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# METHODOLOGY FOR THE ECOLOGICAL ENVIRONMENTAL IMPACT ASSESSMENT OF THE FOREST FIRE CONSEQUENCES UNDER COMPLEX RADIATION CONDITIONS OF FIRE LOAD

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**Abstract**

In the paper, the methodology for the ecological environmental impact assessment of the forest fire consequences under complex radiation conditions of fire load has been proposed on the basis of the scientific researches of leading experts in the field of forest fires simulation, such as Abramov Yu. O., Komyak V. O., Kutsenko L. M., Lytvyn N. V., Pokrovsky R. L., Tarasenko O. A., Vasyliev S. V., Soznik O. P.

The analysis determines that the stochastic nature of the processes of forest fires occurrence, development, extension and variation of the degree of vegetation burning in the forest areas depend on the fire load, season of the year and other fire-technical and meteorological factors, which in turn are complicated by the content of radionuclides with different activity times. The information base of this technique is a model where forest is considered as a single-layer two-phase medium consisting of air and gaseous pyrolysis products during combustion of forest combustible materials and their solid pyrolysis products.

While constructing a physical-mathematical model of a two-phase heterogeneous mixture the methods of solid-state mechanics was used, which made it possible to present the fire load as a two-component continuum with interpenetrating phase motion and interphase mass, momentum, and energy exchange.

During the research, the adequacy of the proposed methodological apparatus was checked and the main directions of its further application as a basis for solving the problems of forecasting the negative environmental impact on the environment were determined.

The practical significance of the obtained results is the possibility of their use for complex ecological audits of the territory which is subject to the secondary radiation influence both inside and outside the exclusion zone of the Chornobyl NPP.

**Key words:** environmental safety, forest fire, radiation exposure, complex fire load.

## Problem setting

Recent years' statistics show an increase in the number of wildfires which in turn lead to devastating consequences and sometimes even irreparable losses. Up to 400,000 forest fires occur annually on the planet, damaging about 0.5% of the total forest area. The prevention and extinguishing of forest fires is one of the most urgent and important tasks in Ukrainian forestry. In dry years, fires cover large areas, causing direct material damage during the period of burning and smouldering, as well as indirect, which is manifested in the reduction of water management, protection, hygienic, aesthetic and climatic role of the forest. During the fire season, hundreds of forest fires occur daily in the territory of Ukraine. To determine effective response scenarios, forest fire dynamics and a model of combustion products (CP) emissions into the environment are required.

At the present stage of the fire science development, there are many researches in which, with the help of mathematical models, different aspects of forest fires are examined, their characteristic parameters, extension processes, and models of extinguishing are described. Studies in this area are also being conducted in Ukraine; they are presented in the works of Abramov Yu. O., Komyak V. O., Kutsenko L. M., Lytvyn N. V., Pokrovsky R. L., Tarasenko O. A., Vasyliev S. V., Soznik O. P. and others [1–4].

Despite the huge amount of information accumulated on forest fires and numerous and fruitful efforts aimed at experimental and theoretical study of the processes of their occurrence and scenarios, a simple, adequate and practically applicable model of CP emissions from the forest fire zone does not exist. Thus, the study of the mechanisms of CP formation caused by forest fires under complex radiation conditions of fire load formation is an urgent problem both from the point of view of population and ecological environment safety.

## Recent research and publication analysis

The problem of forest fire protection is one of the most difficult to solve by forestry workers who protect forests from the fires and, in the event of their occurrence, eliminate them in most cases jointly with the units of the State Emergency Service of Ukraine [1]. A number of fundamental works on modelling the processes of occurrence, extension and elimination of forest fires [5–8], including the issues of the fire load peculiarities [9, 10], should be considered as the scientific basis for effective actions in this direction. However, the issues of the environmental impact modelling in the event of a forest fire under complex conditions of the fire load have been investigated sporadically so far [11–14], which does not allow using the mathematical apparatus for predicting the environmental situation inside and outside the exclusion zone to the full extent.

## Problem solution

The problem of the environmental impact modelling in the event of CP emissions during the forest fire under complex radiation conditions consists of a number of independent tasks conditioned by the phases of their occurrence and extension.

The research purpose is to create a methodology for estimation the environmental impact of the aftermaths of a forest fire under difficult conditions of fire to proceed from existing problems. The following tasks to achieve this purpose need to be solved:

1. Current experience in environmental monitoring of forest fires should be analysed. Based on this, the methodology for assessment of the secondary ecological impact on the environment of the hazardous consequences of a forest fire in the complex radiation conditions of fire load formation need to be formulated.
2. The adequacy obtained methodology should be check.
3. Recommendations for its further practical application of this methodology should be identified.

There are at least several phases of the development of CP emissions migration process. In the first phase, CP goes into the environment in the form of a smoke cloud. In the second phase, the smoke plume moves mainly along the earth’s surface. As the smoke moves away from the fire, fewer and fewer smoke particles remain as a result of their “dry” deposition and dispersion. Different dynamic models can be used to describe this complex CP migration process. However, to calculate the flow of the fast-flowing CP emissions from several fire sources, it is necessary to use the calculation methods that are more physically sophisticated and simpler in mathematics.

The equations of turbulent diffusion of CP entering the atmosphere from the forest fire sources with coordinates ($x, y, z$) located in unlimited space, in the approximation of the constancy of wind speed and turbulent diffusion coefficients can be written as follows [15]:

$$\frac{\partial C}{\partial t} = k_x \frac{\partial^2 C}{\partial x^2} + k_y \frac{\partial^2 c}{\partial y^2} + k_z \frac{\partial^2 C}{\partial z^2} - \sum_{i=1}^{3} V_i \frac{\partial C_i}{\partial x_i}; \quad (1)$$

$$-\infty < x, y, z < \infty; \quad t > 0; \quad C(0,\ 0,\ \Delta h_{ef},\ 0) = Q/\Delta W,$$

where $C\ (x, y, z, t)$ – is the concentration of CP in the air depending on the spatial coordinates and time; $k_x$, $k_y$, $k_z$ – are coefficients of turbulent CP diffusion in the surface atmosphere; $V_x$, $V_y$ – are wind speed projections on the $x$ and $y$ axes, respectively; $V_z$ – is the sum of the gravitational sedimentation velocities of CP and the movement of the smoke cloud in the vertical direction (the z-axis is perpendicular to the surface of the earth); $Q$ – is the amount of CP released into the atmosphere during a forest fire; $\Delta W$ – is the amount of CP emitted by the fire into the environment; $\Delta h_{ef}$ – is the effective elevation of the smoke cloud relatively to the Earth’s surface.

We shall simplify the expression by replacing the variables [16]:

$$C(x,y,z,t) = q(x,y,z,t)\exp\left[V\left(2x - V_t\right)/4k_x\right];$$

$$\frac{\partial q}{\partial t} = k_x \frac{\partial^2 q}{\partial x^2} + k_y \frac{\partial^2 q}{\partial y^2} + k_z \frac{\partial^2 q}{\partial z^2}; \quad (2)$$

$$-\infty < x, y, z < \infty; \quad t > 0; \quad C(0,\ 0,\ \Delta h_{еф},\ 0) = Q/\Delta W.$$

A desired solution to the equation (2):

$$C(x, y, z, t) = QG(x, y, z, t), \quad (3)$$

where

$$G(x,y,z,t) = \prod_{i=1}^{3} A_i \exp\left[-\frac{\left(x - V_t\right)^2}{4k_x t} - \frac{y^2}{4k_y t} - \frac{\left(z - h\right)^2}{4k_z t}\right]$$

is the Green’s function, where

$$A_i = \frac{1}{2\sqrt{\pi k_i t}}.$$

We shall assume that the forest fire source begins to operate at time $t = 0$, and ceases to exist at $t = t_n$. We shall imagine the forest fire source that acts during the time $t_n$, as a continuous sequence of instantaneous forest fire sources. The expression for calculating the CP concentration in the air, formed by such forest fire source, in accordance with the properties of the Green function are as follows:

$$C(x,y,z,t) = \int_0^T P(\tau)\cdot G(x,y,z,t)\,\partial\tau;$$

$$T = \begin{Bmatrix} t_n,\ if\ t > t_n \\ t,\ if\ t \le t_n \end{Bmatrix}. \quad (4)$$

The power of the source of CP emissions from the forest fire can be determined by dividing the total amount of CP emitted into the atmosphere at the time of the source activity:

$$P_t = Q/t_n. \quad (5)$$

The process of transferring CP from a continuous emission $P(t) = const$, can be calculated using (4) provided $t_n \to \infty$ and $t \to \infty$, in which case the integral will be taken analytically. The concentration $\bar{C}_n$ at any point in the space $\bar{X}_j = \left(x^j, y^j, z^j\right)$, “created” by the action of $n$ point sources of forest fires and the power of CP emission source – $P_j$ each that coordinates $\bar{L}_j = \left(l_1^{\,j}, l_2^{\,j}, l_3^{\,j}\right)$, are calculated according to the formula:

$$\bar{C}_n\left(\bar{X}_j, \bar{L}_j\right) = \sum_{j=1}^{N} C\left(P_j, \bar{X}_j, \bar{L}_j\right). \quad (6)$$

Formula (6) can be used to calculate the process of CP migration from multiple forest fire sources that have a complex shape. It is also possible to calculate the CP concentration fields in the air that are formed from the area, linear or volumetric fires. For example, approximating the time fluctuations in the power of a forest fire source by a simple periodic function of time.

$$Q(t) = Q_0\left(1 - \cos\omega \cdot t\right), \tag{7}$$

the solution of equation (7) looks as:

$$C(x,y,z,t) = \frac{Q}{2\pi \cdot R\sqrt{k_x k_y k_z}}\left[\exp\left(\frac{V_t}{2k_x} - R\sqrt{\frac{V_\tau^{\,2}}{4k_x} - \lambda}\right) + \exp\left(\frac{V_\tau}{2k_x} - MR\right)\cos\left(NR - \omega t\right)\right], \tag{8}$$

where $R = \sqrt{\frac{x^2}{k_x} + \frac{y^2}{k_y} + \frac{z^2}{k_z}}$; $M = \frac{1}{\sqrt{2}}\left[\sqrt{\left(\frac{V^2}{4k_x} + \lambda\right)^2 + \omega^2} + \frac{V^2}{4k_x} + \lambda\right]^{1/2}$; $N = \frac{1}{\sqrt{2}}\left[\sqrt{\left(\frac{V^2}{4k_x} + \lambda\right)^2 + \omega^2} - \frac{V^2}{4k_x} - \lambda\right]^{1/2}$.

Here, λ is the coefficient of impurity concentration of aerosols and smoke particles as a result of dry deposition.

It can be seen that at a distance $L_m$

$$L_m = \sqrt{k_i / 2\pi \cdot N}, \tag{9}$$

from the fire source, a front of high CP concentration will be formed, which will be maximum at ($x = L$) at $t = \frac{2\pi}{\omega}$.

$$C_{\max} = \frac{Q_0 N}{A_i^2}\left[1 + \exp\left(\frac{\pi V}{N\sqrt{k_i}} - \frac{2\pi M}{N}\right)\right]. \tag{10}$$

The height of the smoke cloud is calculated by the formula [3]:

$$\Delta h_{ef} = \xi_i \cdot M^{1/3} \cdot X^{2/3} \cdot U^{-1}, \tag{11}$$

where $\xi_i$ – is the transition coefficient for the $i$-th stability of the atmosphere; $M$ – is power of thermal source; $X$ – is the vertical width of the smoke plume; $U$ – is the wind speed at the height of the smoke cloud mixing.

The distance from the point of the smoke cloud emission to the site of the CP fallout was calculated by the formula:

$$L = \varepsilon_1 \cdot M^{3/5} \cdot U^{-1}, \tag{12}$$

where $\varepsilon_1$ – is the transition coefficient for the $i$-th stability of the atmosphere.

Table 1 presents the data of the transition coefficients for the $i$-th stability of the atmosphere.

A three-dimensional model was developed to describe the formation and propagation of the smoke plume and the fallout of the CP particles using the levels of momentum, mass and energy of the airflow and the number of the CP software particles in the smoke plume [17]. The system of ordinary differential equations for the airflow velocity along the jet axis, its overheating with respect to ambient air, the smoke jet radius, and the concentration of CP in the smoke jet was solved numerically. Each layer was considered as a separate independent source of CP, for which the concentration of software in the atmosphere was calculated at different distances from the emission site. Real wind and temperature fields obtained from the radio sounding data were used as input information to the simulation. It was assumed that the forest fire occupied a circular area of 100 meters with a convective forest fire duration of one hour. The minimum smoke jet height varied from 2000 to 2500 m depending on the stratification of the boundary layer and the wind velocity profile therein.

Fig. 1 demonstrates the dynamics of the smoke cloud formation and movement during a forest fire.

During the computer simulation, the heated smoke cloud of CP was considered, which, due to the Archimedean force, rose into the atmosphere at a speed of no more than 10 m/s. The volatile particles of the CP had a complex morphological and chemical composition at densities of (3–10) mg / cm$^3$, and their spectrum varied over a wide range of sizes (0.1–100) μm at an aerodynamic diameter (AMAD) from 30 to 50 μm. It was assumed that after stabilization of the smoke cloud, the transfer and dispersion of fine fractions was carried out in a calm atmosphere, and the dispersion of the volatile particles in the smoke cloud changed only due to gravitational deposition.

Table 1 – The data of the transition coefficients for the Pasquill atmosphere characteristics

| The qualitative characteristics of the atmosphere stability according to Pasquill | | The values of the transition coefficients of the atmosphere stability , $\xi_i$ | The values of the transition coefficients of the atmosphere stability, $\varepsilon_1$ | |
|---|---|---|---|---|
| | | | M > 10MVt | M ≤ 10MVt |
| Unstable state | A, B | 3.34 | 146 | 112 |
| Neutral state | C, D | 2.84 | 102 | 78.5 |
| Stable state | E | 3.30 | 85.2 | 63.4 |
| | F | 3.34 | 14.7 | 32.1 |

As the equation of formation and displacement of the smoke cloud of CP, the equation of dynamics of the body with variable mass was used. In the process of mathematical modelling, the following processes were analysed:

- the transfer of the volatile particles of CP was directed by the atmospheric current;
- the development of the jet in the release of heated gases in the atmosphere was characterized by the changes of the wind speed, temperature and pressure, as well as the constant mixing of the heated gases with ambient air;
- the scattering of the fine particles of CP was due to atmospheric turbulent diffusion and their sedimentation in the gravity field, as well as interaction with the underlying surface.

The final picture of the contamination of the terrain was formed in a time that depended on the distance to the point of the forest fire and meteorological parameters.

The numerical experiment was carried out in the field of modelling – migration of the volatile particles of CP – parallelepiped (10×10×5) km$^3$, lower boundary – function $z = \delta\,(x, y)$, which describes the terrain relief, and the values of which are equal to the absolute elevation marks of the exclusion zone terrain, in the nodes of a uniform grid, given in steps $\Delta x = \Delta y = 100$ m. The dimensions of the grid section are 45×40×30 nodes. Vertically an uneven step was used. The time step was $\Delta\tau = 30$ s. The surface temperature of the underlying surface was calculated accounting the relative height of the terrain point and stratification of the background atmosphere. The calculation of the dynamics of formation, extension and emission of the volatile particles of CP during a medium-scale forest fire took about 2.5 hours.

Fig. 2 demonstrates the dynamics of change in the density of the volatile particles of CP along the trail of the smoke plume.

Adaptation of the developed algorithm and program, as well as verification of the reliability of the calculated data were carried out by comparison with the experimental data obtained in the field.

## Conclusions

Thus, the methodology of the ecological monitoring conducting and assessment of the secondary ecological impact of hazardous consequences of the forest fire under complex radiation conditions of fire load has been created.

Its adequacy has been verified and the main directions of its further application as a methodological basis for solving the problems of forecasting the negative ecological environmental impact have been determined.

The practical significance of the work lies in the possibility of using the results obtained to conduct an ecological audit of the territory subjected to the secondary radiation exposure both inside and outside the exclusion zone of the Chornobyl NPP.

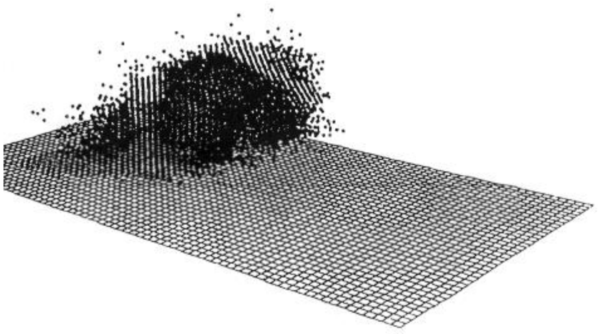
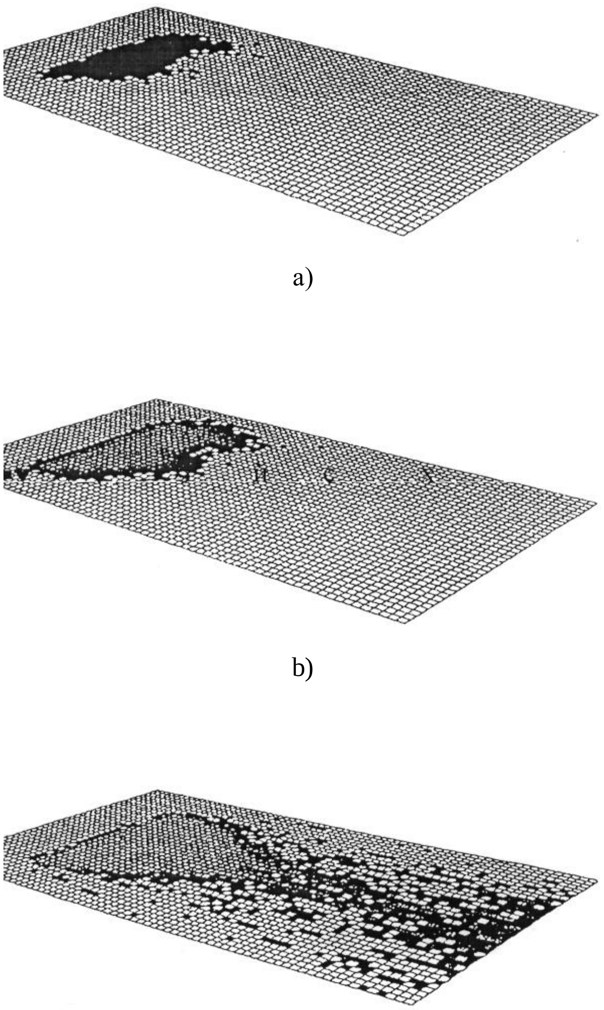


Figure 1 – Dynamics of the smoke cloud formation and movement in space



a)

b)

c)

Figure 2 – Dynamics of change in the density of the volatile particles emission of CP along the trail of the

a – $t_1$=30 min; b – $t_2$=120 min; c – $t_3$=210 min.

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**Азаров С. І., Машков В.А., Шевченко Р. І., Щербак С. С.**

## ФОРМУВАННЯ МЕТОЛОГІЇ ОЦІНКИ ЕКОЛОГІЧНОГО ВПЛИВУ НА ДОВКІЛЛЯ ВІД НАСЛІДКІВ ЛІСОВОЇ ПОЖЕЖІ В СКЛАДНИХ РАДІАЦІЙНИХ УМОВАХ УТВОРЕННЯ ПОЖЕЖНОГО НАВАНТАЖЕННЯ

В роботі базуючись на сукупності наукових досліджень провідних фахівців у сфері моделювання лісових пожеж, як-то Абрамова Ю. О., Комяка В. О., Куценка Л. М., Литвина Н. В., Покровського Р. Л., Тарасенка О. А., Васильєва С. В., Созніка О. П. сформована методологія оцінки екологічного впливу на довкілля небезпечних наслідків лісової пожежі в складних умовах утворення пожежного навантаження.

З аналізу визначено, що стохастичний характер процесів виникнення, розвитку і поширення лісових пожеж та варіювання ступеня горіння рослинності в лісових масивах, залежать від пожежного навантаження, сезону року та інших пожежотехнічних і метеорологічних факторів, що у свою чергу ускладнюються вмістом радіонуклідів з різним часом активності. Інформаційною основою наведеної методики є модель, де ліс розглядається як одношарове двофазне середовище, що складається з повітря і газоподібних продуктів піролізу при горінні лісових горючих матеріалів та їх твердих продуктів піролізу.

Такий підхід дозволив при побудові фізико-математичної моделі двофазної гетерогенної суміші на основі методів механіки суцільного середовища представити пожежне навантаження як двокомпонентний континуум з взаємопроникним рухом фаз та міжфазним обміном масою, імпульсом і енергією.

Під час дослідження здійснена перевірка адекватності запропонованого методологічного апарату та визначені основні напрями його подальшого застосування у якості основи для вирішення задач прогнозування негативного екологічного впливу на навколишнє середовище.

Практичне значення отриманих результатів полягає у можливості їх застосування для проведення комплексного екологічного аудиту території, яка підпадає під дію вторинного радіаційному впливу як всередині так і зовні зони відчуження Чорнобильської АЕС.

**Ключові слова:** екологічна безпека, лісова пожежа, радіаційний вплив, складне пожежне навантаження.

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