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EXPERIMENTAL STUDIES OF ENERGY CONSUMPTION AND THERMAL STATE OF THE BODY OF FIREFIGHTERS IN PROTECTIVE CLOTHING

In Ukraine, extreme microclimatic conditions (elevated temperature, high and low humidity, air velocity, gassiness, smoke) occur at production or during emergency rescue operations by units of the State Emergency Service of the Ministry of Internal Affairs of Ukraine and the State Militarized Mining and Rescue Service.

The performance of emergency and rescue work at fires and liquidation of accidents requires the personnel of the Operational and Rescue Service of the Emergency Situations of Emergency Situations to respond quickly to emergency situations, make effective technical decisions, high professionalism and is associated with high physical and psychoemotional stress on the body of the firefighter-rescuer.

The training of firefighters and rescuers to carry out rescue operations in conditions of ergothermic loads is a professional necessity in the conditions of a real fire and liquidation of the consequences of missile and bomb attacks as a result of the aggression of the occupiers on the infrastructure of Ukraine.

The works of fire safety specialists, in which the influence of various types of performed operations and the conditions of their execution, are devoted to the study of the energy consumption of the body of firefighters and mine rescuers.

The article examines the results of experimental studies of energy consumption and the thermal state of the body of firefighters in protective clothing.

The main components of the heat balance, on which the duration of a person's work depends, are the internal energy produced by his body - the heat production of the firefighter's body, which in turn depends on the amount of energy consumption, and external energy that penetrates from the outside. At the same time, external energy is, as a rule, a factor independent of a person, and internal energy depends on many parameters.

Key words: *protective clothing, thermal condition, firefighter-rescuer, temperature, training, step test.*

Formulation of the problem. In Ukraine, extreme microclimatic conditions (elevated temperature, high and low humidity, air velocity, gassiness, smoke) occur in production or during emergency rescue operations by units of the State Emergency Service of the Ministry of Internal Affairs of Ukraine and the State Militarized Mining and Rescue Service. The performance of emergency and rescue work at fires and liquidation of accidents requires the personnel of the Operational and Rescue Service of the Emergency Situations of Emergency Situations to respond quickly to emergency situations, make effective technical decisions, high professionalism and is associated with high physical and psychoemotional stress on the body of the firefighter-rescuer. The training of firefighters and rescuers to carry out rescue operations in conditions of ergothermic loads is a professional necessity in the conditions of a real fire and liquidation of the consequences of missile and bomb attacks as a result of the aggression of the occupiers on the infrastructure of Ukraine.

The main components of the heat balance, on which the duration of a person's work depends, are the internal energy produced by his body - the heat production of the firefighter's body, which in turn depends on the amount of energy consumption, and external energy that penetrates from the outside. At the same time, external energy is, as a rule, a factor independent of a person, while internal energy depends on many parameters. The works of fire safety specialists, in which the influence of various types of performed operations and the conditions of their execution, are devoted to the study of the energy consumption of the body of firefighters and mine rescuers.

Analysis of recent achievements and publications. The authors considered the problems of heat protection of firefighters and rescuers (Bolibrukh B.V., 2017). Determination of the maximum working time of a firefighter in heat-protective clothing based on a three-dimensional model, (Bolibrukh B.V. et al., 2019). Complex influence of dangerous and harmful factors on the firefighter-rescuer (Lusch V. I. et al., 2020). The method of conducting practical classes in a multi-functional simulator of the container type.

Therefore, the goal is to conduct experimental studies of energy consumption and thermal state of the body of firefighters in protective clothing during emergency rescue operations.

Setting the problem and solving it. Для вирішення поставленої мети, а саме: проведення експериментальних досліджень енерговитрат і теплового стану організму пожежників в захисному одязі при виконанні аварійно-рятувальних робіт.

For this purpose, an increase in heart rate up to 150 min^{-1} is accepted as a criterion for acceptable physical exertion.

The following types of exercises were chosen for research [12]:

- walking slowly on a horizontal surface at a speed of (3.0 ... 3.5) km / h;
- walking accelerated on a horizontal surface at a speed of (4.0 ... 4.5) km / h;
- walking quickly on a horizontal surface at a speed of (5.0 ... 5.5) km / h;
- accelerated running on a horizontal surface at a speed of (6.5 ... 7.5) km/h;
- horizontal movement at a passage height of 1.5 m;
- crawling on the knees.

The research was carried out with the participation of firefighters and gas and smoke protection officers who have experience in working in oxygen-insulating gas masks and conducting fire-rescue operations [3].

A total of seven firefighters were selected for permanent participation in the research, who differed from each other in anthropological and physiological indicators, age and experience of work in the fire and rescue service.

Presentation of the main material of the study with a full justification of the obtained results. The main components of the heat balance, on which the duration of a person's work depends, are the internal energy produced by his body - the heat production F_{ch}, which in turn depends on the energy consumption F_m, and the external energy that penetrates from the outside. At the same time, external energy is, as a rule, a factor independent of a person, while internal energy depends on many parameters.

Works, in which the influence of various types of performed operations and the conditions of their execution, are devoted to the study of the energy consumption of the body of mining rescue workers.

In this regard, the purpose of the research is to determine the dependence of the energy expenditure of the body of firefighters on the type and conditions of fire-rescue work [1].

The following parameters are accepted as variables: weight of cargo, speed of movement, height of passage of the covered section, angle of inclination and direction of movement (up or down). The "Running Bridge" and "Endless Stairs" stands of the thermal complex, as well as the "Respirator" research and experimental training ground of the NDIGS, which allow to vary the listed parameters, were used for the tests.

In the process of performing the exercises, timekeeping was carried out, and the determination of energy consumption was carried out during physiological studies of the gas exchange of the tester's body, taking into account the variety of possible types of work of different intensity when extinguishing fires and rescuing people.

Before conducting research, subjects were asked about their well-being, weighed, their growth and vital capacity of the lungs were measured, and physical performance was assessed using the Harvard Step Test.

The study was conducted in the morning (1.5...2.0) hours after eating in order to eliminate the specific dynamic effect of its intake.

After (15...20) minutes of rest, physiological parameters were measured (oxygen consumption, carbon dioxide excretion, pulmonary ventilation, respiratory rate, heart rate, and blood pressure.

After that, the tester put on overalls, a gas mask (without being included in it) and performed exercises. The duration of the exercises was 10 minutes or the time required to climb the stairs. Studies of climbing stairs at an angle of 45 and 65º were carried out on the "Endless Stairs" stand, on which the required angle of ascent was set before the start of the experiment. The speed of movement was selected by the method of preliminary tests with the participation of the tester.

The study of energy consumption when moving along a belt and carrying a load on a horizontal surface and at an angle was carried out at the "Moving Track" stand. Before each test, the required speed of the belt was set, after which the tester started moving.

During the exercise, samples of exhaled air were taken for the study of gas exchange and the frequency of breathing was determined. After the exercise, at the beginning and the next exercise, heart rate was determined.

During one day, 3-4 experiments were conducted, which were repeated after 20 ... 50 minutes, after the full recovery of physiological indicators.

Gas exchange studies of testers were carried out while breathing through a breathing system, which consists of corrugated hoses, a valve box and a mask. The exhalation hose was connected to a modernized gas meter of the company „Medy", equipped with a summing device, which allows determining the volume of pulmonary ventilation for any period of time during the experience. From the gas meter, air entered the breathing bag.

In order to simulate the conditions of breathing in oxygen masks, the inhalation hose was equipped with a special diaphragm, which together with the hose creates the appropriate resistance to breathing [4].

To study the effect on the respiratory organs in the gas mask, a volume meter was installed in the exhalation hose, which allows determining the minute volume of breath, and samples of exhaled air were taken through a fitting into a Douglas bag attached to the exhalation hose.

Air samples were analyzed using an Ors gas analyzer and gas clocks. The content of oxygen and carbon dioxide was determined.

According to these data, gas exchange (oxygen consumption) was calculated on the basis of known methods, and through the calorimetric equivalent - the tester's energy consumption.

All obtained experimental data were grouped according to research tasks and subjected to processing by mathematical statistics methods to determine average values and their estimates.

The main goal of research into the thermal state of the body of firefighters in insulating clothing is to determine the main value of the parameter of its technical characteristics - the time of protective action (duration of work) when performing the given types of work and the corresponding temperature and climatic conditions, as well as the confirmation of this parameter obtained as a result of theoretical studies.

The tests were carried out in a thermal chamber and at the research and experimental training ground of the NDIGS "Respirator", the equipment and apparatus of which are certified, with the participation of three volunteer firefighter testers aged 25 to 40 with at least 3 years of work experience who participated in firefighting. In the thermal chamber, the duration of work was determined under the influence of, mainly, the temperature of the surrounding air, on the test site - the thermal radiant flow from the fire flame.

The protective clothing consisted of an outer suit with heat-resistant and heat-reflective material, manufactured by the "Index" enterprise, and an inner suit - with a water-ice cooling system - NDIGS "Respirator", as well as using ice on the upper surface of the hands, in the insoles of the feet and without a cooling system. that is, only from the "Index-1" suit. An RS-type respirator, which is on the equipment of fire and rescue service units, was used as a breathing apparatus.

In the thermal chamber, the research was carried out at an ambient air temperature of (100±1) °C and a relative humidity of (98±2) %. Before the tests in the thermal chamber and on the training ground, the firefighters underwent a medical examination and received the conclusion "Suitable for participation in the tests of individual heat protection equipment", studied the conditions of the tests and learned how to work in clothes.

The mass of testers and clothes on medical scales, the effect of clothes on the mobility of the firefighter in optimal microclimatic conditions according to self-assessment by the testers in terms of limitation of movements when walking, bending of the body, squatting, raising and moving to the side of arms and legs, their rotation, squatting and bending were determined in advance.

In laboratory conditions, testers were fitted with thermometers that fit tightly to the outer surface of clothing, with a maximum scale of 473 K (200°C) and temperature sensors in the undersuit space in the areas of: forehead, chest, forearm, lower leg, foot, and hand [5].

In order to determine the effectiveness of the suit's protection against thermal radiant flux during a fire, tests were conducted at an experimental training ground. As a bonfire, wooden beams were used, laid in a checkerboard pattern along the perimeter with an area of 16 m^2 and a height of 2 m. At a height of 2.2 m from the surface, two thermocouples were fixed to measure the temperature of burning wood using a potentiometer of the MPSHr type, which is graduated to the maximum temperature one thousand seven hundred and seventy-three K (1500 °C).

Measurements of the temperature of the dressing space and heart rate were carried out with the help of sensors and equipment similar to those used in studies in a thermal chamber. To measure the temperature of the outer surface of the suit, a thermometer with a maximum scale of 1000 °C, fixed in the chest area, was used.

Results and discussions

The results of studies of energy consumption $Q_м$, Wt, firefighters when moving on a horizontal surface in full height depending on the speed of movement $V_д$, m/min, oxygen consumption, q_r, l/min, in regular equipment without additional load, with a load weighing 30 kg and when carrying victims on stretchers are given in the table. 1 [8].

Table 1. Experimental results of firemen's energy consumption when moving on a horizontal surface in full height

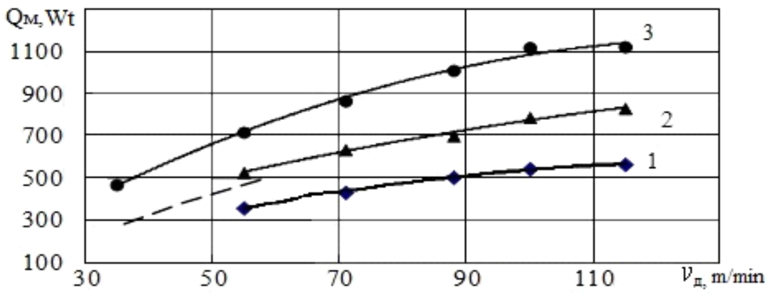
$v_д$ m/min	Without cargo		With cargo 30 kg		Carrying the victim	
	q_r, l/ min	$Q_м$, Wt	q_r, l/ min	$Q_м$, Wt	q_r, l/ min	$Q_м$, Wt
35	–	–	–	–	1,44±0,21	467,3
55	1,10±0,04	357,1	1,62±0,14	525,4	2,21±0,19	716,8
71	1,33±0,06	431,4	1,96±0,17	634,3	2,67±0,23	865,4
88	1,55±0,07	503,3	2,16±0,16	700,2	3,11±0,23	1010,0
100	1,67±0,06	543,6	2,43±0,19	787,4	3,45±0,20	1118,6
115	1,74±0,05	564,3	2,56±0,21	830,2	3,46±0,22	1122,4

Energy expenditure was determined according to a known dependence

$$Q_м = 324.5\, q_r . \qquad (1)$$

At the same time, they believed, as for rescuers, that the degree of severity of firemen's work is determined by the following change in the range of energy consumption: 160 Wt (rest in a respirator) - light; more than 160 to 320 Wt - average; more than 320 to 480 - heavy; more than 480 Wt - very heavy.

According to the table 1 approximating dependencies (pic. 1) are obtained from the data, which are described by equations (2) (3) (4).



Pic. 1. Dependence of energy expenditure of members of fire protection units on the speed of movement on a horizontal surface in full height: 1 - in equipment without additional cargo; 2 - with a load of 30 kg; 3 - transfer of the victim; 4 - for rescuers without additional cargo

$$Q_м\,(1) = -\,0{,}0356\, v^2_д + 9{,}59\, v_д - 65{,}14; \qquad (2)$$
$$Q_м\,(2) = -\,0{,}0242\, v^2_д + 9{,}22\, v_д + 93{,}39; \qquad (3)$$
$$Q_м\,(3) = -\,0{,}0722\, v^2_д + 19{,}31\, v_д - 125{,}09. \qquad (4)$$

The equations show that there is a slight non-linearity of the dependence of the energy consumption of firefighters on the speed of movement without a load and with a load of 30 kg, which is confirmed by the calculation results, significant - when moving with the victim, and their values vary from 360 to 1150 Wt. Such energy expenditure belongs to the categories of "heavy" and "very heavy" physical load. At the same time, the ratio of the energy consumption of mining rescuers (dashed line 4) to the energy consumption of firefighters in the specified range when moving, in particular, without additional cargo, is equal to 1.43.

The results of studies of the energy consumption of firefighters when moving along a passage with a limited height are shown in the table 2, and the resulting dependencies are presented in pic. 2. When drawing diagrams on it, the abscissa is taken as the relative height Ho, calculated by the formula

$$H_0 = h_2 / H_{max}, \quad (5)$$

Where: h_2, H_{max} – real and maximum height of passage, m.

Table 2. Experimental data of movement speed, consumption oxygen and energy consumption of firefighters at different height of the passage

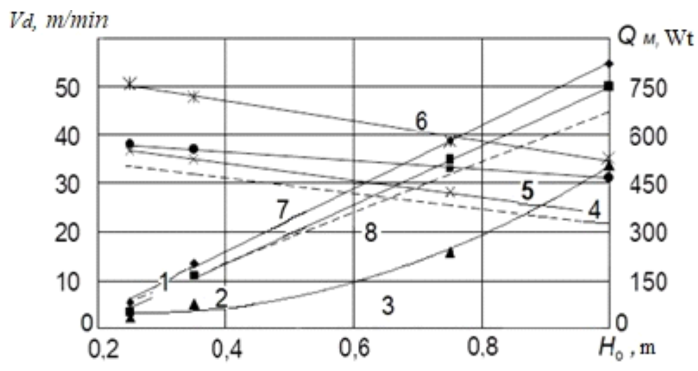
Height, H_{max}, m	Movement speed, $v_д$, m/min			Oxygen consumption q_r l/min			Energy consumption, $Q_м$, Wt		
	Without cargo	With cargo 30 kg	Carrying the victim	Without cargo	With cargo 30 kg	Carrying the victim	Without cargo	With cargo 30 kg	Carrying the victim
2.0	55.0	50.0	35.0	1.10	1.64	1.44	357.0	531.4	467.0
1.5	39.4	35.4	15.9	1.30	1.79	1.55	422.8	581.3	502.2
0.7	13.5	11.2	5.2	1.62	2.22	1.71	524.0	719.2	555.9
0.5	5.5	3.7	2.4	1.71	2.35	1,76	554.8	762.2	572.3

At the same time, it is assumed that H_{max} = 2 m, and its further increase practically does not affect the speed of movement and energy consumption of firefighters.

In pic. 2 points reflect experimental data, and curves – approximating equations selected from these points.

As a result of the approximation, the following dependences were obtained for the speed of movement and energy consumption:

$$v_д\,(1) = 65{,}315\ H_o - 10{,}123; \quad (6)$$
$$v_д\,(2) = 61{,}066\ H_o - 10{,}902; \quad (7)$$
$$v_д\,(3) = 60{,}975\ H^2_o - 34{,}757\ H_o + 8{,}4688; \quad (8)$$
$$Q_м\,(1) = -260{,}95\ H_o + 617{,}97; \quad (9)$$
$$Q_м\,(2) = -312{,}24\ H_o + 831{,}87; \quad (10)$$
$$Q_м\,(3) = -138{,}84\ H_o + 605{,}91. \quad (11)$$



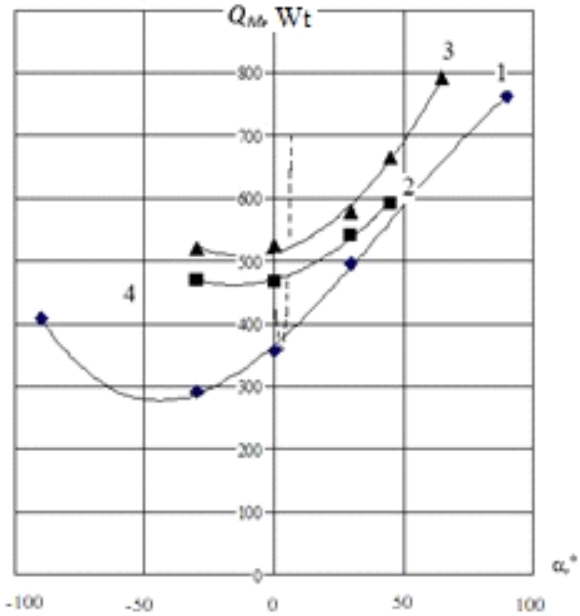
Pic. 2. Dependencies of movement speed (1-3) and energy consumption of firefighters (4-6) on the relative height of the passage of the area to be overcome 1, 4 – without cargo; 2, 6 – with a load of 30 kg; 3, 5 – when carrying the victim on a stretcher; 7, 8 – according to data for rescuers (without additional cargo)

The results of research on determining the energy consumption of firefighters when moving on stairs located at different angles are shown in table. 3. at the same time, it is accepted that the movement down is carried out at a negative angle, and up – at a positive angle.

Based on the data given in table 2 obtained dependencies shown in pic. 3. As before, the experimental data are marked by points, and the curves reflect the approximation results, which are described by the following equations:

Table 3. Energy consumption of firefighters when climbing a ladder

Angle, α^o	Without cargo		With cargo 30 kg		Carrying the victim	
	q_r, l/min	$Q_м$, Wt	q_r, l/min	$Q_м$, Wt	q_r, l/min	$Q_м$, Wt
– 90	1,26±0,14	408,6	–	–	–	–
– 30	0,90±0,13	291,9	1,60±0,15	520,0	1,45±0,13	470,2
0	1,10±0,15	357,0	1,62±0,14	525,3	1,44±0,15	467,0
30	1,53±0,13	496,2	1,78±0,14	577,2	1,67±0,15	541,6
45	–	–	2,05±0,16	664,3	1,83±0,16	592,4
65	–	–	2,45±0,13	794,4	–	–
90	2,35±0,15	762,1	–	–	–	–



Pic. 3. Dependence of the energy consumption of firefighters when moving on the angle of the inclined surface:1 – without cargo; 2 – when carrying the victim on a stretcher; 3 –– with a load of 30 kg, 4 – for rescuers without a load

$$Q_м(1) = -0,00002\,\alpha^3 + 0,027\,\alpha^2 + 3,585\,\alpha + 364,94; \quad (12)$$

$$Q_м(2) = 0,0366\,\alpha^2 + 1,126\,\alpha + 470,15; \quad (13)$$

$$Q_м(3) = 0,049\,\alpha^2 + 1,1035\,\alpha + 513,05. \quad (14)$$

It follows from this that energy consumption is nonlinearly related to the angle of inclination of the stairs, and the largest nonlinearity corresponds to movement without additional load.

The behavior of the curves also shows that they all have a region of minimum, and it corresponds to negative angles, and the higher the load, the more this angle tends to the horizontal.

Obviously, this can be explained by the fact that when descending the stairs, the force caused by the body weight of the firefighter in the equipment initially facilitates movement, but when the angle of inclination exceeds certain values, additional energy has to be spent to ensure balance.

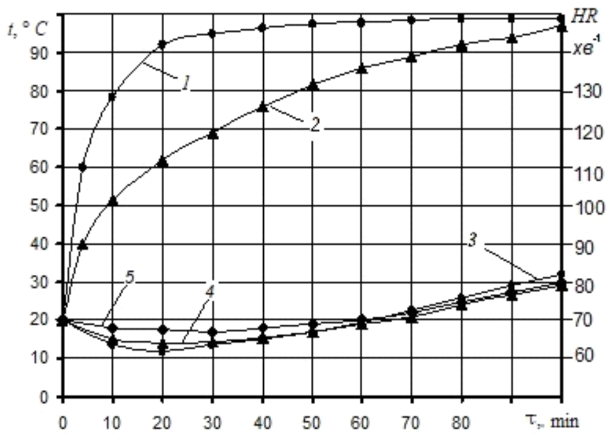
Energy expenditure varies mainly in the range of more than 320 to 800 Wt, which belongs to the category of physical load as "heavy" and "very heavy". The ratio of the energy consumption of mountain rescuers (dashed line 4) to the energy consumption of firefighters, in particular, when moving up without additional load, is equal to 1.13, down - 1.45 at $\alpha = 60°$.

The resulting equations (12-15) make it possible to determine the energy consumption of members of the firemen's units depending on the individual parameters mentioned above. Taking into account the two most characteristic fire parameters: the speed of movement and the mass of the transported cargo in m_c, kg, the dependence that approximates the energy consumption of F_m with a maximum relative error of 4% has the form

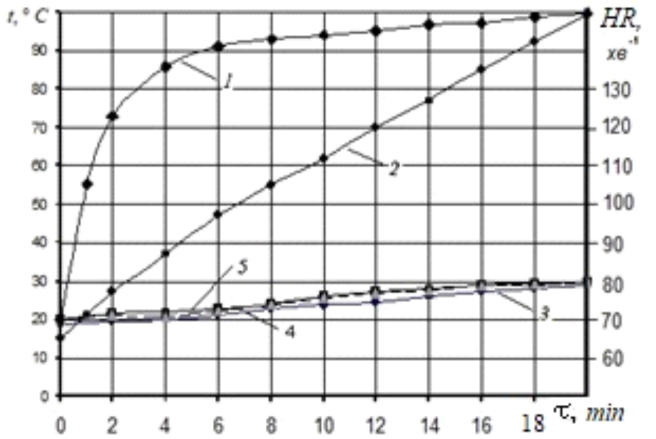
$$Q_м = 9,9733v_д – 0,0451v_д^2 – 19,2152m_c + 0,5188\, m_c^2 + 0,1077v_д\, m_c + 24,0896. \quad (15)$$

Based on the above dependencies, a program has been compiled that allows you to determine the energy load on members of the fire and rescue service units when planning various routes on training grounds, conducting fire and rescue operations, including extinguishing fires, and also allows you to conduct research on the thermal balance in protective clothing, while ensuring efficiency of work and firefighter safety.

As a result of research conducted in a thermal chamber, at an ambient temperature of (100±1) °C, the protective clothing of firefighters, consisting of a heat-resistant and heat-reflective outer suit with a water-ice cooling system, including additional cooling of hands and feet legs, as well as without a cooling system (one outer suit), the obtained time dependences of the temperature of the outer surface, the wearable space, and the heart rate are shown in pic. 4 and 5. At the same time, in connection with the uniform distribution of cooling element (CE-2) in the area of the main part of the body of firefighters, the temperatures of the under-clothing space in these places are almost equal, therefore the results are given in the form of one curve, and for heart rate (HR) - their maximum values when performing exercises in a thermal chamber excluding rest [7].



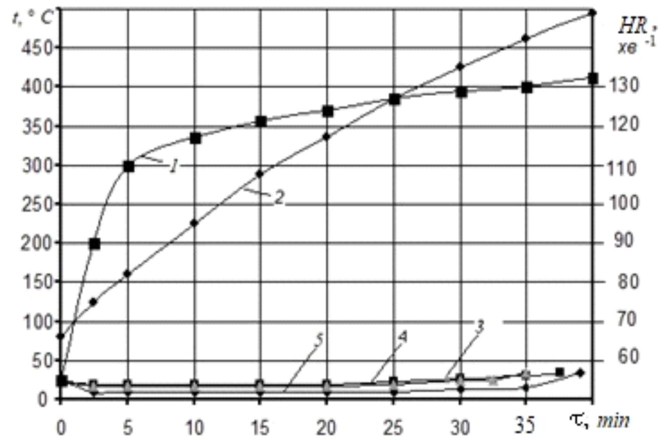
Pic. 4. Results of experimental studies of temperature dynamics on the outer surface (1), in the under-clothing space in the area of the main part of the body (3), hands (4), feet (5) and heart rate (HR) (2) in a suit with a cooling system.



Pic. 5. Results of experimental studies of temperature dynamics on the outer surface (1), in the space under the suit in the area of the head (3), hands (4), feet (5) and heart rate (2) in a suit without cooling

The obtained results show that, taking into account the sanitary norm of temperature in the under-clothing space of about 30 °C, the permissible duration of work of firefighters in clothing with a cooling system is about 5 times higher than without it, and this fact is confirmed by the value of the heart rate, which is equal to about 150 min^{-1}, and the temperature in the area of hands and feet with additional ice cooling is lower than in the rest of the firefighter's body and, conversely, in clothes without this cooling.

The results of experimental studies of firemen's protective clothing with a similar cooling system under the influence of thermal radiant flow from the fire source are shown in pic. 6.



Pic. 6. Results of experimental studies of temperature dynamics on the outer surface (1), in the undersuit space of the main part of the body (3), hands (4), feet (5) and heart rate (2) of firefighters in a suit with a cooling system under the influence of thermal radiant flux from the fire source of 5 kWt / m^2

A list of the main factors that affect the accumulation of heat in the body of a firefighter with an indication of the real range of changes in their values in a practical environment and the number of experiments that must be performed to study the influence of each factor regardless of the values of others is given in the table. 4.

To solve the given task experimentally according to the table. 7 it would be necessary to conduct 5184 unit experiments. However, even such a large volume of work would not give statistically reliable results. To take into account the individual differences of testers, each experience must be repeated on several testers with the same initial parameters.

Table 4. The main initial parameters of the heat exchange process between the firefighter's body and environment

Parameter name	Parameter measurement range	The number of experiment options
Air temperature, ^0C	25 – 70	6
Relative humidity, %	40 – 100	3
Air speed, m/s	0 – 15	3
Thermal radiant flow, kWt/m^2	1,2 – 4,1	3
Physical load, energy consumption, Wt	160 – 800	2
Thermal resistance of clothing, KLO	1,0 – 1,5	2
Heat removal due to breathing in a respirator, Wt	15 – 30	2
Initial mean body temperature (WBT), ^0C	35 – 36	2
The difference between the temperature of the surface of the room (underground structures) and the air, ^0C	0 – 20	2

To ensure the necessary statistical reliability of the results of the experiments, each experience should be repeated six times, that is, conducted on six testers. In this case, the total number of experiments would be 31104, which is practically impossible to do. In this regard, some less important parameters, the number of options and parallel experiments are usually excluded from research, thereby reducing the statistical reliability of the results, and in this way, the required number of experiments is reduced by one or two orders of magnitude. However, even in this case, the amount of experimental research is quite time-consuming and requires a lot of time and money to implement [9].

Therefore, to solve this problem, another way was adopted - mathematical modeling of the process of heat exchange between the body of the firefighter and the surrounding environment, taking into account all the parameters listed in the table. 7, a compiled program with the possibility of its adjustment based on experimental data. In this case, it became possible to significantly reduce the required number of individual experiments with the participation of people, conducting them at the most characteristic, nodal values of the initial parameters. In addition, and what is especially important, it is advisable to fully use the results of experimental studies previously conducted at the Respirator National Research Institute and abroad in the analysis.

The correctness and legality of the calculation results based on the refined mathematical model was checked based on the results of three series of experiments performed by us and the works of the Institute of Mining Rescue in Germany.

The calculation of PTR according to the refined and (for comparison) according to the existing mathematical models was carried out for the following separate initial data during fire-rescue operations by firefighters in non-insulated clothing: relative air humidity - 100%, air movement speed - 0.1 m/s, human energy consumption - 320 W, human efficiency – 0,2, the difference between the temperature of the air and the surface of the room (underground structures) is 0 °C, the weight and height of a person, respectively - 70 kg and 170 cm, heat dissipation by the cost of breathing in a respirator with chemically bound oxygen is 30 W. Comparative data of this calculation are given in table. 5.

Table 5. Results of calculation of PTR, min, according to existing and refined mathematical models

The name of the mathematical model	Ambient air temperature, ^0C					
	27	30	35	40	45	50
Existing	240	99,3	39,6	23,2	15,5	11,2
Clarified	152,8	68,9	33,7	21,0	14,5	10,6

Table 6. Comparative results of the safe duration of work of testers during experimental ones researches of the Institute of Mining Rescue of the Federal Republic of Germany and calculations based on a refined mathematical model

Results of experiments			Results of calculations based on the refined model, min
Temperature and humidity index WD, ^0C	Number of experiments (total 223)	Average duration of work, min	
29,00	–	–	115,2
29,75	20	110	94,4
30,50	25	76	79,7
31,05	26	65	71,3
34,40	37	44	42,5
37,35	40	30	30,4
40,05	28	23	23,6
43,20	25	18	18,4
46,50	22	15	14,6
50,00	–	–	11,7

It should be noted that a direct comparison of the data of the institute of Germany and domestic ones on acceptable duration of work (ADW) is illegal. According to domestic standards, we have two criteria: permissible (DPR) and limit (GPR), the duration of each of which is determined by two types of body temperature, namely internal body temperature (IBT) and average body temperature (ABT). Researchers of the German institute use one criterion as the ADW, which they called the maximum duration of work, determined by the value of IBT, equal to 38.5°C, which is between the domestic values of IBT for DPR (38.0°C) and PPR (38.7°C). At the same time, there are no data in the works about the initial VTT of the testers and the dynamics of its change during the experiments, but these data provide an opportunity for comparison with the calculated results of the refined mathematical model.

As you know, in similar experimental studies in the dynamics of heat accumulation of the human body, the level of IBT is always higher than ABT and the difference between them is 0.5-0.8°C. Based on the logical assumption that the dynamics of changes in IBT and ABT in the experiments are the same, we determined an equivalent increase in ABT, which causes an increase in IBT to 38.5 °C. By linear interpolation of the data in the table. 3.9 for air temperatures of 30 and 40°C, the obtained increase in ABT is equal to 2.3°C. Using this criterion, a calculation was made according to a refined mathematical model of the predicted maximum (according to the terminology adopted in Germany) duration of work at eight values of this index from 29 to 50.

A comparison of the results (table 6) shows that a satisfactory match is obtained, because the maximum error at WD = 29.75 °C is about 14%. Analyzing the results, it should be noted that in the air temperature range of 30 °C and below, the ADW changes very quickly when the temperature increases by tenths of a degree. According to the data of the Institute of Germany, with an increase in the Wd index by 0.75 °C (from 29.75 to 30.5 °C), the duration of work decreased by 34 minutes, and according to the calculation results of the refined model

- by 14.7 minutes. Obviously, the value of 110 min here is unjustified, because in the work tables for use in practice, the authors previously accepted a working duration of 95 min for a temperature of 30°C.

A comparison of the experimental research data of the Institute of Germany and the calculation results based on the refined mathematical model (see table 6) confirms the correctness of the developed mathematical model.

And finally, a control series of six experiments was performed with the participation of three professional firefighters.

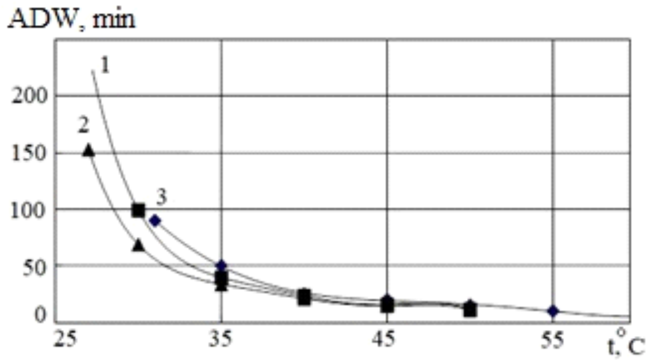
The research methodology was basically similar to the above. The actual energy load was additionally specified by analyzing the chemical absorption of the respirator before and after the experiment, with the subsequent calculation of the amount of absorbed carbon dioxide and the corresponding energy consumption. They turned out to be equal to (380...420) Wt. Actual energy expenditure was calculated for each of the three subjects according to their body weight by linear interpolation, starting from a baseline of 70 kg body weight, energy expenditure equal to 356 Wt.

As it follows from the results of this control study, despite the small number of experiments, with a maximum error of 12.4%, they confirm the possibility of using a refined mathematical model of the heat balance of a firefighter in non-insulated clothing and developing a calculation program based on it [10].

Comparative results of calculation of ADW based on the existing and refined mathematical models of the heat balance of mining rescuers, as well as data of DPR of firefighters in non-insulated clothing at a relative humidity of 100% and an average load depending on the ambient temperature, are shown in pic. 7.

It follows that the ADW values obtained according to the refined mathematical model, in comparison with the results of calculation according to the existing mathematical model for temperatures of 27, 30, and 35 °C, are less by approximately 1.6, 1.5, and 1.2 times, respectively. At the same time, the normative data of ADW for firefighters compared to the results of calculations based on a refined mathematical model for temperatures of 31 and 35 °C are 1.5 and 1.2 times higher, respectively, which can lead to heat damage to their bodies. As a last resort, fire and rescue units should be equipped with means for emergency cooling of firefighters in case of overheating.

On the basis of the above research results, an algorithm was developed and a program was developed for calculating the safe duration of work of firefighters in non-insulated protective clothing, which are given in the previous article.



Pic. 7. Comparative results of calculating the permissible duration of work of rescuers (1, 2) and firemen (3) depending on the ambient temperature at a relative humidity of 100% and an average load: 1 – according to the existing mathematical model; 2 – according to a refined mathematical model; 3 – according to experimental data for firefighters.

Based on the obtained data, we can draw the following conclusions.

Conclusions. The following conclusions can be drawn:

• On the basis of the results of the above studies, algorithms were developed and programs "Thermoextreme-1" and "Thermoextreme-2" were developed for calculating the safe duration of work of firefighters in insulating clothing with and without a cooling system, respectively, as well as substantiated designs and technical characteristics of heat-resistant suits for fire departments.

• From this it follows that the permissible duration of work when calculating according to the existing mathematical model in comparison with the calculation according to the refined model at an ambient air temperature of 27°C exceeds by more than 1.6 times, at 30°C - by 1.5 times, and at 35°C - about 1.2 times.

• The results of calculating the acceptable duration of work according to the developed mathematical model with a confidence probability of statistical processing of experimental data equal to 0.95, in comparison with experimental data obtained in Germany, are shown in the table. 6.

• The research results were obtained for the following initial data: air movement speed - 0.4 m/s, energy consumption - 315 Wt, human efficiency - 0.2, thermal resistance of overalls - 1.0 KLO, increase in average human body temperature (up to achieving in experiments the level of internal body temperature - 38.5°C) - 2.3°C, the respirator removes 15 Wt of heat from the body.

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ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ЕНЕРГОВИТРАТ І ТЕПЛОВОГО СТАНУ ОРГАНІЗМУ ПОЖЕЖНИКІВ В ЗАХИСНОМУ ОДЯЗІ

В Україні на виробництві або при проведенні аварійно-рятувальних робіт підрозділами ДСНС МВС України та Державної воєнізованої гірничо-рятувальної служби виникають екстремальні мікрокліматичні умови (підвищена температура, підвищена і понижена вологість, швидкість руху повітря, загазованість, задимлення).

Виконання аварійно-рятувальних робіт на пожежах та ліквідації аварій вимагає від особового складу Оперативно-рятувальної служби ДСНС швидкого реагування на аварійні ситуації, прийняття ефективних технічних рішень, високого професіоналізму та пов'язане з високими фізичними та психоемоційними навантаженнями на організм пожежника-рятівника.

Підготовка пожежників та рятувальників, для проведення рятувальних робіт в умовах ерготермічних навантажень, є професійною необхідністю в умовах реальної пожежі та ліквідації наслідків ракетно-бомбових ударів в результаті агресії окупантів по інфраструктурі України.

Дослідженням енерговитрат організму пожежників і гірничорятувальників присвячені роботи фахівців пожежної безпеки, в яких проаналізовано вплив різних видів виконуваних операцій і умов їх виконання.

У статті досліджено результати експериментальних досліджень енергоспоживання та теплового стану організму пожежників у захисному одязі.

Основними складовими теплового балансу, від яких залежить тривалість роботи людини, є внутрішня енергія, що виробляється її організмом - теплопродукція організму пожежника, яка в свою чергу залежить від величини витрат енергії, і зовнішня енергія, яка проникає ззовні. При цьому зовнішня енергія, як правило, незалежний від людини фактор, а внутрішня енергія залежить від багатьох параметрів.

Ключові слова: *захисний одяг, тепловий стан, пожежний-рятувальник, температура, навчання, степ-тест.*