International Journal of Occupational Safety and Ergonomics

ISSN: 1080-3548 (Print) 2376-9130 (Online) Journal homepage: https://www.tandfonline.com/loi/tose20

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To cite this article: Anna Marszałek, Grażyna Bartkowiak, Anna Dąbrowska, Sylwia Krzemińska, Krzysztof Łężak, Krzysztof Makowski & Joanna Bugajska (2018) Mine rescuers' heat load during the expenditure of physical effort in a hot environment, using ventilated underwear and selected breathing apparatus, International Journal of Occupational Safety and Ergonomics, 24:1, 1-13, DOI: 10.1080/10803548.2017.1335971

To link to this article: https://doi.org/10.1080/10803548.2017.1335971

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Published online: 07 Aug 2017.

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International Journal of Occupational Safety and Ergonomics (JOSE), 2018
Vol. 24, No. 1, 1–13, https://doi.org/10.1080/10803548.2017.1335971

Mine rescuers' heat load during the expenditure of physical effort in a hot environment, using ventilated underwear and selected breathing apparatus

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Mine rescuers' heat load under the same physical effort load (25% of the maximal oxygen uptake), using three types of breathing apparatus, in newly developed heat-removing underwear and outerwear was assessed for typical work conditions of mine rescuers, under milder and harsher ambient conditions of 32 and 38 °C, respectively, both at relative humidity of 85% and air velocity of 1.0 m/s. Expending physical effort at the same load while using different kinds of breathing apparatus resulted in a similar heat load. Under both milder and harsher ambient conditions, heat storage and sweating intensity were greater than the average limit value recommended by hygienic standards, which indicates that the use of breathing apparatus significantly hinders heat exchange with the environment. The developed clothing for mine rescuers was highly rated, and was considered by most people to be better than that used currently.

Keywords: mine rescuers; heat load; ventilated underwear; protective clothing; breathing apparatus

1. Introduction

Mine rescuers' work is carried out under very difficult climatic conditions, and involves great physical effort.

After the revision to the Regulation of the Minister of Environment of 29 January 2013 [1], the main criterion for the assessment of a climatic hazard in coal mines is the occurrence of a climate substitute temperature higher than 26 °C at the workstation. The air temperature during the performance of mining work should not exceed 28 °C at a cooling intensity of less than 11 wet kata degrees [2].The work can then be performed on a full-time basis. In accordance with the aforementioned regulation, within the temperature range of 28–33 °C and at the same cooling intensity, technical measures should be taken in order to reduce the air temperature, otherwise the working time must be reduced to 6 h. Under even harsher conditions, when the air temperature measured with a dry-bulb thermometer exceeds 33 °C, people can only be hired for rescue operations.

An analysis of hazards faced by mine rescuers and their working conditions during the performance of rescue operations [3] indicates that the second cause of rescuers' fatal accidents, following thermal burns of large areas of the body and of the respiratory tract, is the difficult microclimate conditions which result in overheating of rescuers' bodies and death from heat stroke, accounting for 26% of the total number of deaths [4].

Apart from the air temperature, which at many locations in coal mines exceeds 30 °C, the occurrence of high air humidity changing within the range of 70–100% also makes working conditions more difficult [5].

In the hot environment which is found in coal mines, during the performance of work with varying intensity, heat which not only originates from the environment but also from work being carried out accumulates in the exposed person's body [6,7]. In order to prevent the body from overheating, conditions should be ensured for effective heat exchange between the body and the environment. Under working conditions in coal mines this is often impossible, particularly for mine rescuers who bring help to the injured. Typically they wear clothing protecting against heat and flame, and are equipped with rescue equipment weighing approximately 25.0 kg. These determinants significantly contribute to the obstruction of heat release from the rescuer's body. In addition, due to the presence of toxic gases, rescuers are required to use respiratory protective equipment, which adds approximately 15.0 kg of equipment to be carried, mainly on their backs. In many rescue operations, it is also necessary to transport the injured on stretchers, which provides an additional weight of 45.0–50.0 kg/person [4]. Because they are carrying equipment and people of considerable weight, and moving in rough terrain, the level of effort is very high, which contributes to the generation and storage of heat in the rescuer's body.

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In recent years, attempts have been made to develop clothing for mine rescuers which would improve the removal of heat from the surface of their skin. A set of protective clothing and underwear with an air ventilation system has been developed, which aims to transfer heat from the surface of the skin in order to facilitate its release to the environment, and, consequently, to facilitate the evaporation of sweat from the skin. This article presents results of tests on this set of clothing with three types of standard breathing apparatus used in rescue operations under conditions of lower and higher heat stress caused by the air temperature. The developed clothing was assessed based on a survey.

2. Protective underwear and clothing for mine rescuers

Given the risks faced by a mine rescuer during a rescue operation, mine rescuers' protective clothing and underwear should ensure protection against ignition and static electricity, as well as minimize the effects of body overheating resulting from the climatic hazard. This means that these articles should meet essential requirements of Directive 89/686/EEC [8] on personal protective equipment and relevant standards harmonized with it, namely Standard No. EN ISO 11612:2015 [9] and Standard No. EN 1149-5:2008 [10].

2.1. Underwear with a ventilation system

The developed underwear was made from a knitted fabric with the following composition: 90% Lenzing FR, 8% para-aramid and 2% antistatic fibre. The underwear is in the form of a T-shirt with an air ventilation system, which enables the release of excess heat from the underclothing microclimate. In the back part of the underwear, from the height of the waist line up to the shoulder blade line, five vertical channels have been formed by crimping the fabric, in which polyurethane tubes at graduated heights have been permanently placed. The tubes are connected via a three-way coupling with a horizontal air-distributing tube placed in a tunnel and led outside the underwear through a hole located on the side of the T-shirt. The air-distributing tube is connected to a self-contained breathing apparatus which is the source of cooled air. Where closed-circuit oxygen breathing apparatus is used, the underwear is connected to and supplied from an additional compressed air cylinder. The appearance of the developed underwear with a ventilation system is shown in Figure 1, and a diagram showing the connection of the air supply system to the underwear is presented in Figure 2.

The system for supplying air to the underwear is equipped with a ventilation function, and has been installed in positive pressure self-contained breathing apparatus adapted to be connected to two composite cylinders with a capacity of 9.0 dm^3 (Figure 2). The aforementioned self-contained breathing apparatus to be used as a respiratory protection device is designed for special applications during the performance of rescue operations in underground coal mines, and additionally offers the possibility for supplying air to the underwear at two air flow rates. This enables control of the efficiency and duration of cooling.

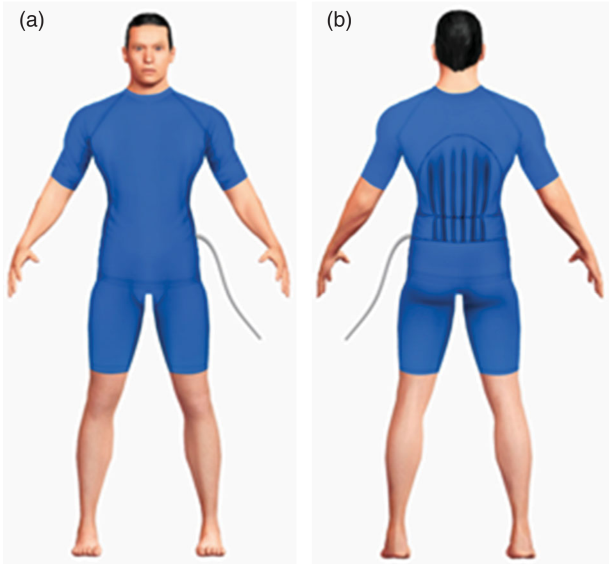

Figure 1. General appearance of cooling underwear with an air ventilation system: (a) front; (b) back.

2.2. Protective clothing

Under conditions of an increased risk of a fire or an explosion during a rescue operation, it is required that a rescuer also wears protective outerwear. Protective clothing for mine rescuers consists of a blouse and bib-and-brace trousers. The clothing is made of a woven fabric with the following composition: 93% meta-aramid fibres, 5% para-aramid fibres and 2% antistatic fibres. The essential feature of the developed clothing is the compatibility of its design with the equipment used by mine rescuers. Pockets located on the front of the blouse and on the sides of the trousers are specifically arranged to ensure convenient access to them (with account taken of the surfaces pressed down by the rescuer's additional equipment). In the back parts of the stand-up collar and on the back of the blouse, where the sleeves connect (below the stand-up collar), bags of knitted fabric mesh have been placed, which are filled with macrocapsules containing phase change materials (PCM) supporting thermoregulatory functions of the body. In addition, on the lateral side of the sleeve, along the torso and on the lateral side of the leg, vents have been incorporated in order to support the process of cooling the rescuer's body. The appearance of the developed protective clothing for mine rescuers is shown in Figure 3.

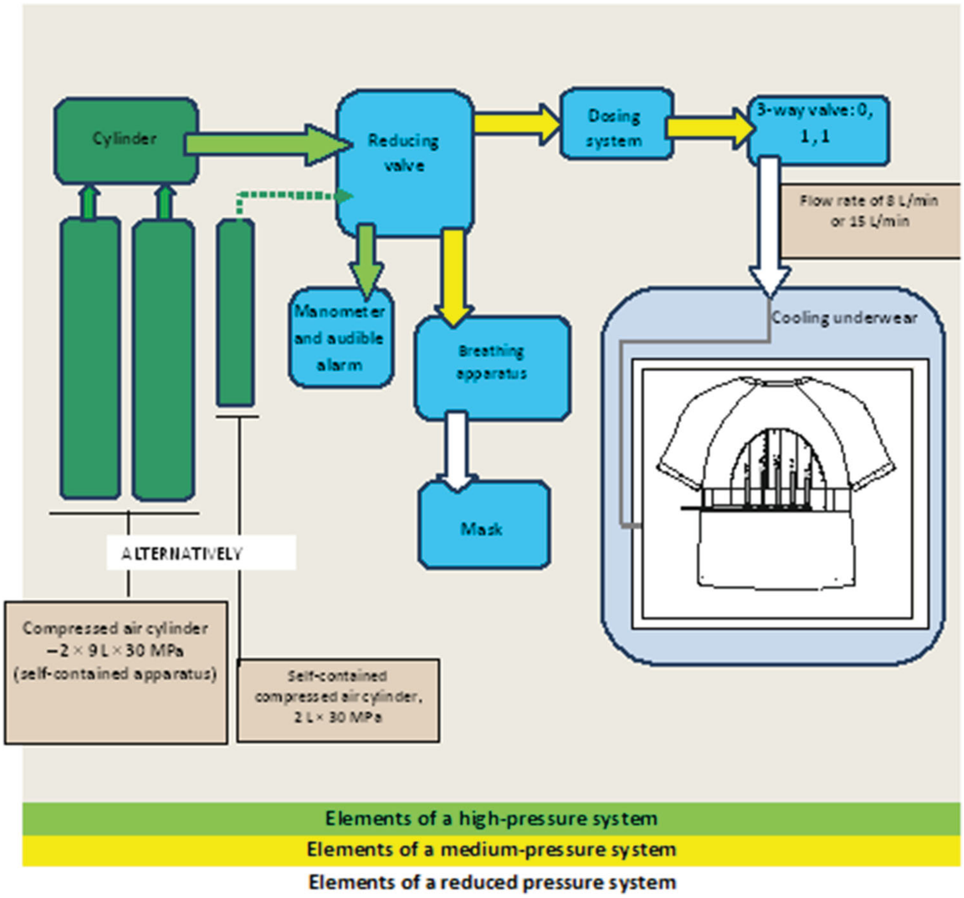

Figure 2. Diagram of the connection of the air supply system to the cooling system of the underwear.
Note: The full colour version of this figure is available online.

3. Methodology

3.1. Participants

Six mine rescuers aged 34.5 (± 6.2) years, with a body weight of 82.0 (± 4.8) kg and physical endurance of 48.2 (± 5.2) ml O_2/kg/min, participated in the study. The selection of participants for the study was preceded by qualification examinations comprising an enquiry concerning the current state of health, a physical examination and additional tests including a cardiac stress test, 24-h Holter electrocardiogram (ECG) monitoring, spirometry and a physical work capacity (PWC_{170}) test.

3.2. Variations of the tests

Tests were carried out under laboratory conditions, in a climatic chamber, at two levels of ambient air temperature: a milder one of 32 °C, and more burdensome one of 38 °C. In both cases, the air velocity was 1.0 m/s and the relative humidity of the air was at a level of 80–85%.

The participants took part in a total of six variations of the tests, involving the use of three types of breathing apparatus at two levels of ambient air temperature.

The test variations are presented in Table 1, and the appearance of mine rescuers wearing selected clothing variations is shown in Figure 4.

3.3. Equipment

The participants' equipment consisted of a helmet, a lamp and gloves in each test, and of oxygen closed-circuit breathing apparatus W-70 and BG-4 as well as APS/3N breathing apparatus. Closed-circuit compressed oxygen breathing apparatus was equipped with an additional compressed air cylinder with a capacity of 2.0 L, a pressure reducer and a harness with a total mass of 4.9 kg.

The closed-circuit compressed oxygen breathing apparatus type W-70 (Faser, Poland) is the basic equipment for Polish rescue services, used as a respiratory protective device. It operates in a closed circuit, and completely insulates the user from the surrounding atmosphere. This is a negative pressure device operating in a closed-circuit breathing system, with oxygen compressed in a steel cylinder. It provides protection for 4 h. The weight of the apparatus without the face piece is approximately 14.0 kg [11]. During the tests, the apparatus was equipped with a SAT-2M inhaled air cooler (Faser, Poland).

Figure 3. General appearance of the protective clothing for mine rescuers.

Table 1. Variations of tests involving mine rescuers.

Designation of variation of test	Description of variation of test
32 VU W70	Underwear with a ventilation system (VU), outerwear, W-70 closed-circuit rebreather, air temperature of 32 °C
32 VU BG4	Underwear with a ventilation system, outerwear, BG-4 closed-circuit rebreather, air temperature of 32 °C
32 VU APS	Underwear with a ventilation system, outerwear, PSS 7000 breathing apparatus, air temperature of 32 °C
38 VU W70	Underwear with a ventilation system, outerwear, W-70 closed-circuit rebreather, air temperature of 38 °C
38 VU BG4	Underwear with a ventilation system, outerwear, BG-4 closed-circuit rebreather, air temperature of 38 °C
38 VU APS	Underwear with a ventilation system, outerwear, PSS 7000 breathing apparatus, air temperature of 38 °C

The closed-circuit compressed oxygen breathing apparatus type PSS BG-4 EP (Dräger, Germany) is apparatus in which oxygen is compressed in an oxygen cylinder. It is equipped with an electronic control system with an option of using a reusable carbon dioxide absorber and an internal breathing air cooler. Under difficult conditions, the apparatus uses ice cartridges, which significantly improves comfort when working and extends the working time in the hazardous area. It provides protection for 4 h. The weight of the apparatus without the face piece is approximately 14.5 kg (including the ice in the cooler) [12,13].

Modified compressed air breathing apparatus type APS/3N (Faser, Poland) was equipped, for the purposes of the project, with two composite air cylinders with a capacity of 9.0 L. The weight of the air-filled apparatus with the face mask is approximately 22.0 kg. The device operates in a positive pressure system under the face mask. It is equipped with a switch that allows the device to be maintained in readiness with the cylinder valves open and, after putting the face mask on, to be switched to operation in a positive pressure system [14]. The apparatus with an underwear supporting system operates for 90 min.

The weights of the types of breathing apparatus used were not identical. Relevant detailed data are presented in Table 2. The BG-4 apparatus was the lightest of the types used and the W-70 apparatus mass was similar to the APS apparatus.

The breathing apparatus was modified to support ventilation in the developed underwear. Therefore, it was equipped with a different cylinder carrier and different cylinders as compared with the standard solution. The cylinders were of a greater capacity, i.e., 9.0 L instead of the 6.8-L cylinders used in the APS/3N apparatus. This modification affected the weight of the breathing apparatus.

3.4. *Protocol of the experiment*

It was assumed that the test would last for 120 min. However, not every condition specified in the study was favourable for the possibility of expending physical effort in a hot environment. The following limit values of physiological parameters, which determined the test duration, were adopted:

- internal temperature measured in the gastrointestinal tract (T_{abd}) > 38.5 °C;
- heart rate (HR) > 85% HR_{max};
- subjective signs of ill-being or fatigue.

The participants gave written consent to participate in the study. The safety of participants was ensured by the presence of a physician.

Prior to the test, each participant replenished fluids by drinking 500 ml of water. ECG electrodes, sensors for the measurement of skin temperature, air temperature and relative humidity as well as an HR recorder were placed on the participants' skin.

Each participant put on the underwear with the air ventilation system switched off, protective clothing, socks and

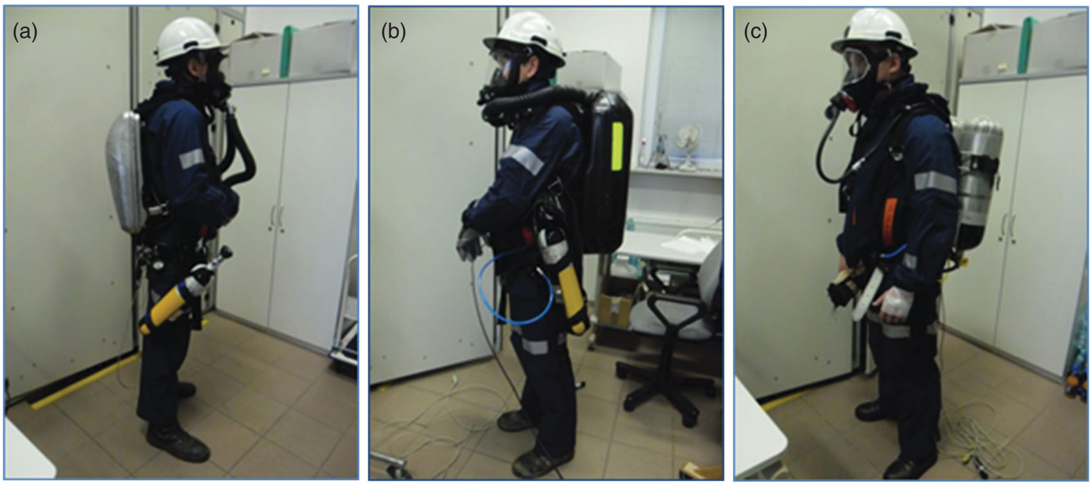

Figure 4. Participants using closed-circuit rebreathers (a) W-70 and (b) BG-4, and (c) APS/3N breathing apparatus.

Table 2. Initial mass ($M \pm SD$) of the types of rescue apparatus used.

Apparatus	Weight (kg)
BG-4	20.02 ± 0.08
W-70	22.94 ± 0.10
APS	23.01 ± 0.09

boots. The participant wearing such clothing stayed for 45 min under the conditions of ambient temperature of 21 °C and relative humidity of the air of 50%, in order to stabilize the thermal conditions of the body.

After the completion of acclimatization, prior to leaving the acclimatization chamber, each participant changed their jacket because the PCMs were permanently located in the collar. The change of jacket enabled the full-range operation of the PCMs. The clothing and equipment were then supplemented, depending on the test variation to be carried out.

The participants proceeded to another climatic chamber in which they expended physical effort on an electric treadmill with intensity accounting for 25% of physical endurance (V_{O2max}) determined individually for each rescuer participating in the test. The physical effort load was calculated before the participant entered the climatic chamber. The rate of the belt on the electric treadmill was constant and equal to 3 km/h. The inclination angle of the treadmill was calculated individually based on the weight of a fully dressed rescuer equipped with the appropriate equipment depending on the test variation to be carried out. During the tests in the second climatic chamber, the air ventilation system in the underwear was activated.

The test procedure was approved by the Ethics Committee of the Medical University of Warsaw, which granted consent for tests on protective clothing carried out in a climatic chamber with the participation of rescuers under difficult microclimatic conditions.

3.5. Parameters

During the tests, the following physiological and physical parameters were measured:

- internal temperature measured in the gastrointestinal tract (T_{abd}) using a thermometric physiological monitoring system (VitalSense, USA);
- local skin temperatures and relative humidity above the skin at four locations as per Standard No. EN ISO 9886:2004 [15], measured using i-Button wireless sensors (Maxim Integrated, USA);
- the body and clothing weight prior to and after the test, in order to determine sweating intensity, using a platform scale F 150 S-D2 (Sartorius, Germany).

Throughout the test, HR was monitored both using an FX 2000 cardiac monitor (Emtel, Poland) and wirelessly using a professional monitor (Polar Electro Oy, Finland) and the arterial blood pressure was measured using medical equipment (Omron, Vietnam) prior to and after the test.

Based on the local measurements of temperatures of the skin, the average weighted temperature of the skin ($\bar{T}_{sk}$) was calculated as per Standard No. EN ISO 9886:2004 [15]. Heat accumulation (S) was determined using the following equation:

$$S = (3.55 \times m_{cp}/A_{Du}) \times (0.9\Delta T_{abd} + 0.1\Delta \bar{T}_{sk}) \times t_{ex}^{-1},$$

where m_{cp} = initial body weight; A_{Du} = body surface; T_{abd} = internal temperature measured in the gastrointestinal tract; $\bar{T}_{sk}$ = average weighted temperature of the skin; t_{ex}^{-1} = exposure duration.

During the tests, subjective assessments concerning the feeling of heat as per Standard No. EN ISO 10551:2001 [16] and the skin moisture according to Nielsen and Endrusick [17] were collected at 15-min intervals.

A survey was also conducted with questions about the level of comfort of use of the developed underwear and outerwear, and about a comparison with the currently used clothing.

3.6. *Statistical analysis*

In the analysed measurement data, normality of distribution was determined (Shapiro–Wilk test) and then either Student's *t* test or a Wilcoxon non-parametrical signed-rank test was carried out. Analysis of variance (ANOVA) was performed for the comparison of clothing variations having previously checked the homogeneity of variance using Levene's test. The least significant difference (LSD) test was used as the *post-hoc* test. A level of significance of the differences of 0.05 was adopted. The statistical analysis of the measurement data was performed using Statistica version 9.1.

4. Results

4.1. *Test duration*

The average duration of tests at the lower ambient temperature was slightly longer in the test variation involving self-contained breathing apparatus than in the test variations involving two closed-circuit rebreathers, and was 55.4 (± 7.5) min (Figure 5). At the higher ambient temperature, the test durations were more similar, close to 30 min, and shorter by approximately 20 min than those in tests performed at the lower air temperature.

4.2. *Reasons for termination of the study*

Reasons for termination of the study are presented in Table 3. It can be noted that when closed-circuit rebreathers were used at the higher ambient temperature, the number of cases of study termination due to reaching HR limit values was higher. This fact was not determined in tests involving breathing apparatus. In this case, at both levels of ambient temperature, the frequency of study termination due to reaching the adopted HR limit was higher.

Table 3. Numerical summary of the reasons for termination of the study.

	Reason for termination of the study			
Test variation	T_{abd}	*HR*	Subjective	Duration
32 VU W-70	1	4	1	–
38 VU W-70	1	5	–	–
32 VU BG-4	4	–	2	–
38 VU BG-4	2	3	–	–
32 VU APS	2	4	–	–
38 VU APS	2	4	–	–

Note: For an explanation of the symbols of test variation, see Table 1. *HR* = heart rate; T_{abd} = internal temperature measured in the gastrointestinal tract.

4.3. *Weight of breathing apparatus*

During the tests, the weight of the used types of breathing apparatus changed (Table 4).

Closed-circuit compressed oxygen breathing apparatus decreased slightly in weight, i.e., approximately 10.0 g at the lower and 16.0 and 50.0 g at the higher ambient temperature, respectively, for W-70 and BG-4 apparatus. Theoretically, weight gain of those apparatus should be

Table 4. Change in weight ($M \pm SD$) of rescue apparatus used (kg).

Apparatus	Temperature of 32 °C	Temperature of 38 °C
BG-4	−0.01 ± 0.03	−0.05 ± 0.02
W-70	−0.009 ± 0.006	−0.016 ± 0.01
APS	−3.44 ± 0.51	−1.88 ± 0.44

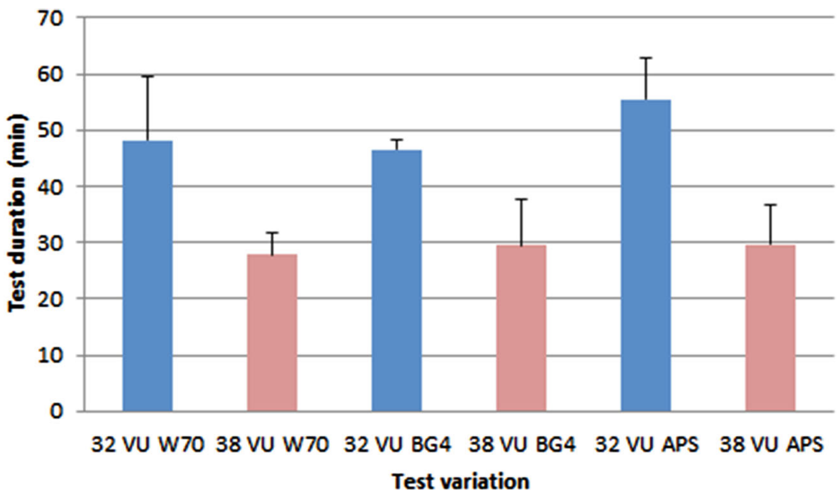

Figure 5. Duration of tests involving mine rescuers at two levels of air temperature, namely 32 °C (blue column) and 38 °C (pink column), and with the use of three types of breathing apparatus.
Note: For an explanation of abbreviations, see Table 1. Error bars denote *SD*. The full colour version of this figure is available online.

observed because of accumulation of steam and carbon dioxide (CO_2) exhaled by its users, but the received results could be a result of not using the same manner of stacking apparatus on our platform scale and a small value for those mass changes, close to the precision of the scale (0.005 kg). On the other hand, the modified compressed air breathing apparatus decreased significantly in weight. The decrease in weight was less at the higher ambient temperature (1.9 kg) than at the lower (3.4 kg) but the duration of tests was shorter at the higher temperature. These differences in weights at the lower and higher temperatures were statistically significant. However, upon conversion of these changes according to the duration of the test, it was found that the intensity of the decrease in weight of compressed oxygen breathing apparatus was similar and amounted to 62.4 and 63.9 g/min, respectively, for the lower and higher ambient temperature.

Changes in the weight of rescue apparatus contributed to the effort load. Changes in the effort load from the beginning to the end of the test were minor when the W-70 and BG-4 apparatus were used, and accounted for approximately 0.5% of the initial load. When compressed air breathing apparatus was used, changes in the load due to the duration of the effort were greater and accounted for 3.5 and 1.4% of the initial load, respectively, at the lower and greater ambient temperature. Therefore, in the tests involving the use of compressed air breathing apparatus, the physical load decreased significantly during the course of the tests compared with changes in the test involving the use of the oxygen breathing apparatus.

4.4. *Internal temperature*

The results of internal temperature measurements are presented in Figure 6. At the lower air temperature, changes in T_{abd} were more diverse, while at the higher temperature they were more uniform. No statistically significant differences were found, either depending on the ambient air temperature or depending on the breathing apparatus used.

4.5. *Average weighted skin temperature*

Results concerning the determined $\bar{T}_{sk}$ are presented in Figure 7. As early as during the first few minutes of the test, the level of obtained $\bar{T}_{sk}$ exceeded 34 °C. While at the lower temperature of the test the changes to $\bar{T}_{sk}$ were moderate, at the higher temperature the increase in $\bar{t}_{sk}$ was more rapid. The final values of $\bar{T}_{sk}$ at the lower air temperature were 36.2 °C but at the higher temperature they were higher by 1.2 °C.

For all types of breathing apparatus used, the differences between $\bar{T}_{sk}$ at the lower and higher air temperature were statistically significant from the 5th to the 35th minute, and up until the 30th minute for the test variation involving W-70 apparatus.

4.6. *Relative humidity of the air above the skin*

The results concerning relative humidity above the skin are presented in Figure 8. When the breathing apparatus was used, changes in humidity above the skin occurred similarly for particular types of apparatus. In these tests, the average value of relative humidity above the skin exceeded the value of 80% in the 15th minute at the higher ambient temperature, and in the 25th minute at the lower ambient temperature.

Average values of relative humidity above the skin at the time of study termination were close to 90%. It was found that the differences between the tests carried out at the lower and higher temperatures were statistically significant from the 5th to the 35th minute of the test for each type of apparatus used.

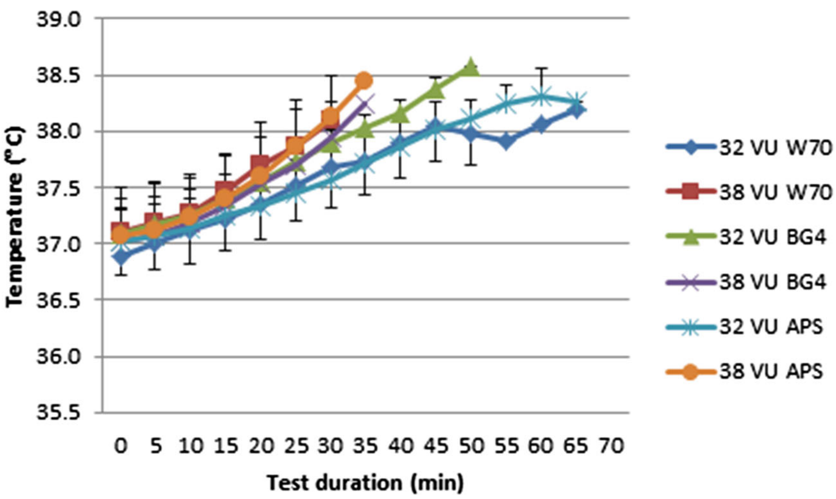

Figure 6. Changes to the internal temperature (T_{abd}) during tests involving mine rescuers at two temperature levels of 32 and 38 °C, and with the use of three types of breathing apparatus.
Note: For an explanation of abbreviations, see Table 1. Values are $T_{abd} \pm SD$, error bars denote *SD*.

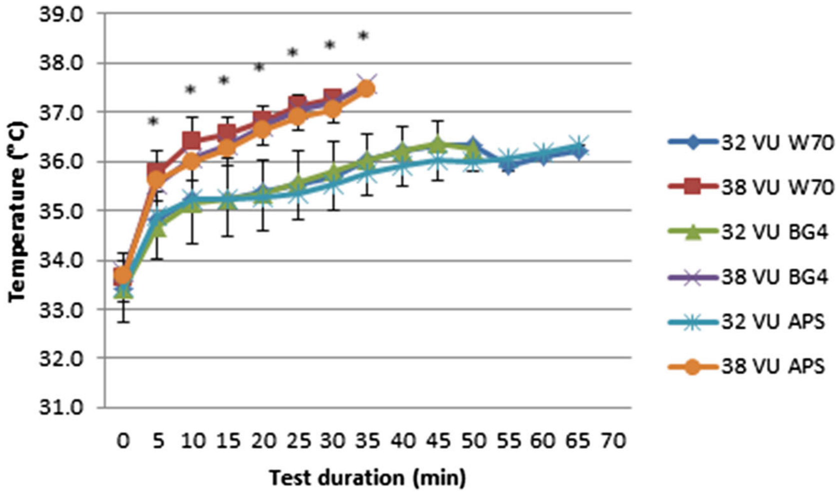

Figure 7. Changes to the average weighted skin temperature ($\bar{T}_{sk}$) during tests involving mine rescuers at two temperature levels of 32 and 38 °C, and with the use of three types of breathing apparatus. *$p < 0.05$.
Note: For an explanation of abbreviations, see Table 1. Values are $\bar{T}_{sk} \pm SD$, error bars denote *SD*.

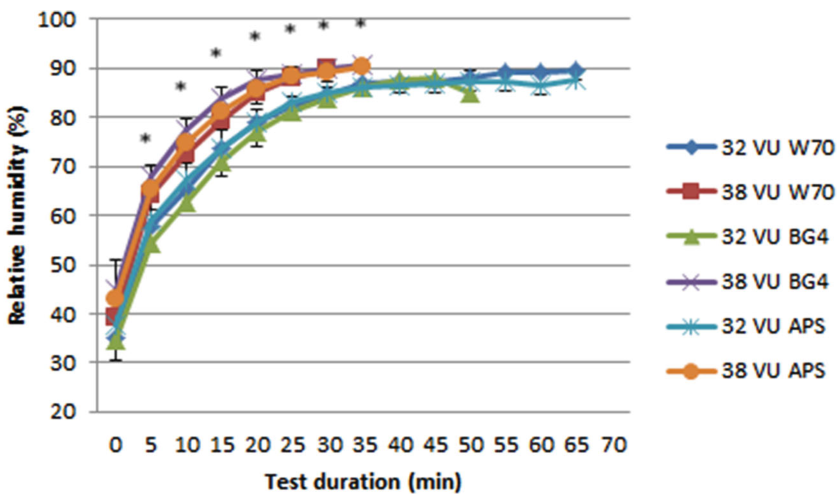

Figure 8. Relative humidity above the skin during tests involving mine rescuers at two temperature levels of 32 and 38 °C, and with the use of three types of breathing apparatus. *$p < 0.05$.
Note: For an explanation of abbreviations, see Table 1. Error bars denote *SD*.

4.7. Heat storage

The intensity of heat storage is presented in Figure 9. At the air temperature of 32 °C, the level was statistically significantly lower when compressed air breathing apparatus was used, as compared with the tests involving the use of W-70 and BG-4 oxygen apparatus. In addition, the intensity of heat storage in the tests involving the use of compressed air breathing apparatus was statistically significantly lower at the lower air temperature than it was at the higher temperature. At the higher temperature, the intensity of heat storage was greater by 27% when closed-circuit oxygen apparatus was used, and greater by 41% when the APS apparatus was used.

If we take the test duration into consideration, it appears that the total heat gains at the lower air temperature were 477.3, 447.3 and 425.3 kJ, respectively, for the tests involving the use of W-70, BG-4 and APS apparatus. At the higher air temperature, the storage of heat was lower and similar for the use of each of the breathing apparatus, close to 380.0 kJ.

4.8. Sweating intensity

The results of tests associated with sweating intensity are shown in Figure 10. At the lower temperature, the sweating level slightly exceeded the value of 1.0 kg, while at the higher temperature it was approximately 0.7 kg. The sweating level was statistically significantly lower during the tests at the higher air temperature as compared with the tests at the lower temperature, both for tests involving the use of W-70 oxygen apparatus and compressed air breathing apparatus.

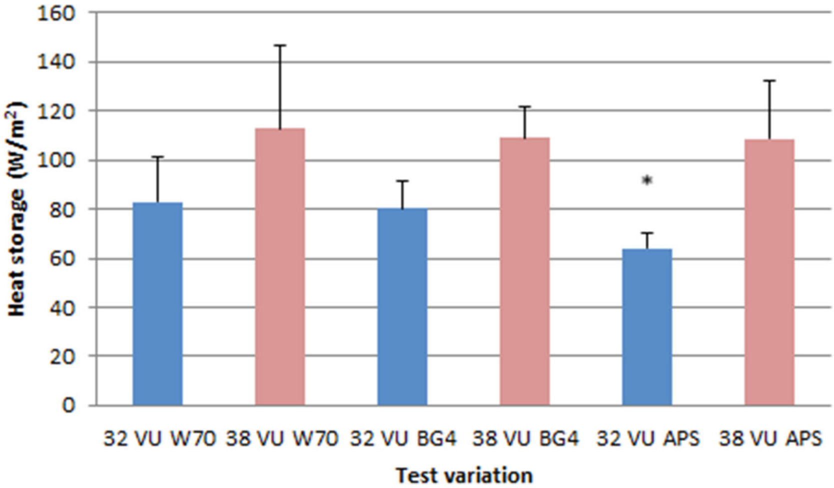

Figure 9. Intensity of heat storage during tests involving mine rescuers at two temperature levels of 32 °C (blue column) and 38 °C (pink column), and with the use of three types of breathing apparatus. $*p < 0.05$.
Note: For an explanation of abbreviations, see Table 1. Error bars denote *SD*. The full colour version of this figure is available online.

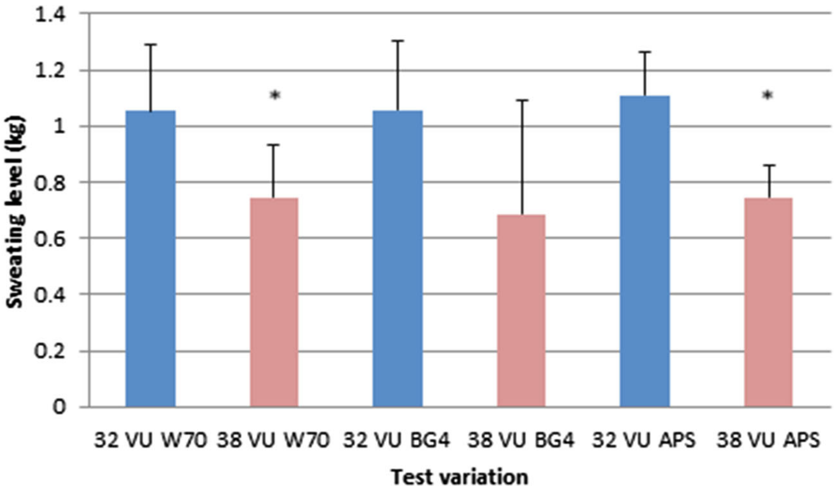

Figure 10. Sweating level during tests involving mine rescuers at two temperature levels of 32 °C (blue column) and 38 °C (pink column), and with the use of three types of breathing apparatus. $*p < 0.05$.
Note: For an explanation of abbreviations, see Table 1. Error bars denote *SD*. The full colour version of this figure is available online.

If we take the test duration into consideration, then the intensity of sweating is as shown in Figure 11. The lowest sweating intensity per unit of time was found in the tests involving the use of compressed air breathing apparatus, at both the lower and the higher air temperatures. These differences in tests at the lower and higher temperatures with apparatus of this type were statistically significant.

4.9. Subjective assessments

Assessments of the thermal sensations are presented in Table 5. A trend can be noticed towards higher (worse) ratings at the higher air temperature than at the lower, but the differences in the discussed sensations between the tests carried out at the lower and higher air temperatures were not statistically significant. Thermal sensations at the lower air temperature were at a level of moderate intensity (approximately 2), while at the higher temperature they quickly received high ratings.

The sensations of skin moisture (Table 6) were also assessed as worse at the higher air temperature than at the lower, and statistically significant differences were found in the tests involving the use of breathing apparatus in the 15th and 30th minute of the test, and in the 15th minute with the use of W-70 apparatus. The average assessments of the sensations of skin moisture did not reach the highest values at the lower air temperature, and they were much worse at the end of the tests carried out at the higher temperature.

Results of the survey on the developed underwear and outerwear are presented in Table 7. The effect of thermoregulatory elements was assessed positively by almost

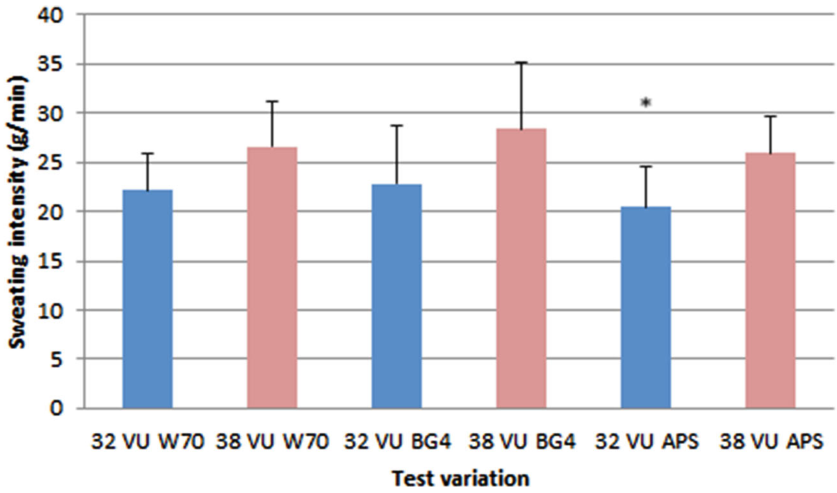

Figure 11. Sweating intensity per unit of time during tests involving mine rescuers at two temperature levels of 32 °C (blue column) and 38 °C (pink column), and with the use of three types of breathing apparatus. $^*p < 0.05$.
Note: For an explanation of abbreviations, see Table 1. Error bars denote *SD*. The full colour version of this figure is available online.

Table 5. Thermal sensations ($M \pm SD$) during tests involving mine rescuers at two temperature levels of 32 and 38 °C, and with the use of three types of breathing apparatus.

Duration of exposure (min)	Air temperature 32 °C			Air temperature 38 °C		
	Apparatus			Apparatus		
	W-70	BG-4	APS	W-70	BG-4	APS
0	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
15	1.7 ± 0.5	1.5 ± 0.5	1.2 ± 0.7	1.8 ± 0.4	1.8 ± 0.4	1.8 ± 0.6
30	1.8 ± 0.4	2.0 ± 0.2	1.7 ± 0.5	2.7 ± 0.5	2.7 ± 0.5	2.6 ± 0.5
45	2.4 ± 0.5	2.5 ± 0.5	2.0 ± 0.2	–	–	–
60	3.0 ± 0.0	–	2.0 ± 0.0	–	–	–

Table 6. Sensations of skin moisture ($M \pm SD$) during tests involving mine rescuers at two temperature levels of 32 and 38 °C, and with the use of three types of breathing apparatus.

Duration of exposure (min)	Air temperature 32 °C			Air temperature 38 °C		
	Apparatus			Apparatus		
	W-70	BG-4	APS	W-70	BG-4	APS
0	0.0 ± 0.0	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
15	1.7 ± 0.6	1.5 ± 0.5	1.0 ± 0.0	2.0* ± 0.6	2.0 ± 0.7	2.5* ± 0.8
30	2.7 ± 0.5	3.0 ± 0.6	2.2 ± 0.6	3.5 ± 0.6	4.7 ± 0.9	3.6* ± 0.8
45	3.6 ± 0.5	3.8 ± 0.8	2.8 ± 0.7	–	–	–
60	5.0 ± 0.0	–	2.5 ± 0.7	–	–	–

$^*p < 0.05$.

all participants. Most participants (60%) assessed the developed underwear and outerwear as better than the clothing used previously. Others stated that the currently used and the newly developed clothing are similar in use.

5. Discussion

The performed tests indicate that at the higher ambient temperature (i.e., 38 °C) the abilities to expend physical effort are impaired in comparison with the test conditions at the lower temperature (i.e., 32 °C). At 38 °C, the test duration related to the reaching of the assumed limit values of the internal temperature or HR was reduced by approximately 20 min.

In tests at the lower air temperature, changes to the physiological parameters were less severe than those at the higher temperature. This is particularly clearly evident in the course of changes to $\bar{T}_{sk}$. The tests at a temperature of

Table 7. Collected responses to survey questions concerning the clothing developed for mine rescuers.

1. Do you feel the effects of the use of thermoregulatory elements in the underwear? If so, to what extent and in which places?	5 responses
(a) No	1
(b) A slightly cool sensation on the ...back...	4
(c) A cool sensation on the..........................	–
(d) A sensation of severe cold on the...........	–
(e) A sensation of cold on the.......................	–
2. How do you assess the tested underwear and protective clothing in comparison with the previously used underwear and clothing in terms of ergonomic properties?	5 responses
(a) Significantly better	–
(b) Better	3
(c) Comparable	2
(d) Worse	–
(e) Significantly worse	–

32 °C were terminated at a level of this parameter slightly exceeding 36 °C, while at the higher temperature the final values of $\bar{T}_{sk}$ were higher by 1.2 °C in a much shorter time. This fact and more cases of termination of the tests due to reaching the assumed HR limit value indicate the intense supply of heat to the skin at the higher air temperature. Similar results were obtained in tests in a moderate and hot environment, involving artillery technicians [18]. This is a response to increased heat storage in the body. During the expenditure of physical effort in a hot environment, redistribution of blood takes place, which involves a reduction in the visceral and renal blood flow, and the directing of blood to the skin to enable heat dissipation on its surface [19]. The level of heat storage in rescuers' bodies was lower in the tests carried out at the higher air temperature, but the storage intensity was greater in this case. The slower storage of heat at the lower ambient air temperature contributed to a higher heat storage level.

Changes to the internal temperature also occurred with a lower intensity at the lower ambient air temperature, but in the case of this parameter the differences between tests, which depended on the air temperature, were less pronounced. This fact may be associated with the high level of heat accumulation in rescuers' bodies. In each of the test variations, the level of heat storage reached a greater value than the average limit value for this parameter, which is 335.0 kJ [20].

Smaller changes in the described levels of both the test duration and physiological parameters were observed depending on the type of breathing apparatus used. This can be explained by the method for determination of physical effort load. The load on the electric treadmill was calculated by taking into account the weight of a fully dressed and equipped rescuer, and thus the differences in the weight of types of breathing apparatus were eliminated. This, however, allowed the same effort load to be achieved by each participant.

It is worth noting that when using compressed air breathing apparatus, the average test duration was slightly longer than that when using closed-circuit oxygen apparatus. The intensity of heat storage and sweating intensity were lower than those in tests involving closed-circuit oxygen apparatus. This may result from the breathing apparatus design. The weight of this apparatus is distributed differently, namely in the same way as in a backpack, and it includes two cylinders with air between them. As regards closed-circuit rebreathers, the entire surface of the back is covered by the apparatus, and its weight primarily rests on the shoulders. This may indicate that in this case the advantage is not the apparatus weight but the weight distribution, as well as the greater flow of air over the surface of the back, similarly to the study by Griefahn et al. [21].

During the tests involving the use of compressed air breathing apparatus, the weight decreased due to the consumption of air from the bottle for the purposes of both breathing and supplying the ventilation system in the developed underwear, and was 2.0 and 3.4 kg, respectively, for the higher and lower ambient temperature. The situation was different when the closed-circuit oxygen apparatus were used. Their weight decreased by approximately 10.0 g at the lower and by 50.0 g at the higher ambient air temperature. The decrease in weight of the breathing apparatus accounted for 1.4 and 3.5% of the initial load as compared with the level of 0.5% for closed-circuit oxygen apparatus. However, this appears to be a small change in weight as compared with the initial weight of a participant with the equipment, which was approximately 110.0 kg. An argument to support this interpretation may be provided by other tests assessing the effects of ballistic vests, differing in weight by 4.5%, on physiological responses during the expenditure of physical effort with vests either warmed or cooled prior to their use [22]. The study did not find any statistically significant differences in the levels of physiological parameters such as the internal temperature, weighted average temperature of the skin, heat storage, sweating intensity or physiological cost of the effort.

The conditions of the air temperature of 32 °C were milder for the exposed persons because the level of this temperature was lower than the initial level of $\bar{T}_{sk}$, which offered a possibility for heat release to the environment by different routes (convection, radiation, conduction) at the initial stage of the study. At the higher air temperature, the situation was different because in this case the only route of heat release to the environment was evaporation of the produced sweat [23].

With the assumed limit values of T_{abd} and HR, the obtained sweating level was higher in the tests at the lower air temperature, and reached values close to 1.0 kg; however, under difficult conditions in a thermal environment, the sweating intensity per unit of time is more significant. In most tests carried out, except for the variation involving use of the APS apparatus, at the lower air temperature the sweating intensity exceeded 20.8 g/min, which is considered an acceptable intensity for acclimatized persons [15].

Sweating intensity affected the level of air humidity above the skin. This humidity was greater at the higher ambient temperature, and a humidity level of 80%, which is considered to cause a feeling of discomfort [24], was reached 10 min earlier than at the lower ambient temperature. The final level of humidity above the skin was as high as 90%, which may indicate an advantage of the developed clothing because it did not cause accumulation of moisture underneath, which was instead removed to the outside until equilibrium was reached with the environmental conditions.

The measured levels of physiological parameters were confirmed by subjective feelings. Both thermal sensations and sensations of skin moisture were worse under the conditions of the higher ambient air temperature, when compared at the same time. The final assessments of the thermal sensations were less clear as the number of participants was getting lower and lower, because various participants terminated the tests at different times.

The survey indicated that the developed clothing was well received by the users, and it was assessed by most participants as better than that currently used. The adopted manner of cooling was felt by the study participants, and was very much approved of.

6. Conclusions

Expending physical effort at the same load while using different types of breathing apparatus resulted in a similar heat load. Under both milder and harsher ambient conditions, both heat accumulation and sweating intensity were greater than the average limit value recommended by hygienic standards, which indicates that the use of breathing apparatus significantly hinders heat exchange with the environment, even when using underwear facilitating heat release. The developed clothing for mine rescuers was highly rated, and was considered by most people to be better than that used currently.

Acknowledgements

In the article, the results of Project No 11, 'Development of Protective Clothing for Mine Rescuers', implemented as part of the strategic research project 'Improving Work Safety in Mines' financed by the National Centre for Research and Development, were used.

Consortium:

- Central Institute for Labour Protection – National Research Institute (CIOP-PIB) (the Leader);
- Central Mines Rescue Station (CSRG S.A.);
- Manufacturer of Fire Uniforms (ZOSPRP WUS).

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by Narodowe Centrum Badań i Rozwoju (PL).

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References

[1] Rozporządzenie Ministra Środowiska z dnia 29 stycznia 2013 r. w sprawie zagrożeń naturalnych w zakładach górniczych [Regulation of the Minister of the Environment of 29 January 2013 on natural hazards in mines]. Dziennik Ustaw. 2013;(0):item 230. Polish.

[2] Rozporządzenie Ministra Gospodarki z dnia 28 czerwca 2002 r. w sprawie bezpieczeństwa i higieny pracy, prowadzenia ruchu oraz specjalistycznego zabezpieczenia przeciwpożarowego w podziemnych zakładach górniczych [Regulation of the Minister of Economy of 28 June 2002 on occupational health and safety, traffic management and specialized fire protection in underground mines]. Dziennik Ustaw. 2002;(139):item 1169. Polish.

[3] Bartkowiak G, Dąbrowska A, Krzemińska S, et al. Odzież ochronna i bielizna dla ratowników górniczych – wymagania ochronne [Protective clothing and underwear for mine rescuers – protective requirements]. In: Musioł D, Pierzyna P, editors. Poprawa bezpieczeństwa pracy w kopalniach. Teoria i praktyka [Improving of work safety in mines. Theory and practice]. Gliwice: Politechnika Śląska; 2014. p. 341–359. Polish.

[4] Bugajska J, Sobolewski A, Marszałek A, et al. Bezpieczeństwo ratowników górniczych w czasie akcji w trudnych warunkach klimatu w kopalniach węgla kamiennego – obciążenie cieplne [Safety of mine rescuers in action in the difficult climate conditions in coal mines – the thermal load]. In: Konieczny J, editor. Bezpieczeństwo zdrowia publicznego w zagrożeniach środowiskowych. Postępy metodologii badań [Public health safety in environmental hazards. Progress in research methodology]. Poznań: Garmond; 2012. p. 617–628. Polish.

[5] Drenda J. Ocena klimatycznych warunków pracy górników w polskich kopalniach węgla kamiennego i rudy miedzi [Rating of climatic working conditions of miners in Polish coal mines and copper ore]. Górnictwo i Geologia. 2012;7(3):19–35. Polish.

[6] Leveritt S. Heat stress in mining. Work-Safe Australia Ergonomics Review. 1998. Available from: http://ergonomics.uq.edu.au/eaol/leveritt.pdf

[7] Kalkowsky B, Kampmann B. Physiological strain of miners at hot working places in German coal mines. Ind Health. 2006;44:465–473. doi:10.2486/indhealth.44.465

[8] Directive 89/686/EEC of the European Parliament and of the Council of 21 December 1989 on the approximation of the laws of the Member States relating to personal protective equipment. OJ.1989;L399:18–38.

[9] European Committee for Standardization (CEN). Protective clothing – clothing to protect against heat and flame – minimum performance requirements. Brussels: CEN; 2015. Standard No. EN ISO 11612:2015.

[10] European Committee for Standardization (CEN). Protective clothing. Electrostatic properties. Material performance and

design requirements. Brussels: CEN; 2015. Standard No. EN 1149-5: 2008.

[11] Świrski M, Toczyłowski P, Głowik S. Nowe typy aparatów ratowniczych w kopalniach KW SA [New types of rescue devices in the mines KW SA]. Prezentacja na I Warsztatach Ratowniczych CSRG SA [Paper presented at: The 1st Lifesaving workshops CSRG SA]; 2012 Oct 25; Bytom, Polska. Accompanied by: a CD-ROM. Polish.

[12] Bagiński M. Sprzęt ratowniczy do ochrony układu oddechowego. Walory techniczne i użytkowe [Emergency equipment for respiratory protection. Technical and functional qualities]. Ratownictwo Górnicze. 2003;3:16–19. Polish.

[13] Bagiński M, Konwerski T, Ożóg Z, et al. Aparaty ratownicze wczoraj i dziś, kierunki rozwoju oraz praktyczne ich wykorzystanie w ratownictwie górniczym [Rescue cameras yesterday and today, developments and their practical use in mine rescue]. Prezentacja na I Warsztatach Ratowniczych CSRG SA [Paper presented at: The 1st Lifesaving workshops CSRG SA]; 2012 Oct 25; Bytom, Polska. Accompanied by: a CD-ROM. Polish.

[14] Konwerski T. Sprzęt ochrony układu oddechowego [Respiratory protection equipment]. Ratownictwo Górnicze. 2012;2(67):20–27. Polish.

[15] International Organization for Standardization (ISO). Ergonomics – evaluation of thermal strain by physiological measurements. Geneva: ISO; 2004. Standard No. ISO 9886:2004.

[16] International Organization for Standardization (ISO). Ergonomics of the thermal environment – assessment of the influence of the thermal environment using subjective judgement scales. Geneva: ISO; 2004. Standard No. EN ISO 10551:2001.

[17] Nielsen R, Endrusick TL. Sensations of temperature and humidity during alternative work/rest and the influence of underwear knit structure. Ergonomics. 1990;33(2):221–234. doi:10.1080/00140139008927112

[18] Stewart IB, Stewart KL, Worringham CJ, et al. Physiological tolerance times while wearing explosive ordnance disposal protective clothing in simulated environmental extremes. PLoS One. 2014;9(2):e83740. doi:10.1371/journal.pone.0083740

[19] Rowell LB. Cardiovascular adjustments to thermal stress. In: Shepard JT, Abboud FM, editors. Handbook of physiology. Bethesda (MD): American Physiological Society; 1983. p. 967–1023.

[20] ASHRAE. Physiological principles for comfort and health. In: Fundamentals handbook. Atlanta (GA): American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE); 1985. p. 8.1–8.32.

[21] Griefahn B, Künemund Ch, Bröde P. Evaluation of performance and load in simulated rescue tasks for a novel design SCBA: effect of weight, volume and weight distribution. Appl Ergon. 2003;34:157–165. doi:10.1016/S0003-6870(02)00143-6

[22] Marszałek A, Tokarski T, Kozłowska M, et al. Sprawozdanie z badań fizjologicznych prowadzonych w komorze klimatycznej z udziałem policjantów z zastosowaniem kamizelek skrytego noszenia, etap 3.3. [A report on the physiological research conducted in a climate chamber with the participation of police officers using hidden vests to wear, stage 3.3.] Warszawa: Centralny Instytut Ochrony Pracy – Państwowy Instytut Badawczy (CIOP-PIB); 2015. (Projekt nr DOBR-BIO4/045/13067/2013) Indywidualizacja konstrukcji wielofunkcyjnych kamizelek balistycznych skrytego noszenia [Individualization of multi-purpose ballistic hidden vest construction]. Polish.

[23] Rhoades RA, Tanner GA. Medical physiology. Boston (MA): Little, Brown; 1995.

[24] Mihal CP. Effect of heat stress on physiological factors for industrial workers performing routine work and wearing impermeable vapor-barrier clothing. Am Ind Hyg Assoc J. 1981;42(2):97–103. doi:10.1080/15298668191419424