i,j,k} - C^n_{i,j,k}}{\Delta t} + \left(L^+_x C^{n+k} + L^+_y C^{n+k} + \mathrm{L}^+_z \mathrm{C}^{n+k}\right) + \frac{\lambda}{2}C^{n+k}_{i,j,k} = \frac{1}{2}\Big(M^+_{xx}C^{n+k} + M^-_{xx}C^k + M^+_{yy}C^{n+k} + M^-_{yy}C^n + M^-_{zz}C^{n+k} + M^-_{zz}C^n\Big) + \sum_{l=1}^{N}\frac{Q_{ijk}}{2}\delta_l\,; \quad (8)$$

2) the second splitting step ($k$ = $n$+1; $c$ = $n$+1/2):

$$\frac{C^k_{i,j,k} - C^c_{i,j,k}}{\Delta t} + \left(L^-_x C^k + L^-_y C^k + L^-_z C^k\right) + \frac{\lambda}{4}C^k_{i,j,k} = \frac{1}{2}\Big(M^-_{xx}C^k + M^+_{xx}C^c + M^-_{yy}C^k + M^+_{yy}C^c + M^-_{zz}C^k + M^+_{zz}C^c\Big) + \sum_{l=1}^{N}\frac{Q_{ijk}}{2}\delta_l\,; \quad (9)$$

At each step of splitting (8), (9) the unknown value of volumetric activity is determined by an explicit formula.

On the basis of the developed numerical model (5) – (9), the code "NUCLEA" was created, the programming language is FORTRAN.

## Modeling the development of an accident at NPP power unit and its visualization

The developed numerical model and the computer code created on its basis were used to predict the level radioactive contamination in the case of the emission isotopes contained in the gas stream coming out of the first unit the nuclear power plant.

In Fig. 2 shows the site of the leak radionuclides. It is believed that this jet contains the following isotopes: $^{41}Ar$, $^{85m}Kr$, $^{87}Kr$, $^{133}Xe$, $^{131}I$.

The intensity of an isotope emission is characterized by the power $Q=1.5$ Ci/s.

The wind speed $u_1$=3.5 m/s. It is assumed that the rate of the deposition radioactive particles in an atmosphere $w_s$=0 (gas emission).

Since the dynamics of the formation the area radioactive contamination within the industrial site of the nuclear power plant is being considered, and such an area is formed very quickly, the calculation takes $\lambda=0$.

Next, the figures show how the area of the radioactive contamination is formed at the industrial site of the nuclear power plant for different moments of time after the start the isotope leak (Figs. 3-5).


**Fig. 2.** Calculation area "red dot" - the place of an emission radionuclides; "yellow dot" – the position of the receptor (person)

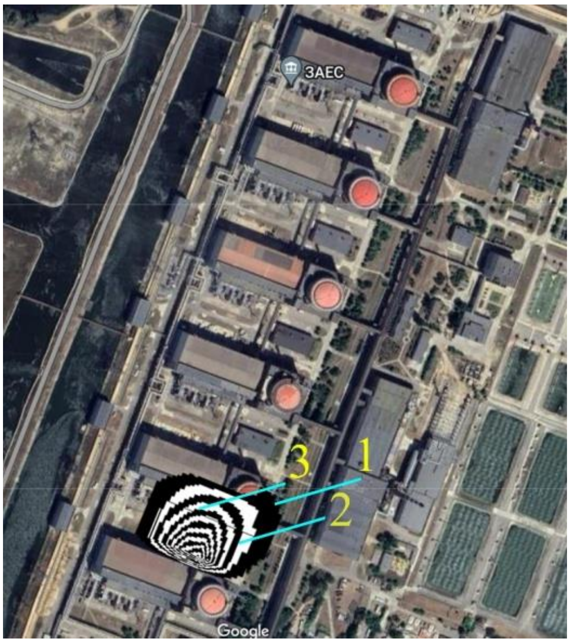


**Fig. 3.** The area of radioactive contamination at the moment of time t=34 s, level z=12 m^
1 – C=0,058 Ci/m$^3$; 2 – C=0,135 Ci/m$^3$;
3 – C=0,213 Ci/m$^3$

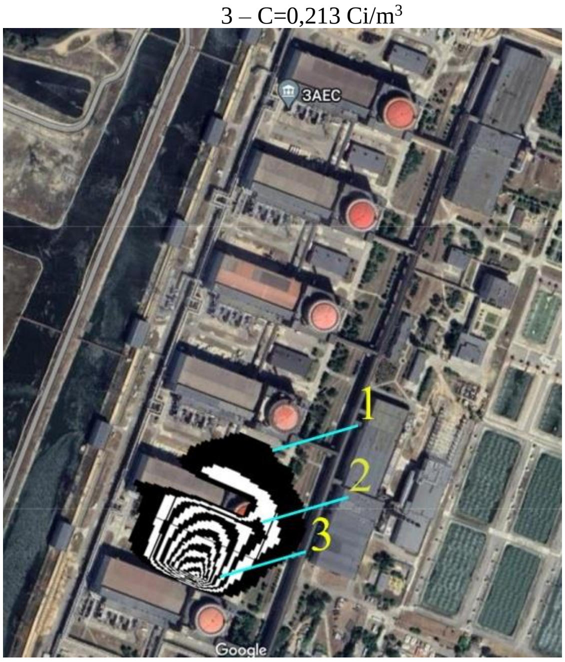


**Fig. 4.** Area of the radioactive contamination at time t=55 s, z=12 m:
1 – C=0,061 Ki/m$^3$; 2 – C=0,142 Ki/m$^3$;
3 – C=0,224 Ki/m$^3$

The obtained model makes it possible to evaluate the development of an accident at a power unit of a nuclear power plant with the release of radionuclides in real time.

This simplifies the process of determining the actual contamination of the territory and organizing people's protection works.

## Discussion of research results

As can be seen from Fig. 3–5, the area of radioactive contamination spreads very quickly over the industrial site of the NPP.


**Fig. 5.** Area of the radioactive contamination at time t=86 s, z=12 m
1 – C=0,063 Ki/m$^3$; 2 – C=0,144 Ki/m$^3$;
3 – C=0,226 Ki/m$^3$

It can also be seen that power units deform the area of the pollution, which significantly distinguishes it from the area of the pollution that forms in space without obstacles and has the appearance of a "tongue" [16].

To analyze the injury risk to personnel at the station, it is important not only to predict how radioactive emissions spread in an atmosphere and the formation of a zone the radioactive contamination at the industrial site, but also to predict the dose per person from external photon radiation.

The following dependence is used to calculate the equivalent dose from an external photon radiation for a person located on the territory of the industrial site of the NPP:

$$H = B_{\alpha\gamma} \int_0^T C(x, y, z) dt, \qquad (10)$$

where $H$ – equivalent dose per time; $B_{\alpha\gamma}$ – dose factor.

Note that dependence (10) uses the time-varying value of volumetric activity C(x,y,z) at the location of the person. For the above list of isotopes contained in an emission.

Thus, in order to determine the injury risk to a person located at any point on an industrial site, it is necessary to calculate the dynamics of changes in volume activity at the point of location of a person based on model (1) and calculate the parameter based on dependence (10).

In Fig. 6 shows the dynamics of changes in the equivalent dose for a person who is near the third power unit, level z=1.7 m (Fig. 3, "yellow dot").

If we take into account that the maximum permissible dose for NPP personnel is 5 ber per year, then as can be seen from Fig. 5, this value is reached 1.5 min after the start of an isotope emission. That is, it is a risk of a fatal damage to a person.

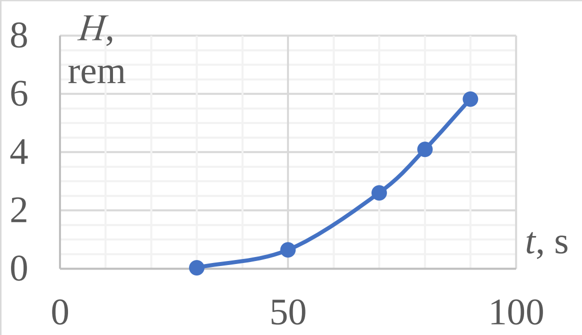


**Fig. 6.** The value of the equivalent dose for a person

The application of the proposed approach can be used to predict the development of any accident with the release of nuclides.

This allows timely identification of the risks of people's impressions.

Also, the obtained results make it possible to determine the areas of safe stay of people in the event of an emergency situation and the location of storage facilities in case of accidents.

## Conclusions

1. The developed mathematical model of the distribution an emission products the nuclear power plant takes into account the value of the initial volumetric activity an emission products, the rate of a deposition radioactive particles in an atmosphere, the components of the wind speed, which are the most critical indicators that affect the development of the accident. The advantage of the model is taking into account changes in the intensity of radionuclide emissions over time.

2. A methodology for the solving the boundary value problem of modeling in the conditions of a complex shape the calculation area, which takes into account the presence of obstacles to the spread emission products, has been developed.

Finite-difference methods of numerical integration are used for the solution. The use of the speed potential equation in an evolutionary form made it possible to speed up the calculation process.

The chosen splitting scheme of the alternating-triangular method allows finding the speed potential at each splitting step according to an explicit formula. This allows for easy software implementation of the CFD model.

3. The obtained emission cloud propagation models and their visualization make it possible to determine the state of environmental pollution under various initial conditions during the development of the accident. The models make it possible to determine the pollution at each point of the territory within a few seconds and to predict changes in the pollution in the space and time.

## References


1. Ravshanov, N., Narzullayeva, N. and Muradov, F. (2021), “Model and Numerical Algorithm for Monitoring and Forecasting Transfer and Diffusion of Active Aerosol Particles in the Atmosphere”, *Int. Conf. on Inf. Science and Comm. Technologies: Applications, Trends and Opportunities, ICISCT* 2021, doi: https://doi.org/10.1109/ICISCT52966.2021.9670344
2. Zhan, Dou, Zhe, Liu, Lili, Li, Hang, Zhou, Qianlin Wang, Jianwen, Zhang and Liangchao, Chen (2022), “Atmospheric dispersion prediction of accidental release: A review”, *Emergency Management Science and Technology*, vol. 2, no. 9, doi: https://doi.org/10.48130/EMST-2022-0009
3. Yang, Zhiyi, Li, Fengchen and Chai, Guohan (2022), “Status and Perspective of China’s Nuclear Safety Philosophy and Requirements in the Post-Fukushima Era”, *Frontiers in Energy Research*, vol. 9, doi: https://doi.org/10.3389/fenrg.2021.819634
4. Hossny, K., Villanueva, W. and Wang, H.D. (2023), “Distinctive physical insights driven from machine learning modelling of nuclear power plant severe accident scenario propagation”, *Scientific Reports*, 13, Article number: 930, doi: https://doi.org/10.1038/s41598-023-28205-y
5. Voutilainen, M., Peltonen, T., Ukkonen, A., Mattila, A., Routamo, T., Muikku, M. and Vesterbacka, P. (2022), *Potential consequences of hypothetical nuclear power plant accidents in Finland*, STUK-A 268, 120 p., URL: https://www.julkari.fi/bitstream/handle/10024/144398/STUK-A268_Potential_consequences_of_hypothetical_nuclear_power_plant_accidents_in_Finland.pdf?sequence=1&isAllowed=y
6. Shuliang, Zou, Na, Liu and Binhai, Huang (2021), “Study on Airborne Radionuclide Dispersion in Floating Nuclear Power Plant under the Loss-of-Coolant Accident”, *Science and Technology of Nuclear Installations*, article ID 1299821, doi: https://doi.org/10.1155/2021/1299821
7. Abe, T., Yoshimura, K. and Sanada, Y. (2021), “Temporal Change in Atmospheric Radiocesium during the First Seven Years after the Fukushima Dai-ich Nuclear Power Plant Accident”, *Aerosol Air Qual. Res.*, vol. 21, iss. 7, 200636, doi: https://doi.org/10.4209/aaqr.200636
8. Bohanec, M., Vrbanic, I., Basic, I., Debelak, K. and Strubelj, L. (2020), “A decision-support approach to severe accident management in nuclear power plants”, *Journal of Decision Systems*, vol. 29, iss. 1, pp. 438–449, doi: http://doi.org/10.1080/12460125.2020.1854426
9. Levchenko, L., Biliaiev, M., Biliaieva V., Ausheva, N. and Tykhenko, O. (2023), Methodology for modeling the spread of radioactive substances in case of an emergency release at a nuclear power plant. *Advanced Information Systems*, vol. 7, no. 3, pp. 13–17, doi: https://doi.org/10.20998/2522-9052.2023.3.02
10. Dotsenko, N., Chumachenko, I., Galkin, A., Kuchuk, H. and Chumachenko, D. (2023), “Modeling the Transformation of Configuration Management Processes in a Multi-Project Environment”, *Sustainability (Switzerland)*, vol. 15(19), 14308, doi: https://doi.org/10.3390/su151914308
11. de Sampaio, P.A.B., Junior, M.A.G., Lapa, C.M.F. (2008), “A CFD approach to the atmospheric dispersion of radionuclides in the vicinity of NPPs”, *Nuclear Engineering and Design*, vol. 238(1), pp. 250–273, doi: https://doi.org/10.1016/j.nucengdes.2007.05.009
12. Kovalenko, A. and Kuchuk, H. (2022), “Methods to Manage Data in Self-healing Systems”, *Studies in Systems, Decision and Control*, vol. 425, pp. 113–171, doi: https://doi.org/10.1007/978-3-030-96546-4_3

13. Shutovskyi, A.M. (2023), "Some applied aspects of the Dirac delta function", *Journal of Mathematical Sciences* (United States), 276(5), pp. 685–694, doi: https://doi.org/10.1007/s10958-023-06790-7
14. Kuchuk, G.A., Akimova, Yu.A. and Klimenko, L.A. (2000), "Method of optimal allocation of relational tables", *Engineering Simulation*, Vol. 17(5), pp. 681–689.
15. Malachivskyy, P.S., Melnychok, L.S., Pizyur, Y.V. (2023), "Chebyshev Approximation of a Multivariable Function with Reproducing the Values of the Function and Its Partial Derivatives", *Cybernetics and Systems Analysis*, 59(4), pp. 660–671, doi: https://doi.org/10.1007/s10559-023-00601-2
16. Vasylkivskyi, I., Ishchenko, V., Kochan, O. and Ivakh, R. (2023), "Environmental Pollution from Nuclear Power Plants: Modelling for the Khmelnytskyi Nuclear Power Plant (Ukraine)", *Lecture Notes on Data Engineering and Communications Technologies*, 181, pp. 815–826, doi: https://doi.org/10.1007/978-3-031-36118-0_71


Received (Надійшла) 19.01.2024
Accepted for publication (Прийнята до друку) 10.04.2024

ВІДОМОСТІ ПРО АВТОРІВ / ABOUT THE AUTHORS

**Біляєва Вікторія Віталіївна –** доктор технічних наук, доцент, професор кафедри енергетичних систем та енергоменеджменту, Український державний університет науки і технологій, Дніпро, Україна;
**Viktoriia Biliaieva –** Doctor of Technical Sciences, Associate Professor, Professor of Department of Energy Systems and Energy Management, Ukrainian State University of Science and Technologies, Dnipro, Ukraine;
e-mail: vikabelyaeva604@gmail.com; ORCID ID: http://orcid.org/0000-0001-9987-6384;
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57193154882

**Левченко Лариса Олексіївна** – доктор технічних наук, професор, професор кафедри цифрових технологій в енергетиці, Національний технічний університет України «Київський політехнічний інститут ім. Ігоря Сікорського, Київ, Україна;
**Larysa Levchenko** – Doctor of Technical Sciences, Professor, Professor of Department Digital Technologies in Energy, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Kyiv, Ukraine;
e-mail: larlevch@ukr.net; ORCID ID: http://orcid.org/0000-0002-7227-9472;
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57194577942

**Мищенко Ірина Анатоліївна –** кандидат біологічних наук, спеціаліст лабораторії безпеки праці, гірничо-геологічний факультет, Політехніка Вроцлавська, Вроцлав, Польща;
**Iryna Myshchenko -** dr MHSc, Laboratory of Occupational Health and Safety, Faculty of Geoengineering, Mining and Geology, Wroclaw University of Science and Technology, Wroclaw, Poland
e-mail: iryna.myshchenko@pwr.edu.pl; ORCID ID: http://orcid.org/0000-0003-0872-9499;
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57074151700

**Тихенко Оксана Миколаївна** – доктор технічних наук, професор, професор кафедра екології, Національний авіаційний університет, Київ, Україна;
**Oksana Tykhenko –** Doctor of Technical Sciences, Professor, Professor of Department of Ecology, National Aviation University, Kyiv, Ukraine;
e-mail: okstih@ua.fm; ORCID: https://orcid.org/0000-0001-6459-6497;
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57194569510

**Козачина Віталій Анатолійович –** кандидат технічних наук, доцент, доцент кафедри гідравліка, водопостачання та фізики, Український державний університет науки і технологій, Дніпро, Україна;
**Vitalii Kozachyna –** PhD, Associate Professor, Associate Professor of Department of Hydraulics, Water Supply and Physics, Ukrainian State University of Science and Technologies, Dnipro, Ukraine
e-mail: v.kozachyna@gmail.com; ORCID: https://orcid.org/0000-0002-6894-5532;
Scopus ID: https://www.scopus.com/authid/detail.uri?authorId=57217045570

## Моделювання поширення продуктів аварійного викиду на енергоблоці атомної електростанції

В. В. Біляєва, Л.О. Левченко, І. А. Міщенко, О. М. Тихенко, В. А. Козачина

**Анотація.** Не дивлячись на те, що безпечній експлуатації ядерних енергетичних установок приділяється багато уваги, існує ймовірність аварії з викидом радіонуклідів. Особливо це актуально в Україні, де існує загроза ушкодження ядерних реакторів внаслідок бойових дій. Дослідження розповсюдження продуктів аварійних викидів радіоактивних речовин у лабораторних умовах неможливо. Тому єдиним інструментом прогнозування розвитку аварії є моделювання розповсюдження хмари радіонуклідів. **Метою дослідження** є моделювання поширення продуктів аварійного викиду на енергоблоці атомної електростанції, придатного для оперативного оцінювання розвитку аварії. **Результати дослідження**: Розроблено математичну модель поширення продуктів викиду енергоблоку атомної електростанції, яка враховує значення початкової активності продуктів викиду, швидкість осідання радіоактивних часток, компоненти швидкості вітру, зміни інтенсивності викиду радіонуклідів з часом. Розроблено методику розв'язку крайової задачі моделювання в умовах складної форми розрахункової області, яка враховує наявність перешкод розповсюдженню продуктів викиду. Застосування рівняння потенціалу швидкості у еволюційному вигляді дозволяє пришвидшити процес розрахунків. Обрана схема розщеплення попеременно-трикутного методу дозволяє на кожному кроці розщеплення знаходити потенціал швидкості за явною формою. Це дозволило здійснити програмну реалізацію CFD моделі. Візуалізовані моделі поширення хмари викиду дозволяють визначити радіаційну обстановку у будь-якому місці зони розповсюдження продуктів викиду. **Висновки**: розроблена модель дозволяє оперативно прогнозувати розвиток аварії у просторі і часі, що надає можливість у мінімальні терміни вжити заходи із захисту людей від опромінення.

**Ключові слова:** моделювання; ядерна аварія; радіонукліди; прогнозування.