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INVESTIGATION OF THE EFFECT OF CARBON MONOXIDE ON PEOPLE IN CASE OF FIRE IN A BUILDING

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SUMMARY: The research has been conducted to determine the safe residence time for people in a room where the composition of the gas environment has deteriorated due to fire. Carbon monoxide, which is produced by fire, has been found to be lethal for human life and health. Determination of safe time was made based on the study of the composition and amount of fire load in premises and buildings, physical and chemical properties of carbon monoxide, and its effect on the human body. The graphical dependences of the concentration of carbon monoxide in a room, as a function of time, were obtained for eight variants. The results allow authors to determine the possible residence time of a person in a building during a fire before the lethal concentration of carbon monoxide occurs. Studies made it possible to determine the safe residence time of people in a building on fire in a calculated way and to compare it with the normative indicators of the onset of lethal concentration of carbon monoxide in the air. The results obtained determine the safe time during which a person can escape from the building on fire.

Key words: carbon monoxide, rescuing people, safe residence time, lethal concentration

INTRODUCTION

In Ukraine 31,677 fires occurred in residential buildings in 2018, accounting for 40.3% of the total number of fires. The fires killed 1851 people, accounting for 94.6% of the total casualties. Each fire is characterized by the presence of dangerous factors of fire. These include high temperature, smoke, deterioration of the composition of the gas environment (*Analysis of an array...*, 2019).

Practical experience shows that people dies in fires mainly in the early stages of fire, mainly from toxic products (*Handbook of Chief of fire-fighting...*, 2016). A number of volatile toxic com-

bustion products, such as oxides of nitrogen and carbon monoxide (CO), acrylonitrile, hydrogen fluoride and hydrochloric acid, fluorophosgene and hydrocyanic acid, hydrogen sulfide, sulfur dioxide, etc. are formed in the process of combustion of substances (*Goldstein, 2008, Mu et al., 2011*). Specific consideration should first be given to the most common common toxins. In this case, it is worth highlighting a group of irritants that have more psychological than toxic, action, and surface penetrating toxins, which should be considered as "respiratory poisons". The main representatives of the latter group are carbon monoxide and hydrocyanic acid, the latter being formed only by thermal decomposition of nitrogen-containing basic substances (*Air quality criteria...*, 2000, *Pospelov et al., 2018*).

While determining the safe residence time of people in a room where the composition of the gas environment due to the fire has deteriorated, the characteristics of toxic combustion products

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play a major role, namely their direct impact on the human body, which studies allow to determine this time where there is a likelihood of saving lives (*Pospelov et al., 2017, Danchenko et al., 2017*).

The authors (*Hampson et al., 2019, Huang et al., 2017*) of note that a large number of people are exposed to carbon monoxide poisoning while staying in a room where a fire has occurred. It is also formed during the operation of road transport (*Korytchenko et al., 2018, 2018b, Kasimov et al., 2018*). Experimental studies on the formation and propagation of carbon monoxide indoors during a fire and prevention measures have been carried out in (*Yang et al., 2011, Yuan et al., 2016*). Authors in a study showed that the danger of human, chemical and physical properties of carbon monoxide is exposed (*Aldossary et al., 2015, Zobnine et al., 2010*).

In light of the above, carbon monoxide poisoning is very dangerous for the human body. This danger is compounded by the fact that it is odorless and poisoning can occur unnoticed. Even small amounts of it entering the air and inhaled by a person cause dizziness and nausea, and inhaling air, which contains 0.3% of carbon monoxide, can quickly lead to death. The toxic effect of carbon monoxide is due to the fact that it forms with hemoglobin a relatively stable compound - carb oxyhemoglobin, which causes the blood to lose its ability to transfer oxygen to the body's tissues. The poisoning of this gas occurs as a result of a critical lack of oxygen in the body. The concentration of carbon monoxide in the air of 1 mg/m³ is dangerous for human life (*Hu et al., 2007, 2008*).

The authors discuss methods and technical means for extinguishing fires, but questions regarding the procedure for the application of these funds in the presence of people in need of assistance are not taken into account (*Korytchenko et al., 2018c, Kustov, 2016, Ostapov et al., 2019, Dubinin et al., 2018*). It also does not take into account the condition of the victims. Therefore, in order to summarize and determine the procedure for extinguishing fires, it is necessary to know the safe stay of people in the building.

Thus, determining the safe residence time of people in a room where the composition of the gas environment deteriorated before the lethal concentration of carbon monoxide due to fire is an urgent task during rescue operations.

MATERIALS AND METHODS

To solve and justify scientific tasks and achieve the goal, research methods of generalization and comparison were applied that allowed authors to assess the hazard state of exposure to carbon monoxide on the human body during a fire. The application of mathematical modeling methods allowed authors to determine the concentration of carbon monoxide in the state of the gas environment in the room during a fire depending on the fire load and present this dependence in the form of graphs.

RESULTS AND DISCUSSION

In modern conditions, the development of economically optimal and effective fire-fighting measures is carried out using the forecast of the dynamics of the formation the dangerous fire factors using mathematical modeling. As known, fire in rooms is accompanied by a change in the chemical composition and parameters of the state of the gas environment filling the room. It is about these magnitudes, first of all, that authors are talking about when analyzing the situation on a fire. Studying the state parameters, authors can trace the general patterns of fire extension, identify the most significant features. Knowledge of these patterns is necessary when solving many regulatory, technical and operational-tactical tasks that are associated with ensuring the safe evacuation of people from a burning room (*Pospelov et al., 2018a, 2019*).

To determine the safe time for people to stay in a room where the composition of the gas environment has deteriorated as a result of a lethal concentration of carbon monoxide in a fire, the characteristics of the human body and the fire load of the rooms should be taken into account. From here, authors consider the state of the gas environment in the room in accordance with the

concentration of carbon monoxide (CO). To do this, authors calculate the mass of carbon monoxide in the room, which varies over time dt and determine it by the formula:

$$dm_{CO} = d(\rho_m \cdot x_{CO} \cdot V), \quad [1]$$

x_{CO} – average dimension concentration (CO).

According to the law of conservation of mass, the sum of products must be equal to the change in mass of this product indoors as shown:

$$d(\rho_m x_{CO} V) = \eta\psi L_{CO} dt + G_{CO_2} x_{CO_2} dt - G_{CO_1} n_{CO} x_{CO} dt \quad [2]$$

$\eta\psi L_{CO} dt$ – the amount of CO that is formed over time dt ; $G_{CO_2} x_{CO_2} dt$ – the amount of CO over time dt with gases from the room; $G_{CO_1} x_{CO_1} dt$ – the amount of CO entering the room during the time dt with the air.

Taking into account that, the concentration of carbon monoxide in the gases leaving the room is generally different from the mean dimension, then:

$$\frac{x_{CO_1}}{x_{CO}} = n_{CO} \geq 1. \quad [3]$$

Given the expressions (1-3), the equation takes the form:

$$\frac{d}{dt}(\rho_m x_{CO} V) = \eta\psi L_{CO} + x_{CO_2} G_{CO_2} - n_{CO} x_{CO} G_{CO_1} \quad [4]$$

Determination the safe time for people to stay in a room, where the composition of the gaseous environment has deteriorated as a result of a fire, depending on the concentration of carbon monoxide using equations (4). To conduct a study determining the safe stay of people indoors, have been used software named «Fire», fire development models were developed in 8 living quarters, with typical layout (three living rooms, kitchen and hallway) with a total area 180-300 m². Also, for the study, authors consider 8 (eight) design options for rooms with different types of fire load (Table 1), with a fire developing for 30 minutes: option 1 - buildings of III-IV degree of fire resistance (hereinafter - CO) (furniture + household appliances); Option 2 - rooms (furniture + fabrics) Option 3 - cabinet (furniture + paper); Option 4 - office building (furniture + paper); 5th option - rooms (furniture + PVC linoleum) 6th option - furniture + paper + carpet; Option 7 - buildings of the III degree of fire resistance (furniture + fabrics) Option 8 - a room lined with fiberboard panels (*Conduct research and develop..., 2007*).

Table 1. The parameters of combustible substances**Tablica 1. Parametri zapaljivih tvari**

General options		The release of gases	
1 - variant (building with III-IV degree of fire resistance: furniture + household appliances)			
Lower combustion heat is Q_H , kJ/kg	13800	carbon dioxide - L_{CO_2} , kg/kg	0.203
Linear flame speed - v_l , m/s	0,0465	carbon monoxide - L_{CO} , kg/kg	0,0022
Specific burn rate - u_m , kg/(m ² s)	0,0344	hydrogen chloride - L_{HCl} , kg/kg	0.014
Smoke-forming ability - D_{sc} , N_p m ² /kg	270	water vapor - L_{H_2O} , kg/kg	0,095
Oxygen consumption, - L_{O_2} , kg/kg	1.03		
2 - variant (room : furniture + fabric)			
Lower combustion heat is Q_H , kJ/kg	14700	carbon dioxide - L_{CO_2} , kg/kg	1.29
Linear flame speed - v_l , m/s	0,0465	carbon monoxide - L_{CO} , kg/kg	0,0022
Specific burn rate - u_m , kg/(m ² s)	0,0344	hydrogen chloride - L_{HCl} , kg/kg	0,0060
Smoke-forming ability - D_{sc} , N_p m ² /kg	82,0	water vapor - L_{H_2O} , kg/kg	0.59
Oxygen consumption, - L_{O_2} , kg/kg	1.44		
3 - variant (to office: furniture + paper)			
Lower combustion heat is Q_H , kJ/kg	14000	carbon dioxide - L_{CO_2} , kg/kg	0.64
Linear flame speed - v_l , m/s	0.042	carbon monoxide - L_{CO} , kg/kg	0.032
Specific burn rate - u_m , kg/(m ² s)	0,0129	hydrogen chloride - L_{HCl} , kg/kg	0,0000
Smoke-forming ability - D_{sc} , N_p m ² /kg	53,0	water vapor - L_{H_2O} , kg/kg	0.32
Oxygen consumption, - L_{O_2} , kg/kg	1.16		
4 - variant (and office space: furniture + paper)			
Lower combustion heat is Q_H , kJ/kg	14000	carbon dioxide - L_{CO_2} , kg/kg	1.43
Linear flame speed - v_l , m/s	0.022	carbon monoxide - L_{CO} , kg/kg	0.043
Specific burn rate - u_m , kg/(m ² s)	0.021	hydrogen chloride - L_{HCl} , kg/kg	0,0000
Smoke-forming ability - D_{sc} , N_p m ² /kg	53,0	water vapor - L_{H_2O} , kg/kg	0.69
Oxygen consumption, - L_{O_2} , kg/kg	1.16		
5 - variant (rooms : furniture + PVC linoleum)			
Lower combustion heat is Q_H , kJ/kg	14000	carbon dioxide - L_{CO_2} , kg/kg	1.48
Linear flame speed - v_l , m/s	0.015	carbon monoxide - L_{CO} , kg/kg	0.030
Specific burn rate - u_m , kg/(m ² s)	0,0137	hydrogen chloride - L_{HCl} , kg/kg	0,0058
Smoke-forming ability - D_{sc} , N_p m ² /kg	47,7	water vapor - L_{H_2O} , kg/kg	0.70
Oxygen consumption, - L_{O_2} , kg/kg	0.37		

6 - variant (room: furniture + paper + carpet)			
Lower combustion heat is Q_H , kJ/kg	14300	carbon dioxide - L_{CO_2} , kg/kg	0.76
Linear flame speed - v_l , m/s	0.034	carbon monoxide - L_{CO} , kg/kg	0.068
Specific burn rate - u_m , kg / (m ² s)	0.013	hydrogen chloride - L_{HCl} , kg/kg	0,0008
Smoke-forming ability - D_{sc} , N_p m ² /kg	72,4	water vapor - L_{H_2O} , kg/kg	0.41
Oxygen consumption, - L_{O_2} , kg/kg	1.44		
7 - variant (building with III degree of fire resistance: furniture + fabric)			
Lower combustion heat is Q_H , kJ/kg	14900	carbon dioxide - L_{CO_2} , kg/kg	1.32
Linear flame speed - v_l , m/s	0.04	carbon monoxide - L_{CO} , kg/kg	0,0019
Specific burn rate - u_m , kg/(m ² s)	0,0162	hydrogen chloride - L_{HCl} , kg/kg	0,0000 1
Smoke-forming ability - D_{sc} , N_p m ² /kg	58.5	water vapor - L_{H_2O} , kg/kg	0.62
Oxygen consumption, - L_{O_2} , kg/kg	1.44		
8 - variant (for the room lined with fiberboard panels)			
Lower combustion heat is Q_H , kJ/kg	18100	carbon dioxide - L_{CO_2} , kg/kg	0.69
Linear flame speed - v_l , m/s	0,0405	carbon monoxide - L_{CO} , kg/kg	0.022
Specific burn rate - u_m , kg / (m ² s)	0,0143	hydrogen chloride - L_{HCl} , kg/kg	0,0000
Smoke-forming ability - D_{sc} , N_p m ² /kg	130	water vapor - L_{H_2O} , kg/kg	0.33
Oxygen consumption, - L_{O_2} , kg/kg	1.15		

Using MATLAB software, the carbon monoxide concentration values were calculated at

different time intervals for the above types of rooms (Figs. 1–8).

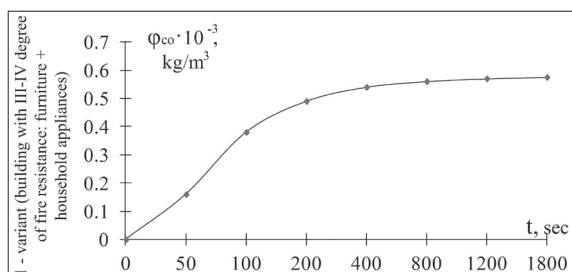


Figure 1. Concentration values of carbon monoxide in building with III-IV degree of fire resistance (furniture + household appliances) according to the first design variant

Slika 1. Vrijednosti koncentracije ugljičnog monoksida u zgradi sa stupnjem III-IV otpornosti na požar (namještaj + kućanski aparati) prema prvoj varijanti dizajna

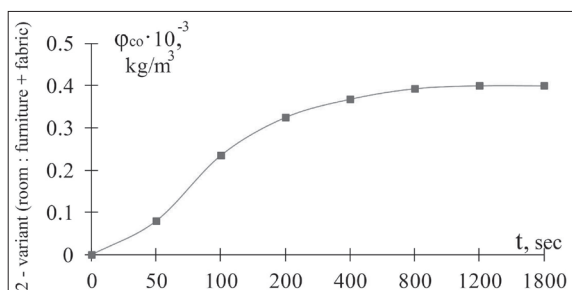


Figure 2. The values of carbon monoxide concentrations in the rooms (furniture + fabrics) according to the second design variant

Slika 2. Vrijednosti koncentracije ugljičnog monoksida u prostorijama (namještaj + tkanine) prema drugoj varijanti dizajna

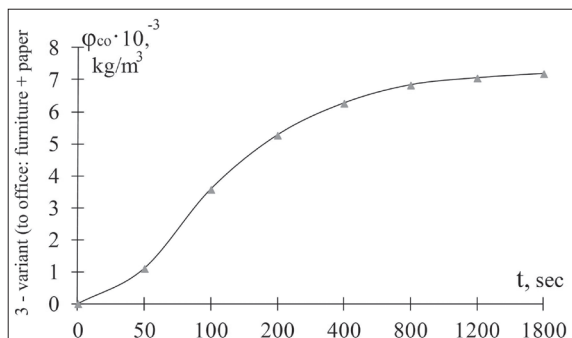


Figure 3. The values of carbon monoxide concentrations in cabinet (furniture + paper) according to the third calculation variant

Slika 3. Vrijednosti koncentracije ugljičnog monoksida u kabinetu (namještaj + papir) prema trećoj kalkulacijskoj varijanti

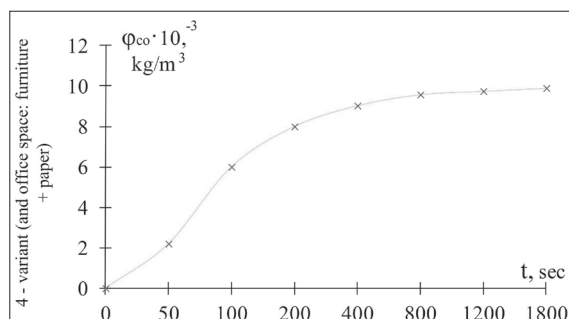


Figure 4. The values of carbon monoxide concentrations in the administrative room (furniture + paper) according to the fourth design variant

Slika 4. Vrijednosti koncentracije ugljičnog monoksida u prostoriji administracije (namještaj + papir) prema četvrtoj varijanti dizajna

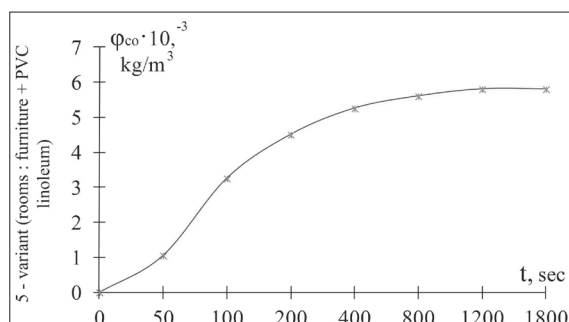


Figure 5. Values of carbon monoxide concentrations in the room (furniture + PVC linoleum) according to the fifth design variant

Slika 5. Vrijednosti koncentracije ugljičnog monoksida u prostoriji (namještaj + PVC linoleum) prema petoj varijanti dizajna

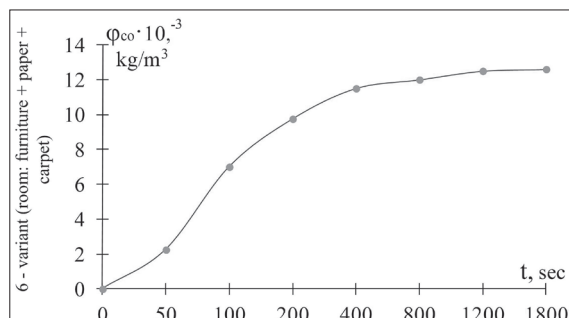


Figure 6. The values of the concentrations of carbon monoxide in the room (furniture + paper + carpet) according to the sixth design variant

Slika 6. Vrijednosti koncentracije ugljičnog monoksida u prostoriji (namještaj + papir + podna obloga/tepih) prema šestoj varijanti dizajna

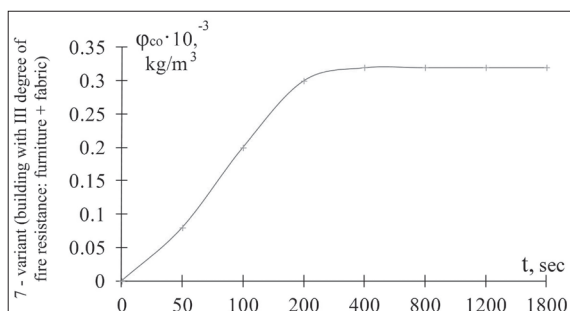


Figure 7. The values of carbon monoxide concentrations in building with III degree of fire resistance (furniture + fabric) according to the seventh design variant

Slika 7. Vrijednosti koncentracije ugljičnog monoksida u zgradi sa stupnjem III otpornosti na požar (namještaj + tkanine) prema sedmoj varijanti dizajna

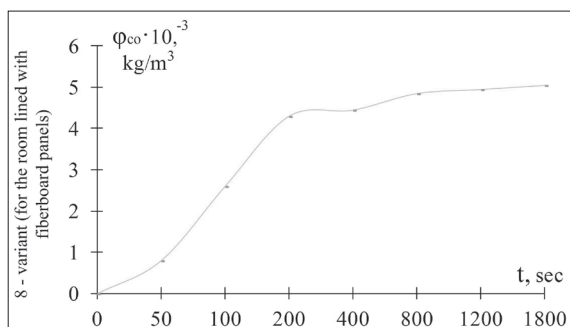


Figure 8. The values of carbon monoxide concentrations in the room, lined with fiberboard panels according to the eighth design option

Slika 8. Vrijednosti koncentracije ugljičnog monoksida u prostoriji obloženoj panelima od vlakana (fibreboard) prema osmoj opciji dizajna

When analyzing the graphs shown on Figure (1-8) found that in each case the value of fire load ranges large range and safe residence time of people, which occurs when a lethal concentration from 2 minutes to 30 minutes.

Comparing the results with medical data on dangerous concentrations of CO for humans and taking into account the dimension of rooms, openings (windows, doors) it is established that a lethal concentration of CO – $3 \cdot 10^{-3}$ kg/m³ is formed in about 12-21 minutes from the beginning of the fire (Prockop, Chichkova, 2017, Weaver, 2009).

Based on this, authors construct an approximating straight line that shows the average value

of the change in the concentration of carbon monoxide over time in a residential building on fire, taking into account the above (Fig. 9).

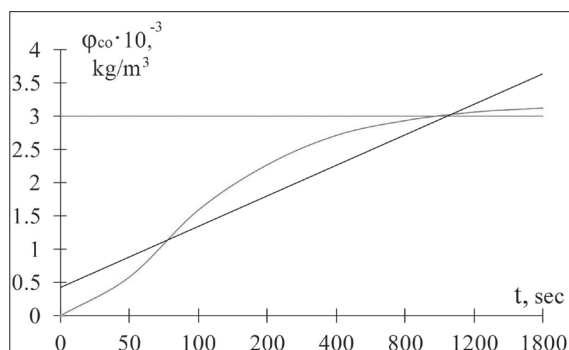


Figure 9. The average change in carbon monoxide concentration as a function of time during a fire in a building

Slika 9. Prosječna promjena koncentracije ugljičnog monoksida kao funkcije vremena tijekom požara u zgradi

Based on this we take the critical value of safe time for which the deadly concentration of carbon monoxide (CO) in the gas environment in the building is 17 minutes.

It has been established that carbon monoxide is very dangerous for the human body (Ragimov et al., 2018, Gorman et al., 2003). The danger lies in the establishment of a deadly concentration of carbon monoxide in the air, which amounts to 0.3% ($3 \cdot 10^{-3}$ kg/m³) in dimension, which will quickly lead to the death of a person in the room. First of all, people who were in the fire zone are killed from it, so in 2018, 1,851 people died, which is almost 95% of the total number of deaths. Also, many people die from the exhaust gases of car engines caught in a closed room (garage). The poisoning effect of CO is determined by the fact that it forms a relatively stable compound, carboxyhemoglobin, with blood hemoglobin, as a result of which the blood loses its ability to transmit oxygen to body tissues. Poisoning with this gas occurs as a result of a critical lack of oxygen in the body.

All combustible materials, regardless of their composition, are capable of emitting highly toxic gases in fire conditions. With a high concentration of them in the air, warm-blooded organisms die within a few minutes. Therefore, authors can

assume that the danger associated with the formation of carbon monoxide during the combustion of solid combustible material (fabrics, furniture) is known. The question inevitably arises, what kind of technology changes were started in order to reduce this danger. On the one hand, there is the possibility of lowering the flammability threshold at the molecular level in the development of new synthetic materials, of which the recently developed flame-retardant modacryl, nomex and Kermel should be mentioned. On the other hand, this effect can be achieved by additional processing of the tissue itself. This method is preferred when used mainly in cotton fabrics.

But with this in mind, it is impossible to make or remake that solid combustible material from which the manufacture of furniture, sofas, carpets, etc. in order to reduce flammability and to reduce the emission of carbon monoxide during combustion. Hence, the main indicator of safety for a person is the length of time spent in the room during a fire until a deadly concentration of carbon monoxide in the air occurs, so this safety indicator is safe time. To determine the safe time for people staying in the room before the lethal concentration of carbon monoxide sets in, rooms were examined in eight design options, depending on the type of fire load. The calculation was carried out on the content of carbon monoxide concentration in the composition of the gas environment was carried out. Each room in the building was distinguished from each other by the presence of furniture equipment, linoleum, the degree of fire resistance, and the like.

Using the MATLAB software, the values of carbon monoxide concentration at different time intervals were calculated for eight design options for the rooms. From the obtained figures (1-8) it was found that the safe time for people to stay in the room, at which a lethal concentration occurs, is from 3 minutes to 30 minutes. So in figures (2-6, 8) from the graphs it can be seen that the safe time for people to stay in the room is about 2-4 minutes. This is because in the composition of the gas environment in the room with standard sizes of $3 \times 4 \times 3$ m, the onset of a lethal concentration of carbon monoxide in the air will take place 2-4 minutes after the start of the fire. On figures (1, 7) from the graphs it can be seen that the safe time for people to stay in the room is about 30 minutes. This is be-

cause a fire in a room can occur until an oxidizing agent is present in the air, if it is not present, then smoldering occurs with the formation of pyrolysis products. Accordingly, in other rooms of the building there is still an oxidizing agent in the air and the environment is suitable for human breathing, and the time people spent in the room increases.

Comparing the results with medical data on dangerous concentrations of CO for humans and taking into account the dimension of the room, openings (windows, doors), it was found that a lethal concentration of CO – $3 \cdot 10^{-3}$ kg/m³ is formed in about 11-19 minutes from the start of a fire. From here, according to Figure 9, the safe time for a person to stay in the building for the upcoming fatal concentration is 17 minutes. This means that person in the building on fire, has only 17 minutes, in order to leave the building and be saved.

CONCLUSIONS

The danger of exposure to carbon monoxide on the human body is formed during a fire in the room. Conducting a study to determine the safe time for people to stay in a room, where the composition of the gas environment deteriorated before a fatal concentration of carbon monoxide occurred because of a fire. The toxicity of CO based on the fact that CO very intensely binds with hemoglobin in the blood and so distributed CO in the body. It has been established that the normative indicator of the lethal concentration of carbon monoxide in dimension is 0.3% ($3 \cdot 10^{-3}$ kg/m³), which will quickly lead to the death of a person in the building on fire.

Carbon monoxide concentrations in the room and buildings were calculated using eight design options depending on the fire load. According to the results of the study, it was found that the safe time a person stays in the building for the upcoming lethal concentration is 17 minutes.

This will increase the efficiency of search and rescue operations made by fire and rescue units in the building on fire. And also provide security measures to ensure human life and health in the event of a deadly concentration of carbon monoxide in buildings, taking into account the safe time.

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ISPITIVANJE DJELOVANJA UGLJIČNOG MONOKSIDA NA LJUDE U SLUČAJU POŽARA U ZGRADI

SAŽETAK: Istraživanje je provedeno kako bi se utvrdilo koliko dugo ljudi mogu boraviti u prostoriji u kojoj je kakvoća zraka smanjena zbog požara. Ugljični monoksid, proizvod požara, jest smrtonosan i opasan za zdravlje. Sigurno vrijeme boravka utvrđeno je na temelju ispitivanja sastava i količine požarnog opterećenja u prostorijama i zgradama, fizikalnih i kemijskih svojstava ugljičnog monoksida i njegova djelovanja na ljudsko tijelo. Grafički je prikazana ovisnost koncentracije ugljičnog monoksida u prostoriji kao funkcije vremena, i to za osam varijanti. Rezultati omogućuju da se utvrdi moguće vrijeme boravka u zgradi tijekom požara prije nego dođe do smrtonosne koncentracije ugljičnog monoksida. Ispitivanjem je izračunato vrijeme sigurnog boravka u požarom zahvaćenoj zgradi te je moguća usporedba s normativnim pokazateljima dostizanja smrtonosne koncentracije ugljičnog dioksida u zraku. Rezultati služe za utvrđivanje sigurnog vremena za bijeg ljudi iz požarom zahvaćene zgrade.

Ključne riječi: *ugljični monoksid, spašavanje ljudi, sigurno vrijeme boravka, smrtonosna koncentracija*

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