ENVIRONMENTAL SAFETY, LABOUR PROTECTION

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PROVIDING THE ENVIRONMENTAL SAFETY BY INCREASING THE EFFICIENCY OF FIREFIGHTING IN UNSHELTERED TIMBER WAREHOUSES

Purpose. To develop a method for reducing the impact of fires in unsheltered timber warehouses on the environmental safety by reducing the duration of free burning of timber, the speed of fire front spread, emissions of combustion products and the duration of the firefighting.

Methodology. During the experimental research, the method of fractional factor experiment was used. Theoretical research was performed using optimization mathematical models. The Monte Carlo method is used to solve optimization problems. To implement this method, block diagrams of algorithms was developed, based on written corresponded computer programs.

Findings. The method was developed for reducing the impact of fires in unsheltered timber warehouses on the environmental safety by reducing the duration of free development of the fire, the speed of fire front spread, the concentration of combustion products and the duration of the fire. Fire prevention measures to reduce the duration of fire and to reduce emissions of combustion products due to fires in unsheltered timber warehouses was implemented by using an automated system to determine the fire extinguishing means and forces by setting an optimization problem, applying the Monte Carlo method and developing software to solve it.

Originality. The scientific novelty is the justification of ways to reduce the duration of the free development of fire and to reduce the amount of toxic emissions using optimization mathematical models.

Practical value. It is possible to use the obtained results in the practical activities of fire and rescue units of the SES of Ukraine and provide environmental safety in case of fire in unsheltered timber warehouse due to the practical implementation of administrative, legal and economic methods.

Keywords: *unsheltered timber warehouses, fire, duration of free burning, toxic emissions, environmental safety*

Introduction. Considering environmental safety, it is established that it is a state of protection of the environment and vital human interests from possible negative effects in natural and man-made emergencies, as well as the consequences of economic and other activities. Environmental security can be implemented at the global, regional, and local levels. The local level includes cities, districts, and various enterprises, including unsheltered timber warehouses.

To ensure the environmental safety at the local level, a number of measures and technologies have already been developed that make it possible to reduce the impact of natural and man-made emergencies on the environment. The developed measures and technologies give an opportunity to protect the environment from various types of pollution effectively. A significant contribution in this direction was made by well-known scientists: A. L. Bolsherotov, B. I. Korobkin, L. V. Peredelsky, Ye. O. Lobanov, and many others. The results of the analysis of works on environmental safety have shown that they consider issues related to the purification of water from toxic substances, the fight against the destruction of regional and local greenery, and so on. But the issues of environmental pollution from fires, the number of which in Ukraine is growing every year, are not considered enough. For example, according to the State Emergency Service of Ukraine (SES) during 2019 in the settlements and facilities of economic entities there were recorded 95 915 fires, which is by 22 % more than in 2018 [1], while in open areas, where there are unsheltered timber warehouses, the number of fires increased almost by 100 % (in 2019 there were 36 304 fires, in 2018 — 19 577 fires), as well as in the area covered by fire — almost by 2.6 times (in 2019 there were 32 340 hectares, in 2018 — 12 466 hectares).

We consider the statistics of fires in supply warehouses. In the United States, there were 1.300 fires in warehouses from 2006 to 2015, as a result of which there were killed 3 and injured 22 persons and they caused $158 million damages. There are large-scale fires in timber warehouses in Ukraine. Thus, in 2020 there was a fire in Kaharlyk, Kyiv region, where 600 m² of lumber burned. In 2018, such fire broke out in Dunaivtsi, Khmelnytskyi region, on an area of 500 m², in Kryvyi Rih — 100 m². This list can be continued.

Despite the fact that single fires have almost no impact on the environment, if you reduce the time of their free development, and thus its area, it will be possible to reduce significantly emissions of combustion products as a consequence of these fires.

In the process of fire in the timber warehouses, the temperature of the environment increases significantly, the concentration of oxygen decreases, the concentration of carbon monoxide, carbon dioxide, hydrogen chloride, and other combustion products affecting environmental pollution significantly and threaten human life increases. Also, smoke arises during a fire and its optical density may prevent the evacuation of people from the fire zone and resist the actions of fire and rescue units in the process of fire suppression.

Therefore, there is a problem related to the ecology of the environment during fires in the unsheltered timber warehouses, including the failure to solve the following questions completely:

1) reducing the duration of free combustion;
2) determining the speed of the fire front spread;
3) changing the concentration of oxygen and combustion products during a fire;
4) determining the duration of the fire suppression depending on the use of a certain amount of fire equipment.

Literature review. Many scientists both in Ukraine and abroad have been studying the reducing of the duration of the free development of fire. The first problem of reducing the duration of the free development of the fire was studied by Prof. M. M. Brushlinsky [3], who on the basis of simulation changed the boundaries of the service areas of the fire and rescue units, taking into account the transport network of the city and the speed of fire trucks. The results of the performed work made it possible to obtain new boundaries of the protected areas, according to which the number of calls was more evenly distributed and the time of arrival to the place of call was reduced by 9 %.

In the United States, the travel time of a fire department in the city to the call site is from 2.4 to 5.9 minutes [4], which is from 3 to 5 times less than in European and Ukrainian cities. This can be explained by the fact that fire and rescue units serve much smaller areas of the call. The fire ground per depot is in the range from 1.7 to 6 km^2 of territory. For example, in Ukraine, the fire ground is in the range from 28 to 30 km^2.

Further studies to reduce the duration of free development of fire, which are presented in [5], show that on the basis of the developed graph model of optimization of the path of fire equipment and fire and rescue units from the fire station to the call site, a technique was proposed to reduce the travel time and accordingly the duration of free development of fire by 2.5–5 min.

Whilst considering the environmental risk, the authors of studies [6] found that its reduction primarily depends on the reduction of fire risk, which in turn depends on the optimization of fire extinguishing systems in timber warehouses. It was found that the environmental safety of a fire is greatly affected by wind speed. Reducing the wind speed reduces the area of distribution of combustion products and in many cases, even makes it impossible for a person to stay in the forest near the fire zone. According to these authors, environmental safety can be managed through the practical implementation of administrative, legal, and economic methods in the case of fire in unsheltered timber warehouses. But practical implementation of these methods is not provided in these studies.

In research [7], the number of emissions of toxic substances into the environment during indoor fires was determined based on the analytical model of mass transfer. The authors showed how to determine the number of toxic products that leave the room during a fire and enter the environment per unit of time. It is established that at the initial stage of the fire (up to 10 min) the release of toxic gases into the environment is insignificant with a gradual increase. After 10 minutes of fire, emissions of toxic substances increase significantly. In the indoor fire the average height of the convection column was also determined, which extends to the outside and can reach an average of 23.5 m. Toxic products formed during the fire rise to this height. The main means to reduce the number of emissions into the environment is to reduce the duration of the free

development of the fire, which is justified by the choice of methodology by choosing the optimal route of the fire and rescue units to the point of fire origin.

The research [8] is devoted to the monitoring of oil and oil products storage facilities from the point of view of their ecological safety. The authors propose a methodology for managing and ensuring fire and environmental safety at oil and oil products storage facilities based on the monitoring results.

The study [9] is devoted to determining the critical time of a fire in a building and ensuring the successful evacuation of people. The duration of free burning in case of fire, which the authors recommend to reduce to ensure environmental safety, is also considered. The parameters that are defined in research [9] are adequate and confirmed by other calculation methods, in particular, methods [10, 11]. The relative error between these parameters does not exceed 8–12 %.

Unsolved aspects of the problem. The results of the analysis of the above scientific works have shown that they do not sufficiently address issues of environmental safety, especially during fires in unsheltered timber warehouses. Therefore, to fully solve the general problem associated with the ecology of the environment during fires in unsheltered timber warehouses, it is necessary to address issues related to the methodology of reducing the duration of free development of fire, the rate of fire front spread, changing the rate of oxygen density and the release of toxic substances during fire, as well as determining the duration of the fire depending on the use of a certain amount of fire equipment.

Purpose. To develop a method to reduce the impact of fires in unsheltered timber warehouses on the environmental safety by reducing the duration of the free development of the fire, the speed of fire front spread, the concentration of combustion products, and the duration of the fire.

Results. According to the state construction standards [12], unsheltered timber warehouses, depending on their volumes, must be placed in quarters with the observance of fire-fighting distances. The number of quarters in the warehouse depends on the total amount of stored timber. The minimum distance between the quarters, in order to maintain fire safety measures, is 40 m.

Each quarter has the form of a rectangle with the dimensions of the sides: 193 m long, 94 m wide. The quarter houses stacks of timber in the number of 90 pieces. The plan size of the stack is 6 × 6 m. The height of the stack depends on the type of wood: for lumber it is 5 m, for round timber — 6 m.

Let us consider the occurrence and development of fire in the most fire-hazardous timber quarter, namely in the quarter with stacks of lumber. According to the results of fire statistics in timber warehouses, 90 % of fires occur on the perimeter of the quarter on the basis of human factors.

The method for reducing the impact of fires of unsheltered timber warehouses on the environmental safety by reducing the duration of the free development of the fire, the rate of spread of the fire front, the concentration of combustion products, and the duration of the fire consists of the following stages:

1. Calculation of emissions of combustion products due to fires in unsheltered timber warehouses.

2. Implementation of fire-fighting measures to reduce the duration of the fire and reduce emissions of combustion products due to fires in unsheltered timber warehouses:

2.1. Introduction of low-pressure or high-pressure fire water supply and pumping stations in accordance with state construction standards.

2.2. Introduction of a fire observation point in accordance with state construction standards.

2.3. Equipment of warehouses with fire-fighting means according to standards and rules.

2.4. Introduction of an automated system for determining the firefighting means and forces by setting an optimization problem and solving it using the Monte Carlo method.

2.5. Introduction of an automated system for optimizing the travel route of firefighting equipment and fire and rescue units from the fire station to the call site by setting an optimization problem and solving it using the Monte Carlo method.

3. Determining the duration of the evacuation time in case of fire from the warehouse, taking into account the implemented measures.

The calculation of emissions of combustion products due to fires in unsheltered timber warehouses consists of 5 stages.

At *the first stage*, we determine the duration of free development (burning) of the fire according to the dependence given in the article [13].

At *the second stage*, we determine the rate of the fire front spread in unsheltered lumber warehouses. According to the results of experimental studies and statistics of extinguished fires, an empirical dependence was obtained to determine the speed V_{fr} of fire front spread, m/min

$$V_{fr} = (0.0007\tau_{f.b}^2 - 0.0304\tau_{f.b} + 1.3981)K_{s.f}K_\alpha, \qquad (3)$$

where $K_{s.f}$ is the coefficient, which takes into account the wind speed on the speed of fire front spread

$$K_{s.f} = 0.2365V_w + 0.1082, \qquad (4)$$

where V_w is wind speed, m/s; K_α is the coefficient, which takes into account the influence of the direction of action of the wind speed vector on the speed of fire front spread

$$K_\alpha = -5\cdot10^{-5}\alpha_w^2 + 0.0123\alpha_w + 0.374, \qquad (5)$$

where α_w is the angle of wind direction (if $\alpha_w = 90°$ the accompanying wind direction is considered, and if $\alpha_w = 270°$ — counter wind direction), deg.

At *the third stage*, we determine the height of the flame above the stack in case of fire and, accordingly, the height of the convective column according to the recommendations [14]

$$H = 1.32\sqrt[3]{x^2\left(\frac{1.4Q_{min}\psi_n S_{f.s}}{tV_w^3}\right)^5}, \qquad (6)$$

where x is the coordinate of the flame axis on the stack, m; Q_{min} is the value of the lowest operating heat of combustion of the combustible load, kJ/kg; ψ_n is specific burnout rate, kg/m²s; $S_{f.s}$ is an area of fire on one stack in the plan, m²; t is ambient temperature, K.

Convection column height H_c is on average by 20—30 times more than the height of the flame. Then

$$H_c = (20-30)H. \qquad (7)$$

At *the fourth stage*, we determine the area of the fire in the timber warehouse quarter depending on the considered time of duration of free development of the fire. In this case, the area of the fire S_f can be determined by dependence

$$S_f = 0.2\alpha V_f^2 t_{f.f}^2 S_{f.s.}, \qquad (8)$$

where α is the coefficient, which takes shape of fire: circular shape 360° $\alpha = 3.14$ rad; corner 180° $\alpha = 1.57$ rad; corner 90° $\alpha = 0.785$ rad.

At *the fifth stage*, we will consider the impact of fire on the environmental safety in the quarter of the lumber warehouse, which is located at the maximum allowable distance from the fire station, namely at a distance of 3 km. The fire broke out during the day on the perimeter of the quarter in the form of an angular shape 180°, for which the coefficient $\alpha = 1.57$ rad, and the speed of the fire truck during the day $V_{f.t.} = 32$ km/hour.

Wind speed $V_w - 5$ m/s, the wind is blowing in the same direction ($\alpha_w - 90°$).

Then the duration of the free development of the fire is determined by the dependence (1) taking into account the dependence (2)

$$T_{f.b} = 3 + 1 + 1 + 3 + 1 + 8 + 7 = 24.$$

We determine the rate of fire front spread by dependence (3) taking into account dependences (4) and (5)

$$V_{fr} = (0.0007 \cdot 24^2 - 0.0304 \cdot 24 + 1.3981)1.29 \cdot 1.08 = 1.5.$$

The area of fire is determined depending on (8)

$$S_f = 0.2 \cdot 1.57 \cdot 1.5^2 \cdot 24^2 \cdot 36 = 14\,650.$$

The height of the flame above the stack is determined in relation to (6)

$$H = 1.32\sqrt[3]{3^2\left(\frac{1.4 \cdot 13\,800 \cdot 0.0145 \cdot 36}{293 \cdot 5^3}\right)^5} = 1.18,$$

where $Q_{min} = 13\,800$ kJ/kg for bars of a pine with density $\gamma_d = 540$ kg/m³, humidity 8—9 % with ignition temperature $T_d = 528$ K; $\psi_n = 0.0145$ kg/m²s.

The height of convective column (average value) is determined in relation to (7)

$$H_c = 25 \cdot 1.18 = 29.5.$$

During the free development of the fire, the volume of combustion products will move at the speed of the wind $V_w - 5$ m/s at a distance l

$$l = 5 \cdot 60 \cdot 24 = 7200.$$

In this case, the combustion products will be placed in the volume W

$$W = S_f l = 14\,650 \cdot 7200 = 105\,480\,000.$$

As a result of the fire during its free development into the environment, in the convective flow there will be released combustion products, kg

$$m = S_f \cdot \psi_n \cdot 60 \cdot \tau_{f.b.} = 14\,650 \cdot 0.0145 \cdot 60 \cdot 24 = 305\,892.$$

Based on the parameters of the fuel load, namely taking into account the specific values L_i of isolated toxic products from burning wood, we determine the value of the mass m_i of each toxic product released in volume W:

- carbon dioxide

$$m_{CO_2} = mL_{CO_2} = 305892 \cdot 1.57 = 480250;$$

- carbon monoxide

$$m_{CO} = mL_{CO} = 305892 \cdot 0.024 = 7341;$$

- nitrogen oxides

$$m_{NO_x} = mL_{NO_x} = 305892 \cdot 0.003 = 918;$$

- hydrocyanic acid

$$m_{HCN} = mL_{HCN} = 305\,892 \cdot 0.00003 = 9;$$

- acrolein

$$m_{Acr} = mL_{Acr} = 305\,892 \cdot 0.004 = 1224;$$

- oxygen consumption

$$m_{O_2} = mL_{O_2} = 305892 \cdot (-1.15) = -351776.$$

We determine the concentration of toxic products in gm/m³, which are in the volume of the environment W by dependence and compare with the allowable value.

The results of the analysis of the obtained data show that when the wind speed decreases, the distance of movement of the volume of combustion products decreases. In turn, this will increase the concentration of toxic products and reduce the density of oxygen to values at which a person's presence in the fire zone is impossible without protective equipment.

The main factor that affects the mass of combustion products entering the environment is the area of the fire. In turn, the area of the fire primarily depends on the duration of the free development of the fire. Therefore, the priority in the event of a fire should be to reduce the duration of the free de-

velopment of the fire, which in turn will reduce environmental safety.

To implement this task, it is necessary to perform the following fire safety measures:

- to equip a low-pressure or high-pressure fire water supply system and fire water supply pumping stations in the warehouse;

- to equip a fire observation point in the warehouse;

- the equipment of warehouses with a system of fire-fighting means, which include: fire-fighting control device (FFCD), fire detectors, audible fire alarms;

- to introduce an automated system for determining the firefighting means and forces;

- to introduce an automated system for optimizing the route of firefighting equipment and fire and rescue units from the fire station to the place of call;

- to determine the duration of evacuation time in case of fire from the warehouse.

Introduction of fire-fighting measures to reduce the duration of fire and reduce emissions of combustion products due to fires in unsheltered timber warehouses. *Introduction of low or high pressure fire water supply and pumping stations.* Each unsheltered timber warehouse that contains a volume of wood of 10 000 m³ and more, must be equipped with a low-pressure fire water supply with a volume of timber up to 10 000 m³ and high pressure with a volume above 10 000 m³, as well as a pumping station [15]. Pumping stations must be located at a distance of at least 40 m from stacks with automatic or remote control from a fire observation point. Pumping stations are built of reinforced concrete, concrete and brick with the placement of pumps and pipes so as to ensure the reliability of their operation and ease of maintenance. Water expenditure to eliminate one fire on average is from 120 to 180 l/s.

Introduction of a fire observation point. There should be light and sound alarms in the premises of the fire observation point, which make it possible to receive a signal about the occurrence of fire with decoding of the zone, about starting of pumps, about the malfunction, and so on [16].

Introduction of warehouse equipment with fire-fighting means. Fire-fighting control device (FFCD) is intended for electrical power supply of system components, data receipt, and processing from fire detectors, formation and transmission to other executive signals devices about detection of signs of burning. To obtain a high level of fire safety as a control panel, it is advisable to use the device "Tiras-16.128P" [16].

The fire-fighting control device is placed in the fire observation point.

Fire detectors are designed to detect a fire by its primary signs and provide information about it for further transmission. Such detectors must be addressed, which provides for the possibility of setting an individual code (address) for each of them, which is transmitted to the FFCD and allows you to judge the state of the environment and the detector's own performance. These requirements are met by the detector fire manual address type SPRA-01V.

The use of fire detectors type SPRA-01V gives the chance to reduce time from the moment of emergence to fire detection up to 1 min.

Audible fire alarms generate audible fire warning signals when a control signal is applied to them. The most common model of a fire alarm is an alarm "Siren" S-03-12. The sound pressure level at a distance of 1 m is not less than 95 dB.

Introduction of an automated system for determining the means and forces of firefighting. According to order No. 325 of 01.07.1993 of the Ministry of Internal Affairs of Ukraine, the time to attract forces and means of the garrison to extinguish fire is 3 minutes. To reduce this time, an automated system has been developed in Lviv State University of Life Safety for determining the firefighting means and forces. The introduction of such a system in the practice of determining the forces and means of the garrison for firefighting makes it possible to reduce significantly the duration of involvement.

A mathematical model was used to develop the automated system, which includes a goal function, a solution evaluation criterion, and a constraint. In this case, the mathematical model is formed as follows:

goal function

$$\tau_s \Rightarrow \min; \qquad (9)$$

by criterion

$$|B_n - B_o| \Rightarrow \min; \qquad (10)$$

under restrictions

$$a_1 \leq N_B^{Ex} \leq b_1; \qquad (11)$$

$$a_2 \leq N_B^{Pr} \leq b_2; \qquad (12)$$

$$a_3 \leq N_A \leq b_3; \qquad (13)$$

$$p \geq [p], \qquad (14)$$

where τ_s is the duration of the fire suppression, min; B_n is the costs of fire and rescue units that participated in the fire suppression, UAH; B_o is direct damage from fire at the facility, UAH; N_B^{Ex} is manual barrel type B, which is used to extinguish fire; N_B^{Pr} is manual barrel type B, which is used to protect firefighters and firefighting facilities; N_A is manual barrel type A, which is used to extinguish fire; a_1, a_2, a_3 are minimum values of restrictions, i. e. it is the existing availability of equipment and firefighting equipment, which is on duty in the nearest fire and rescue units to the object for the period of the fire; b_1, b_2, b_3 are the maximum required values of the constraints, which are determined on the basis of the calculated dependencies of the system; p is the probability of hitting the studied i^{th} point in the area of acceptable solutions; $[p]$ is the allowable value of the probability, the value of which depends on the number of studies to accept the optimal value.

The Monte Carlo method was used to solve the mathematical model. The area of acceptable decisions, which is determined by constraints (11−13), is surrounded with m-dimensional parallelepiped, in which we conduct the research. It is advisable to solve the developed mathematical model using a PC. With the help of a computer sensor sequence of pseudo-random numbers μ_{ji} on interval 0−1 is created. To convert pseudo-random numbers μ_{ji}, which are evenly distributed in the interval 0−1, to values N_B^{Ex}, N_B^{Pr}, N_A use type dependencies, for example, as for N_A

$$N_{Ai} = a_3 + \mu_{3i}(b_3 - a_3), \qquad (15)$$

where μ_{3i} is the pseudo-random number to determine the factor N_{Ai} on a certain i^{th} calculation loop.

In the process of calculation, at each cycle of the program values τ_s and criteria are determined that are compared with the values of the previous cycle. These procedures are performed as long as condition (14) is met. After finishing the running of program, the following data is printed: S_f at the time of the beginning of localization, $\tau_{fol.}$, τ_{loc}, N_B^{Ex}, N_B^{Pr}, N_A, N_b − fire departments, $N_{f.t.}$ − fire trucks, $N_{s.t.}$ − special fire trucks, p.

To implement the mathematical model, a package of applications for working in the Windows environment was developed for the PC. The operating time of the PC was 5−7 s for 5 thousand tests (N_i − loops) with the probability of the studied i^{th} points in entering the area of acceptable decisions $p = 0.94 − 0.96$. The working window of the program is shown in the Figure.

The results of the analysis of statistical data on the use of an automated system for determining the means and forces of firefighting showed that the time spent on the involvement of forces and means of the garrison for firefighting does not exceed 1 minute.

Introduction of an automated system for optimizing the route of firefighting equipment and fire and rescue unit from the fire
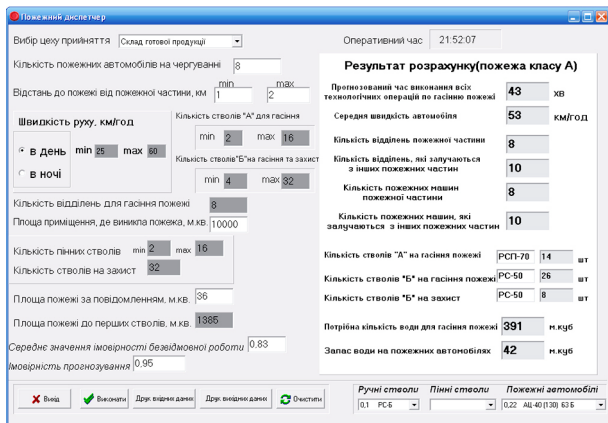
Fig. Working window of the automated system program to determine the means and forces of firefighting

station to the call site. The results of statistics show that, for example, in the United States, the average travel time of a fire department in the city to the scene is from 2.4 to 5.9 minutes [4]. This is from 3 to 5 times less than in European cities and cities of Ukraine. This rapid response of fire and rescue units can be explained by the fact that fire departments serve much smaller areas of the city from 1.7 to 6 km^2 of territory per depot [5], while in Ukraine it is from 28 to 30 km^2.

To solve the problem of reducing the travel time of the fire department to the call site, at Lviv State University of Life Safety an automated system was developed to determine the optimal route of fire equipment and fire and rescue units from the fire station to the call site [5, 7]. The State Fire and Rescue Unit No.1 in Lviv City was taken as a basis for modeling. Based on the optimization mathematical model, an algorithm for solving the problem using the Monte Carlo method was developed.

Using this algorithm, a software product was developed in the system Microsoft Visual Studio 2012 using the environment Windows 7 to determine the optimal route for five directions of the exit area of the fire and rescue unit.

After the calculations, the route is mapped and the estimated travel time to the call site is indicated on the working window of the program.

Calculations by using this program for the selected directions showed that when choosing the optimal route, the travel time is reduced to 2.5−5 minutes (with an average value of 3.8 minutes).

Determining the duration of the evacuation from the warehouse in case of fire. The duration of the evacuation of people from the warehouse in case of fire depends on the critical time of the fire τ_k, i.e. the duration of the possible stay of people in the area of the fire.

To solve this problem, it is necessary to determine the critical time of the fire as a result of reduced oxygen concentration and increased concentration of toxic products of combustion and thermal decomposition. After determining the critical time of the fire from each factor, the lowest value is taken as the basis and it will be the critical time.

We determine the value of the critical time from the reduced oxygen concentration [8]

$$\tau_{crit.O_2} = \sqrt[3]{1442V}, \qquad (16)$$

where V is the volume of combustion products distribution, m^3.

Based on one quarter of the composition at the height of the convection column 29.5 m

$$V = 193 \cdot 94 \cdot 29.5 = 535189.$$

So

$$\tau_{crit.O_2} = \sqrt[3]{1442 \cdot 535189} = 857.$$

Critical time of fire from increasing concentration of combustion products, including toxic [9] is

$$\tau_{conc.tox.prod} = \sqrt[3]{6794V \cdot \ln\left(\frac{1}{1 - \frac{35.9}{L_2}\rho_{2\hat{e}}}\right)}, \qquad (17)$$

where L_2 is the stoichiometric factor for the relevant fire hazards, kg/kg; ρ_{2k} are maximum permissible values of the partial density of toxic products, kg/m^3.

Then by CO_2 concentration, we get

$$\tau_{conc.CO_2} = \sqrt[3]{6794 \cdot 535189 \cdot \ln\left(\frac{1}{1 - \frac{35.9}{0.203}0.11}\right)} = 2482,$$

by CO concentration

$$\tau_{conc.CO} = \sqrt[3]{6794 \cdot 535189 \cdot \ln\left(\frac{1}{1 - \frac{35.9}{0.0022}0.00116}\right)} = 2025.$$

The result of the analysis of the received critical time of a fire shows that the smallest time is time from the lowered concentration of oxygen which we accept as a basis. Then $\tau_k = 857$ s $= 14.3$ minutes.

We determine the duration of the evacuation time in relation to

$$\tau_e = \frac{l_e}{k_e V_e}, \qquad (18)$$

where l_e is evacuation route, m; k_e is the total number of evacuations exits; V_e is the speed of human flow, m/min.

Based on one quarter in which the fire has broken out, the longest evacuation route will be equal to its length and the length of the route from the quarter to the point of run-off. Then $l_e = 200 + 50 = 250$ m. The total number of evacuation exits $k_e = 4$, and the average value of the speed of human flow according to the recommendations [9] $V_e = 50$ m/min. Time from the beginning of the fire to the beginning of the evacuation $\tau_{n.e} = 4$ min started after the completion of all works related to fire detection, transfer of information to the control point of the SES of the district, and so on. In this case

$$\tau_e = \frac{250}{4 \cdot 50} = 1.25.$$

Based on the data obtained, we determine the probability of evacuation of people P_e by the method [17]. As $t_e + t_{n.e.} \le 0.8 \cdot t_\kappa$, the probability of evacuation of people is 0.999, indicating the successful evacuation of people from the timber depot where the fire has broken out.

The results of the analysis of the obtained data make it possible to reduce the impact of fires in unsheltered timber warehouses on the environmental safety when implementing them in firefighting practice. To confirm this conclusion, we use the data of the example, which was considered in order to establish environmental safety in the quarter of the lumber warehouse in case of fire.

Based on the data obtained, we determine the duration of free combustion

$$\tau_{f.b.} = 1 + 1 + 1 + 1 + 1 + 4.2 + 7 = 16.2.$$

Speed of fire front spread is

$$V_{fr} = (0.0007 \cdot 16.2^2 - 0.0304 \cdot 16.2 + 1.3981)1.29 \cdot 1.08 = 1.5.$$

Fire area is

$$S_f = 0.2 \cdot 1.57 \cdot 1.5^2 \cdot 16.2^2 \cdot 36 = 6675.$$

Moving of the volume of combustion products at wind speed $V_b = 5$ m/s at a distance l

$$l = 5 \cdot 60 \cdot 16.2 = 4860.$$

Combustion products will be placed in the volume W

$$W = S_f l = 6675 \cdot 4860 = 32\,440\,500.$$

During the time of free combustion in the environment in the convective flow there will be combustion products released

$$m = S_f \cdot \psi_n \cdot 60 \cdot \tau_{f.b.} = 6675 \cdot 0.0145 \cdot 60 \cdot 16.2 = 34\,077.$$

If we compare the mass of isolated combustion products before taking measures, which amounted to 305 892 kg, it can be argued that reducing the free time of the fire from 24 minutes to 16.2 will reduce emissions of combustion products by 9 times.

Conclusions. Performance of research on ecological safety at fires in unsheltered timber warehouses gave the opportunity to receive the following results.

1. Introduction of all necessary fire-fighting equipment in unsheltered timber warehouses, an automated system for determining fire extinguishing means and forces at the SES control point, and an automated system for optimizing the route of firefighting equipment and fire-rescue unit from the fire station to the call site give the possibility to reduce the duration of free development of fire by 48 % and, accordingly, to reduce the release of combustion products into the environment by about 9 times and, thus, to ensure environmental safety.

2. The use of an automated system for determining the firefighting means and forces at the control center of the SES, taking into account the recommendations given in the work, makes it possible to reduce the duration of time to attract forces and means of the fire suppression by 2–3 times.

3. Introduction to fire and rescue garrisons of the automated system of optimization of travel route of fire equipment and fire and rescue unit from a fire depot to a call site gives the opportunity to reduce the travel time by 1.3–1.9 times.

4. The results of the research show that the critical time of fire depends to a greater extent on the reduction of oxygen concentration. This concentration is particularly affected by wind speed. For example, when the wind speed is halved, the critical time of the fire is reduced by 35–40 %. Therefore, in case of fire in unsheltered timber warehouses for the successful evacuation of people, it is necessary to take into account the critical time of the fire within 10–12 minutes.

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Забезпечення екологічної безпеки шляхом підвищення ефективності пожежогасіння відкритих складів лісоматеріалів

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Мета. Розробити методику зниження впливу пожеж відкритих складів лісоматеріалів на екологічну безпеку шляхом зменшення тривалості вільного розвитку пожежі, швидкості розповсюдження фронту пожежі, концентрації продуктів горіння та тривалості ліквідації пожежі.

Методика. При проведені експериментальних досліджень використано метод дробовофакторного експерименту. Теоретичні дослідження виконували з використанням оптимізаційних математичних моделей. Для розв'язку оптимізаційних задач застосовано метод Монте-Карло. Для реалізації даного методу розроблено блок-схеми алгоритмів, на підставі яких написані відповідні комп'ютерні програми.

Результати. Розроблена методика зниження впливу пожеж відкритих складів лісоматеріалів на екологічну безпеку шляхом зменшення тривалості вільного розвитку пожежі, швидкості розповсюдження фронту пожежі, концентрації продуктів горіння та тривалості ліквідації пожежі. При впровадженні протипожежних заходів для зменшення тривалості пожежі та зниження викидів продуктів горіння внаслідок пожеж, застосована автомати-

зована система для визначення засобів і сил пожежогасіння, шляхом постановки оптимізаційної задачі, застосування методу Монте-Карло й розроблення програмного забезпечення для її розв'язку.

Наукова новизна. Полягає в обґрунтуванні шляхів зменшення тривалості вільного розвитку пожежі та зменшення кількості викидів токсичних речовин із використанням оптимізаційних математичних моделей.

Практична значимість. Полягає в можливості використання отриманих результатів у практичній діяльності пожежно-рятувальних підрозділів ДСНС України та забезпеченні у разі пожежі екологічної безпеки на відкритих складах лісоматеріалів.

Ключові слова: *відкриті лісосклади, пожежа, тривалість вільного горіння, токсичні викиди, екологічна безпека*

Обеспечение экологической безопасности путем повышения эффективности пожаротушения открытых складов лесоматериалов

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Цель. Разработать методику снижения воздействия пожаров открытых складов лесоматериалов на экологическую безопасность путем уменьшения продолжительности свободного развития пожара, скорости распространения фронта пожара, концентрации продуктов горения и продолжительности ликвидации пожара.

Методика. При проведении экспериментальных исследований использован метод дробнофакторного эксперимента. Теоретические исследования выполняли с использованием оптимизационных математических моделей. Для решения оптимизационных задач применен метод Монте-Карло. Для реализации данного метода разработаны блок-схемы алгоритмов, на основании которых написаны соответствующие компьютерные программы.

Результаты. Разработана методика снижения воздействия пожаров открытых складов лесоматериалов на экологическую безопасность путем уменьшения продолжительности свободного развития пожара, скорости распространения фронта пожара, концентрации продуктов горения и продолжительности ликвидации пожара. При внедрении противопожарных мероприятий для уменьшения продолжительности пожара и снижения выбросов продуктов горения в результате пожаров, применена автоматизированная система для определения средств и сил пожаротушения, путем постановки оптимизационной задачи, применения метода Монте-Карло и разработки программного обеспечения для ее решения.

Научная новизна. Заключается в обосновании путей уменьшения продолжительности свободного развития пожара и уменьшения количества выбросов токсичных веществ с использованием оптимизационных математических моделей.

Практическая значимость. Заключается в возможности использования полученных результатов в практической деятельности пожарно-спасательных подразделений ДСНС Украины и обеспечении в случае пожара экологической безопасности на открытых складах лесоматериалов.

Ключевые слова: *открытые лесосклады, пожар, продолжительность свободного горения, токсичные выбросы, экологическая безопасность*