Nataliia Ostapenko[1], Marina Kolosnichenko[1], Larysa Tretiakova[2], Tatyana Lutsker[1], Kalina Pashkevich[1], Alla Rubanka[1], Halyna Tokar[1]
[1] Kyiv National University of Technologies and Design, Faculty of Design, Nemirovich-Danchenko str. 2, 01011 Kyiv, Ukraine
[2] National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", Prosp. Peremohy, 37, 03056 Kyiv, Ukraine

Definition of the Main Features of Material Assemblies for Thermal Protective Clothing During External High-temperature Effect Modelling

Opredelitev glavnih značilnosti modeliranja kompletov materialov za zaščitna oblačila pri visokih okoljskih temperaturah

Original scientific article/*Izvirni znanstveni članek*
Received/*Prispelo* 2-2020 • Accepted/*Sprejeto* 1-2021

Corresponding author/*Korespondenčna avtorica*:
Nataliia Ostapenko, Dr. Eng., Professor
E-mail: cesel@ukr.net
ORCID: 0000-0002-3836-7073

Abstract
A computational-experimental method of material selection for thermal protective clothing design is proposed in this article. The intended operating temperature of the garment lies within the range of 40–170 °C. The prerequisite for the research was the lack of information regarding changes in the physical-mechanical and ergonomic characteristics of material assemblies during their use under high-temperature conditions. During the initial stage of research, there was a problem associated with the selection of the most important and the exclusion of the least significant indicators, in order to further reduce the number of experimental tests in laboratory and industrial conditions. The authors used the method of expert evaluations to solve the problems related to the selection of the most significant indicators for material assemblies. Material assemblies were formed by varying the combinations of heat-resistant, heat-insulation and lining layers of materials. Initial information for the proposed method was obtained from the experimental tests of sixteen material assemblies. According to the results of the ranking, the main parameters of material assemblies were identified as follows: the temperature range for which the use of clothing is intended, thickness, mass per unit density, rupture resistance, relative tearing elongation, change in linear dimensions during mechanical loads, air permeability and change in assembly thickness during cyclic loads. It was established that the assembly that includes heat-resistant material of the Nomex comfort N.307 220 top, Nomex Serie 100 heat-insulation lining and Nomex TER 135 lining provides the necessary level of protection, reliability and ergonomics, and meets cost requirements.
Keywords: laboratory testing, personal protective equipment, uptime, the level of reliability, industrial hazardous, multi-layered material assemblies, metallurgy, thermal aging

Izvleček

V članku je predlagana računsko-eksperimentalna metoda izbire materialov za oblikovanje toplotnozaščitnih oblačil v predvidenem temperaturnem okolju 40–170 °C. Informacije o spremembi fizikalno-mehanskih in ergonomskih lastnosti kompletov materialov pod vplivom visokotemperaturnih učinkov, ki so bile potrebne za raziskavo, niso bile poznane. V začetni fazi raziskave je bilo treba določiti najpomembnejše in izključiti najmanj vplivne kazalnike, kar je omogočilo nadaljnje zmanjševanje števila eksperimentalnih testov v laboratorijskih in industrijskih razmerah. Avtorji so z metodo ekspertnih evalvacij odpravili probleme, povezane z izbiro najpomembnejših kazalnikov kompletov materialov. Kompleti materialov so bili oblikovani s kombiniranjem toplotnoodpornih in toplotnoizolativnih materialov in materialov za podloge. Vhodne informacije za predlagano metodo so pridobili z eksperimentalnimi meritvami šestnajstih kompletov materialov. Glede na rezultate razvrstitve so bili opredeljeni bistveni parametri priprave kompletov materialov, in sicer temperaturno območje, za katero je namenjena raba oblačila, debelina, ploščinska masa, odpornost proti trganju, relativno raztezanje pri trganju, sprememba dimenzij med mehanskim obremenjevanjem, zračna prepustnost in sprememba debeline kompleta pri cikličnih obremenitvah. Ugotovljeno je bilo, da potrebno raven zaščite, zanesljivosti, ergonomije in stroškov zagotavlja komplet, ki je vseboval toplotno odporen material Nomex comfort N.307 220, toplotno izolativno plast Nomex Serie 100 in podlogo Nizdelan TER 135.

Ključne besede: osebna varovalna oprema, dejavniki tveganja v industriji, večplastni kompleti materialov, metalurgija, toplotno staranje

1 Introduction

The creation of personal protective equipment new types and models of protective clothing designed for work under high temperatures does not lose its relevance due to the emergence of new heat-resistant and fire-resistant materials. Modern thermal protective materials have the original raw material structure of fibres, which are subjected to fire-resistant and anti-static treatment [1, 2]. Designers of thermal protective clothing (TPC) have the ability to create ergonomic kits with the necessary protective properties.

According to [3], personal protective equipment must clearly comply with the list and levels of possible industrial hazardous factors. At the same time, they must meet the requirements of ergonomics and not create any additional risks and other adverse factors under the intended conditions of use. The main purpose of personal protective equipment is to guarantee the safety of the worker without hindering the performance of their basic functions. Such requirements can be met through the selection of appropriate materials, which further determine the basic protective functions, the level of reliability and ergonomics of protective clothing and personal protective equipment of common use.

The aim of TPC is to limit the risks associated with work under elevated ambient temperatures [4]. The need for the use of TPC arises at metallurgical plants, at mining, foundry and forging shops, at manufacturing enterprises involved in construction and glass products, and in the engine rooms of power plants etc. At such enterprises, the temperature in the production facilities may fluctuate in the range of 40–170 °C, while work is performed under heavy physical loads. An analysis of the problem of creating effective TPC reveals that its existing varieties partially prevent the access of thermal energy from an external source to the body of the worker, but also limit the process of human heat exchange. Mandatory requirements regarding protective, physical-mechanical and thermophysical characteristics are considered in TPC materials.

The latest heat-resistant materials are distinguished by their raw material composition. Natural fabrics are predominantly used, but the proportion of synthetic and mixed fabrics is increasing over time [5, 6]. The right selection of materials in assemblies plays a leading role in designing TPC that meets the intended requirements. The properties of TPC are determined primarily by the characteristics of material assemblies, which can be divided into four main groups:

- thermophysical characteristics, which determine the range of temperatures at which the material does not lose its protective properties, and the level of fire resistance;
- physical-mechanical characteristics, which determine resistance to mechanical load (tear, bending, puncture, shrinkage, etc.), which in turn as a significant effect on the service life, maintainability and possibility of multiple cleanings;
- ergonomic characteristics, which affect the level of comfort in use (weight and thickness) and mitigate additional risks during movement and heat

load (air permeability, thermal conductivity, water vapor permeability, hygroscopicity and biological inertness); and
- the index of cost-effectiveness, which determines the competitiveness of a product. The cost of the material assembly dictates 60–80% of the cost of a garment.

Appropriate thermo-physical indices make it possible to provide the desired level of protection against prolonged exposure to high temperatures. Physical-mechanical parameters determine the weight of the product and the level of mechanical strength of the structure. Ergonomic indices ensure compatibility with the user (size), taking into account performed movements and working positions in the context of the workload, and with other personal protective equipment that is intended to simultaneously protect individual parts of a worker's body (head, arms and legs). The desire to solve complex problems during the creation of TPC leads to the use of multilayer material assemblies with the consistent arrangement of heat-resistant, heat-insulation and lining layers [8]. Developing a material assembly structure is a challenging task because the selection of materials and their integration into a single system is influenced by a number of requirements, some of which are controversial. In the course of designing, the goal should be to agree on the physical-mechanical and thermophysical parameters, and the requirements for ergonomics and reliability. For example, increasing the number of layers and additional elements makes it possible to improve the protective properties, and increase the level of reliability and uptime. On the one hand, the greater the number of elements, the easier it is to realize a high level of protection, including the possibility of reinforcing the design through the principle of the differentiation of protection (reinforced zonal arrangement of assemblies with one or more thermal insulation layers in the assemblies) in separate areas of the human body [9]. On the other hand, a large number of individual elements increases the likelihood of damage to the structure and leads to an increase in the mass of a product. Obviously, the choice of elements and their degree of detail may vary depending on indicators of the conditions of use and the resolution of certain problems regarding the level of protection and length of use.

A number of design requirements have been established for TPC. Several standardized (mandatory) indicators apply to materials that can be used for the production of TPC: protective properties are determined by the heat resistance of the surface layer; the weight of clothes is determined by the mass per unit area of materials that are part of the assembly and by the number of layers; and the guaranteed length of use under increased mechanical loads is determined by the physical-mechanical characteristics of materials. Such requirements and restrictions necessitate the careful selection of the appropriate materials.

It is known that material assemblies have indicators that are different from those of individual materials, and vary depending on the impact of an aggressive production environment.

The aim of this article was to experimentally determine the physical-mechanical and ergonomic characteristics of material assemblies under external effect of elevated temperatures between 40–170 °C. The material assemblies are intended for the creation of thermal protective clothing for the employees of metallurgical enterprises. The prerequisite for the research was the lack of information regarding changes in the physical-mechanical and ergonomic characteristics of material assemblies during their use under high-temperature conditions. This effect leads to the thermal aging of textile materials and, as a consequence, to changes in their declared properties and indices [7]. The choice of effective material assemblies presupposes the availability of reliable information regarding the main characteristics that meet the conditions of their use.

2 Materials and methods

The study was performed for certain samples of heat-resistant top materials (nine samples of heat-resistant top materials) (Table 1), the insulation pad (three samples) (Table 2) and lining (two samples) (Table 3). Manufacturers provided statements regarding raw material composition, structure, mass per unit area, thickness, change in linear dimensions after wet treatments and breathability.

For the heat-resistant layer, samples of fabrics that meet the thermophysical requirements for TPC, with fire-resistant and oil-protecting properties, and an antistatic effect, were selected. The selected samples of the Proban KS-52, FlameStat Lite, Tecasafe HA 9001 top materials were treated with a special impregnation for protection against high temperatures, while the Nomex BV-107, Nomex ADV 240 and Nomex comfort N307 fabrics contain heat-resistant fibre in their composition [10].

The main purpose of the heat-insulation layer is to provide protection against heat stress and create a comfortable clothing microclimate of TPC.

The lining layer was used to ensure hygienic requirements for water and vapor absorption, and biological inertia [13].

Table 1: Characteristics of heat-resistant materials

Material	Coded marking	Producer	Raw material composition (%)	Mass per unit area (g/m^2)	Thickness (mm)
Nomex BV-120	R1	TenCate Protect, Netherland	Nomex (100%)	265	0.43
Proban XB 9340	R2	TenCate Protect, Netherland	Cotton (75%); Kevlar (25%); impregnation Proban	340	0.50
FlameStat Lite	R3	Carrington, Great Britain	Cotton (100%); impregnation Proban, antistatic	250	0.44
Tecasafe XA 9001	R4	Carrington, Great Britain	PAN (54%); cotton (45%); static-control (1%)	360	0.45
Nomex BV–107	R5	TenCate Protect, Netherland	Nomex (94%); Kevlar (5%); static-control (1%)	230	0.45
Proban KS –52	R6	TenCate Protect, Netherland	Cotton (100%); fire-resistant treatment	343	0.58
Nomex comfort N.307 180	R7	Estambril, Spain	Nomex (93%); Kevlar (5%); static-control (2%)	180	0.41
Nomex comfort N.307 220	R8	Estambril, Spain	Nomex (93%); Kevlar (5%); static-control (2%)	220	0.45
Nomex ADV 240 GR I RS	R9	Estambril, Spain	Para-aramid (60%); Nomex (40%)	240	0.60

Table 2: Characteristics of heat-insulation materials

Material	Coded marking	Producer	Raw material composition (%)	Mass per unit area (g/m^2)	Thickness (mm)
Needled fabric RigChief	I1	Daletec, Norway	Cotton (100%); impregnation Pyrovatex, antistatic	100	2.8
Needled batt fabric	I2	Netkam, Ukraine	Wool (55%); cotton (20%); viscose (25%)	110	3.5
Needled fabric Nomex Serie 100	I3	Dupont, USA	Viscose ignifuga (50%); Nomex (43%); Kevlar (5%); static-control (2%)	100	3.0

Table 3: Characteristics of lining materials

Material	Coded marking	Producer	Raw material composition (%)	Mass per unit area (g/m^2)	Thickness (mm)
Cotton sheeting uniformly dyed, art. 1667/25381	L1	Cherkaschkyi Schovkovyi Kombinat (Cherkaschkyi Silk Plant), Ukraine	Cotton (100%)	195	0.41
Nomex TER 135	L2	Dupont, USA	Nomex III N.302 (50%), Viscose FR (50%)	135	0.38

Table 4: Composition material assemblies

Number of assemblies	Coded composition of assemblies	Heat-resistant material	Heat-insulation material	Lining material
1	R1 I1 L1	Nomex BV-120	Needled fabric RigChief	Cotton sheeting uniformly dyed, art. 1667/25381
2	R2 I1 L1	Proban XB 9340	Needled fabric RigChief	Cotton sheeting uniformly dyed, art. 1667/25381
3	R3 I1 L2	FlameStat Lite	Needled fabric RigChief	Nomex TER 135
4	R4 I2 L1	Tecasafe XA 9001	Needled batt fabric	Cotton sheeting uniformly dyed, art. 1667/25381
5	R5 I2 L1	Nomex BV–107	Needled batt fabric	Cotton sheeting uniformly dyed, art. 1667/25381
6	R6 I2 L1	Proban KS –52	Needled batt fabric	Cotton sheeting uniformly dyed, art.1667/25381
7	R7 I3 L2	Nomex comfort N.307 180	Needled fabric Nomex Serie 100	Nomex TER 135
8	R8 I3 L2	Nomex comfort N.307 220	Needled fabric Nomex Serie 100	Nomex TER 135
9	R9 I3 L2	Nomex ADV 240 GR I RS	Needled fabric Nomex Serie 100	Nomex TER 135

Assemblies of selected materials were developed for further experimental studies (Table 4). Samples of assemblies were developed in order to simulate indicators of individual elements of TPC under production conditions by varying combinations of heat-resistant, heat-insulation and lining material layers.

During the initial stage of the research, there was a problem associated with the selection of the most important and the exclusion of the least significant indicators in order to further reduce the number of experimental tests in laboratory and industrial conditions. The generally accepted procedure of screening factors due to the large number of indicators is quite cumbersome and time consuming, and requires a great deal of time to implement the necessary measures [12]. Such difficulties can be overcome through the use of expert opinions, and by taking into account the ability of the designer to make rational decisions when it is impossible to fully formalize them. The authors used the method of expert evaluations to solve the problems related to the selection of the most significant indicators for material assemblies.

Expert evaluation to determine the main indicators of the material assemblies involved the formation of a group of experts, the surveying of that group, the processing of the expert evaluation, an analysis of the results and an assessment of the reliability of the expert evaluation performed by the group. During the first stage, twelve respondents were selected, including specialists from TPC manufacturing companies, user representatives, and specialists from research and testing centres and laboratories in the textile industry. They were given the task of ranking the group indicators of material assemblies in accordance with their impact on the predicted properties of TPC. The method of direct evaluation of the ranking of the initial requirements was difficult to use due to the large number of characteristics and their indicators. The indicators that were analysed are different in terms of both quantitative estimates and qualitative characteristics. Therefore, the use of standard methods of expert evaluation is inefficient and requires adaptation to the specifics of the tasks. A method for determining the rank of a group of indicators on the basis of a normalized significant coefficient was proposed [13]. Experts identified four groups that determine the requirements for the physical-mechanical, thermophysical, ergonomic and economic characteristics of the material assembly. For each group, the normalized indicators are defined in the following sequence:

1. during ranking m, experts were asked to place n requirements in the order they consider most reasonable and assign to each requirement X rank from 1 to N. According to this, rank 1 received the most preferred indicator, and rank N – the least important; and
2. the normalized coefficient K_q for each of the q group of requirements was determined using the formula:

$$K_q = \frac{\sum_{j=1}^{m} X_q^j}{\sum_{q=1}^{n}\sum_{j=1}^{m} X_q^j} \quad (1),$$

where X_q^j represents the rank of the q-th group of requirements, given by j-th expert; $q = 1 \ldots n$; $j = 1 \ldots m$. In the calculations, $n = 4$ and $m = 12$.

After ranking, the following results were obtained (Table 5).

In the second stage, the experts were offered a ranking of indicators in each group of characteristics. According to the algorithm, the normalized coefficients K_i for 20 materials was determined. The total normalized ranking factor K of alternative solutions was calculated using the formula:

$$K = K_q.K_i \quad (2),$$

where K_i represents the normalized coefficient for each i-th group of indicators.

According to the results of ranking, the most significant 10 indicators with respect to material assemblies were singled out (see Table 6).

The reliability of the evaluation of the expert group depends on the level of agreement of the opinions of the experts participating in the survey. The consistency of experts' opinions is assessed using the

Table 5: Ranking of requirements with respect to material assembly

Characteristics	Physical mechanical	Thermophysical	Ergonomic	Economic
Normalized coefficient, Kq	0.24	0.17	0.28	0.31
Rank	2	1	3	4

Table 6: Ranking of indicators of materials

Characteristics	Indicator	Normalized coefficients			Rank
		Ki	Kq	K	
Thermophysical	Temperature range for the use of clothing	0.013	0.17	0.002	**1**
	Antistatic (ohmic resistance)	0.088	0.17	0.015	12
	Fire resistance	0.092	0.17	0.016	14
Physical mechanical	Thickness	0.028	0.24	0.006	**6**
	Mass per unit area	0.022	0.24	0.005	**5**
	Rupture resistance (warp)	0.015	0.24	0.003	**2**
	Rupture resistance (weft)	0.016	0.24	0.004	**3**
	Relative tearing elongation (warp)	0.058	0.24	0.014	**9**
	Relative tearing elongation (weft)	0.059	0.24	0.014	**10**
	Fabric stiffness	0.083	0.24	0.019	20
	Change of assembly thickness during cyclic loads	0.053	0.24	0.012	**7**
	Change of linear dimensions during mechanical loads	0.055	0.24	0.013	**8**
Ergonomic	Air permeability	0.015	0.28	0.004	**4**
	Thermal conductivity	0.053	0.28	0.015	11
	Vapor permeability	0.055	0.28	0.015	13
	Water-resistance	0.06	0.28	0.017	17
	Water absorbency	0.057	0.28	0.016	15
	Biological hazard	0.058	0.28	0.016	16
Economic	Unit costs	0.059	0.31	0.018	18
	Materials output ratio	0.061	0.31	0.019	19

generalized coefficient W, which is defined as a generalized rank correlation coefficient for a group comprising m experts [14]. The generalized coefficient is calculated with the help of "Concurrer" program. The values of the calculated generalized coefficients were in the range W = 0.79–0.88 for the ranking of the tasks of four groups of characteristics. Such values indicate a high level of consensus between the experts. Based on the results of the rating assessment by specialists in various fields, the main indicators that received the highest ranks (from 1 to 10) were selected for further research: the intended temperature range for the use of clothing, thickness, mass per unit area, rupture resistance, relative tearing elongation, change in linear dimensions during mechanical loads, air permeability and change in assembly thickness during cyclic loads.

The practice of determining the quantitative parameters of material assemblies involves experimental tests. In laboratory conditions, the characteristics of materials are determined under normal conditions (temperature ranging from 20–22 °C and relative humidity ranging between 40–60%).

The results of experimental tests are given as a deterministic quantity, which is represented by the mathematical expectation (average value) of a random variable. The obtained parameters were interpolated under the assumption of linearity and the invariance of the initial conditions, which does not correspond to real operating conditions. It is known that the structure and properties of textile materials change during operation, and high temperature has destructive effect on textile materials [15]. This effect leads to the thermal aging of materials and thus to the gradual failure of TPC. It is therefore expedient to study experimental changes in the quantitative parameters of the main indicators during the simulation of high-temperature effects.

To determine the mathematical expectation of the corresponding characteristic Zi (i = 1, 2…) with a given accuracy, n of independent tests should be performed.

We give the mathematical expectation of each of the characteristics as

$$\grave{I}\ (\underline{Z}_3) = \underline{\grave{A}} \quad (3),$$

where $\underline{\grave{A}}$ represents the estimate of the mathematical expectation of the desired random parameter.

The value of $\underline{\grave{A}}$ will be in the interval

$$\underline{Z}_3 - \Delta \leq \underline{\grave{A}} \leq \underline{Z}_3 + \Delta \quad (4),$$

where Δ represents the upper bound of error of calculation results, which is determined by the known value of route-mean-square deviation σ (Z) and the given accuracy K_r

$$\Delta = \frac{K_r \cdot \sigma(Z)}{\sqrt{n}} \quad (5).$$

It follows from formula (5) that the total number of tests n in laboratory conditions for each indicator will be:

$$n = \left(\frac{K_r \cdot \sigma(Z)}{\Delta}\right)^2 \quad (6).$$

As previous tests have shown, at a given accuracy of 0.95, the required number of measurements is in the range from 5 to 12.

Changes in the performance of assemblies during the tests were characterized by the magnitude of deviations from estimated mathematical expectation, which is calculated using the formula:

$$\delta = \frac{A_1 - A_2}{(A_1 + A_2)/2} \cdot 100\% \quad (7),$$

where A_1 is the estimate of the mathematical expectation the parameters that have been measured before thermal exposure; A_2 is the same parameter after thermal exposure.

For assemblies that are planned for use in the production of TPC, the tests were performed in the laboratory according to standardized methods [16, 17]. Prepared samples of material assemblies were pre-conditioned in a heat chamber at an air temperature of 22–24 °C and relative air humidity of 50–60%. The assemblies were formed in layers and threaded along one side in the direction of the base. Tests to determine air permeability were performed under a pressure of 50 Pa with the help of a FF-12 device (Hungary). The assemblies' thickness change test was performed by applying a variable load of P_l = 50–1100 kPa for 30 seconds and unloading P_{unl} = 1100–50 kPa for five minutes after each of the ten cycles.

To determine the change in the linear dimensions of the assemblies, samples with a size of 300 mm x 300 mm were formed. Control lines 200 mm long and 200 mm wide were applied on the upper and inner layers of the materials. The simulation of high-temperature

effects was carried out in the mode of preliminary thermal exposure on material assemblies in a "Rohs" heat chamber (SPC Technology, Ukraine) at temperature 170 °C ± 5 °C, for 15 minutes.
The research was performed in the accredited "Textile - TEST" analytical and research testing laboratory at the Kyiv National University of Technology and Design.

3 Results

3.1 Indices of the physical-mechanical characteristics of assemblies and changes thereto under the effects of temperature

Prior to testing, the selected material assemblies were kept in a heat chamber to prevent exposure to environmental moisture (1 day). Mass per unit area measurements were performed before and after thermal exposure (Table 7).
As follows from Table 7, the assemblies nos. 2 and 6 have the highest mass per unit area values. The fifteen-minute temperature effect caused the mass per unit area to change due to the thermal aging of the materials. Therefore, it is possible to assume further changes in other physical-mechanical characteristics. Based on the results of studies, it was determined that assemblies nos. 2 and 3 can be excluded from further testing. The mass per unit area of assemblies nos. 2 and 3 increased, which will lead to an increase in the mass of TPC during use.
Experimental tests to determine the rupture resistance and relative tearing elongation of the material assemblies were performed taking into account the conditions of wearing ready-made clothing (Table 8). The size of the lining layer was assumed to be 10%

Table 7: Mass per unit area indices of material assemblies

Assembly number	Coded composition of assemblies	Mathematical expectation and confidence interval of mass per unit area (g/m^2)		Deviation of mass per unit area (%)
		Before thermal exposure	After thermal exposure	
1	R1 I1 L1	541 ± 4	534 ± 5	−1.30
2	R2 I1 L1	754 ± 9	771 ± 11	2.23
3	R3 I1 L2	543 ± 6	553 ± 8	1.82
4	R4 I2 L1	731 ± 9	728 ± 11	−0.41
5	R5 I2 L1	662 ± 6	661 ± 7	−0.15
6	R6 I2 L1	778 ± 12	790 ± 16	1.53
7	R7 I3 L2	463 ± 2	455 ± 4	−1.74
8	R8 I3 L2	518 ± 9	514 ± 3	−0.78
9	R9 I3 L2	534 ± 2	524 ± 3	−1.89

Table 8: Indices of rupture resistance

Assembly number	Coded composition of assemblies	External force direction	Mathematical expectation and confidence interval of rupture resistance (N)		Deviation of rupture resistance (%)
			Before thermal exposure	After thermal exposure	
1	R1 I1 L1	warp	224 ± 3	218 ± 5	−2.71
		weft	175 ± 8	163 ± 6	−7.10
4	R4 I2 L1	warp	173 ± 4	183 ± 5	5.62
		weft	81 ± 5	79 ± 3	−2.5
5	R5 I2 L1	warp	197 ± 4	199 ± 5	1.01
		weft	116 ± 6	126 ± 5	8.26
6	R6 I2 L1	warp	153 ± 5	143 ± 6	−6.76
		weft	93 ± 3	92 ± 5	−1.08

Assembly number	Coded composition of assemblies	External force direction	Mathematical expectation and confidence interval of rupture resistance (N)		Deviation of rupture resistance (%)
			Before thermal exposure	After thermal exposure	
7	R7 I3 L2	warp	156 ± 6	147 ± 6	–5.94
		weft	133 ± 4	146 ± 3	9.32
8	R8 I3 L2	warp	163 ± 6	173 ± 6	5.95
		weft	156 ± 1	167 ± 4	6.81
9	R9 I3 L2	warp	245 ± 3	242 ± 5	–1.23
		weft	200 ± 7	183 ± 6	–8.88

larger than the surface layer in terms of structural features. Due to such features, the tearing of the heat-resistant, heat-insulation and lining layers of the assemblies occurred simultaneously.

As follows from Table 8, the assembly no. 9 (R9 I3 L2) had the largest breaking force, while assemblies nos. 1, 6 and 9 demonstrated a decrease in value for up to 9% after thermal exposure.

The results of the determination of the relative tearing elongation of the thermal protection assemblies before and after thermal exposure are shown in Table 9.

According to the test results, the values of relative elongation decreased by 13% and 11% respectively in material assemblies nos. 1 and 9 with the coded composition R1 I1 L1 and R9 I3 L2. The largest increase in elongation was recorded for assembly no. 4 (R4 I2 L1) – up to 40%.

3.2 Ergonomic performance of the assemblies and changes thereto under the effect of temperature

In the design of protective clothing, preference is given to materials that will subsequently ensure the stable linear dimensions of clothing parts and individual elements during operation [18]. Tests were performed to determine the change in linear dimensions of the assemblies before and after thermal exposure (Table 10). According to the results of the tests, it can be stated that all assemblies have stable dimensions after thermal exposure, as the change in linear dimensions does not exceed 0.4%.

Table 9: Value of relative tearing elongation

Assembly number	Coded composition of assemblies	External force direction	Mathematical expectation and confidence interval of relative tearing elongation (%)		Deviation of elongation (%)
			Before thermal exposure	After thermal exposure	
1	R1 I1 L1	warp	16 ± 1	14 ± 1	–13.33
		weft	6 ± 1	5 ± 1	–18.18
4	R4 I2 L1	warp	16 ± 2	24 ± 2	40.00
		weft	16 ± 1	19 ± 2	17.14
5	R5 I2 L1	warp	16 ± 2	20 ± 1	22.22
		weft	17 ± 2	20 ± 1	16.21
6	R6 I2 L1	warp	10 ± 2	12 ± 1	18.18
		weft	16 ± 1	18 ± 2	11.76
7	R7 I3 L2	warp	39 ± 1	50 ± 1	24.72
		weft	38 ± 2	40 ± 1	5.13
8	R8 I3 L2	warp	37 ± 1	41 ± 2	10.26
		weft	41 ± 2	48 ± 1	15.73
9	R9 I3 L2	warp	19 ± 1	17 ± 1	–11.11
		weft	7 ± 1	6 ± 1	–15.38

Table 10: Values of change in the linear dimensions of thermal protection assemblies

Assembly number	Coded composition of assemblies	External force direction	Mathematical expectation and confidence interval of linear dimensions (mm)		Change in linear dimensions (%)
			Before thermal exposure	After thermal exposure	
1	R1I1 L1	warp	197.8 ± 3.8	197.8 ± 4.9	0
		weft	197.6 ± 1.0	197.4 ± 1.4	−0.10
4	R4 I2 L1	warp	199.3 ± 1.3	198.4 ± 1.5	−0.45
		weft	199.7 ± 1.9	199.2 ± 2.0	−0.25
5	R5 I2 L1	warp	201.5 ± 2.5	201.7 ± 2.2	0.10
		weft	195.8 ± 1.8	195.4 ± 1.7	−0.20
6	R6 I2 L1	warp	199.6 ± 1.4	199.5 ± 1.3	−0.05
		weft	200.3 ± 1.9	199.6 ± 3.6	−0.35
7	R7 I3 L2	warp	198.0 ± 2.6	198.0 ± 2.6	0
		weft	198.0 ± 2.0	198.0 ± 2.0	0
8	R8 I3 L2	warp	199.8 ± 1.5	198.8 ± 2.1	0.05
		weft	199.8 ± 1.5	199.7 ± 1.5	−0.05
9	R9 I3 L2	warp	199.6 ± 1.0	197.9 ± 4.9	0
		weft	199.6 ± 1.0	199.4 ± 1.4	−0.10

TPC should be used continuously for the work shift (up to four hours). Work is performed under a high mechanical load. During their activity, a worker performs work, converting mechanical energy into thermal energy. Under conditions of high ambient temperatures, this can lead to the disruption of heat transfer processes in the body of a worker. Changes in the functional state of the body are caused by the muscular work (static and dynamic) of the torso, and upper and lower extremities [19]. The intensity of heat generation depends on physical activity and the duration thereof, the human and health conditions, the environmental (ambient) temperature, pressure, humidity and air velocity. In different levels of activity, a worker emits from 250 W to 450 W of heat, compared with 100–150 W at rest, meaning that the comfort zone of a worker at rest does not coincide with the comfort zone under a work load [20, 21]. Under such conditions, the air permeability of the assemblies is an important indicator [22] (Table 11).

Based on the results of studies, it was determined that assemblies nos. 1and 9 had the highest levels of breathability. The results of the experiment showed an increase in breathability of up to 4% after thermal

Table 11: Values of air permeability

Assembly number	Coded composition of assemblies	Mathematical expectation and confidence interval of air permeability ($dm^3m^{-2}s^{-1}$)		Deviation in breathability (%)
		Before thermal exposure	After thermal exposure	
1	R1 I1 L1	54.6 ± 2.1	56.8 ± 2.3	3.95
4	R4 I2 L1	11.1 ± 1.4	11.9 ± 1.4	6.96
5	R5 I2 L1	22.6 ± 1.2	22.3 ± 1.8	–1.34
6	R6 I2 L1	22.8 ± 1.3	22.5 ± 1.1	–1.33
7	R7 I3 L2	49.8 ± 2.2	51.6 ± 2.9	3.55
8	R8 I3 L2	27.7 ± 1.2	28.6 ± 1.7	3.19
9	R9 I3 L2	90.04 ± 4.2	92.75 ± 4.2	3.06

exposure, which is due to the uneven structure of such material assemblies.

Under the effect of an external high-temperature environment on a worker in TPC, an increase in the duration of comfort for the human body temperature in the under-clothing space can be achieved by increasing the thickness of the insulating layer [23]. Improving the protective properties of TPC from mechanical stress in terms of design is possible by increasing the thickness of the assemblies in the areas of shoulders and chest, knees and elbows. Such a prerequisite has led to the performance of multi-cycle loading and unloading tests for multilayer assemblies before and after thermal exposure. Such tests were performed for assemblies containing one heat-insulation layer (Table 12) and two heat-insulation layers (Table 13).

Table 12: Value of changing the thickness of assemblies with a single heat-insulation layer

Assembly number	Coded composition of assemblies	Dynamic deforming force (kPa)	Mathematical expectation and confidence interval of material assembly thickness (mm)		Deviation in thickness (%)
			Before thermal exposure	After thermal exposure	
1	R1 I1 L1	100	4.12 ± 0.16	4.14 ± 0.06	0.48
		1000	2.83 ± 0.18	2.88 ± 0.24	1.75
4	R4 I2 L1	100	4.56 ± 0.06	5.14 ± 0.13	11.96
		1000	2.51 ± 0.13	3.09 ± 0.20	20.71
5	R5 I2 L1	100	4.87 ± 0.15	5.48 ± 0.19	11.79
		1000	2.45 ± 0.16	3.10 ± 0.21	23.42
6	R6 I2 L1	100	5.57 ± 0.26	6.03 ± 0.28	7.93
		1000	3.75 ± 0.15	4.17 ± 0.09	10.61
7	R7 I3 L2	100	3.60 ± 0.09	3.60 ± 0.09	0
		1000	2.35 ± 0.06	2.38 ± 0.11	1.27
8	R8 I3 L2	100	4.00 ± 0.07	4.13 ± 0.15	3.2
		1000	2.70 ± 0.04	2.88 ± 0.23	6.45
9	R9 I3 L2	100	4.08 ± 0.27	4.15 ± 0.08	1.21
		1000	2.72 ± 0.15	2.76 ± 0.20	1.46

Table 13: Value of changing the thickness of assemblies with two heat-insulation layers

Assembly number	Coded composition of assemblies	Dynamic deforming force (kPa)	Mathematical expectation and confidence interval of material assembly thickness, mm		Deviation in thickness (%)
			Before thermal exposure	After thermal exposure	
10	R1 2I1 L1	100	7.63 ± 0.22	7.64 ± 0.32	0.13
		1000	5.14 ± 0.27	5.20 ± 0.29	1.16
11	R4 2I2 L1	100	8.10 ± 0.46	8.02 ± 0.20	–0.99
		1000	5.13 ± 0.28	5.16 ± 0.45	0.58
12	R5 2I2 L1	100	7.93 ± 0.29	7.6 ± 0.74	–4.25
		1000	4.91 ± 0.38	4.92 ± 0.44	0.20
13	R6 2I2 L1	100	9.01 ± 0.65	8.85 ± 0.90	–1.79
		1000	5.45 ± 0.24	5.56 ± 0.45	1.2
14	R7 2I3 L2	100	6.8 ± 0.13	6.55 ± 0.10	–3.75
		1000	4.26 ± 0.15	4.30 ± 0.10	0.93
15	R8 2I3 L2	100	7.28 ± 0.17	7.11 ± 0.30	–2.36
		1000	4.90 ± 0.10	4.98 ± 0.38	1.62
16	R9 2I3 L2	100	7.44 ± 0.32	7.41 ± 0.55	–0.40
		1000	5.0 ± 0.34	5.12 ± 0.30	2.37

As follows from Tables 12 and 13, when using one thermal insulation layer, the mechanical loading and thermal treatment of the assemblies increase the thickness of assemblies nos. 4, 5, 6, and 8 (up to 20%), and has practically no affect on the thickness of assemblies nos. 1, 7 and 9. Assemblies with two heat-insulation layers maintained a stable size after multi-cycle loading.

Determining the calculated parameters based on the results of experimental tests involved estimating the mathematical expectation of each indicator with a given accuracy of 0.95. Under such conditions, the number of experimental tests included 5–12 measurements.

According to the results of tests and calculations, it was determined that it is advisable to develop TPC using assembly no. 8 or 9. Comparing the cost of the materials in these two assemblies led to giving preference to assembly no 8.

The results of experimental tests and theoretical research were used during the development of a set of protective clothing for the workers of metallurgical enterprises. The set is designed to perform work under the external effect of elevated temperatures within the range 40–170 °C. The clothes are made of an assembly consisting of heat-resistant material of the Nomex comfort N.307 220 top, Nomex Serie 100 heat-insulation lining, and Nomex TER 135 lining.

New design and technological solutions for clothes that consist of a jacket and overalls or trousers with overlays are offered. The total weight of TPC does not exceed 4.5 kg.

The thermal protective layer of the material consumption for an assembly is 6.8–8.1 m^2. During the manufacture of the products of the set seams of different purpose were used.

4 Conclusion

Protective clothing is designed to ensure that, under the foreseeable conditions of its use, a worker can perform the risk-related work normally with the highest possible degree of protection.

The performed studies made it possible to formulate an improved sequence of execution of works on the design of TPC, which is intended for protection against the high temperatures of the external production environment. The required properties of TPC can be achieved by applying available information regrading the indicators of relevant materials. During the first stage, requirements relevant to the indices of the materials that are of significant importance during the creation of TPC were defined: protective, physical-mechanical, ergonomic and economic. It was shown that the achievement of all requirements is possible when multi-layered material assemblies are used. The tasks related to the selection of the most significant indicators for material assemblies were solved using the method of expert evaluations through the determination of the ranks of the indicators on the basis of standardized coefficients. The consistency of experts' opinions was assessed using the concordance coefficient. During the second stage, nine variants of three-layer material assemblies were developed. Changes in mass per unit area, rupture resistance, percentage tearing elongation, linear dimensions, thickness during mechanical loads, air permeability under normal conditions and after simulation of thermal effects were determined for each assembly. It was established that the assembly that comprises the Nomex comfort N.307 220 top, Nomex Serie 100 heat-insulation lining and Nomex TER 135 lining provides the necessary level of protection, reliability and ergonomics, and meets cost requirements. The obtained research results were implemented during the creation of thermal protective clothing for the workers of metallurgical enterprises. New design and technological solutions for clothing that consist of a jacket and overalls or trousers with overlays were offered. The total weight of TPC does not exceed 4.5 kg.

References

1. ALONGI, Jenny, CAROSIO, Federico, MALUCELLI, Giulio. Current emerging techniques to impart flame retardancy to fabrics: an overview. *Polymer Degradation and Stability,* 2014, **106**, 138–149, doi: 10.1016/j.polymdegradstab.2013.07.012.
2. CAROSIO, Federico, DI BLASIO, Alessandro, CUTTICA, Fabio, ALONGI, Jenny, MALUCELLI, Giulio. Flame retardancy of polyester and polyester – cotton blends treated with caseins. *Industrial & Engineering Chemistry Research,* 2014, **53**(10), 3917–3923, doi: 10.1021/ie404089t.
3. Regulation (EU) 2016/425 of the European parliament and of the council of 9 March 2016 on personal protective equipment and repealing Council Directive 89/686/EEC [accessible from a distance]. EUR-Lex [accessed 29. 9. 2011].

Available on World Wide Web: <http://data.europa.eu/eli/reg/2016/425/oj>.
4. MCQUERRY, M.L. *Clothing modifications for heat strain reduction in structural firefighter protective clothing systems : Ph.D. Thesis*. Raleigh : Faculty of North Carolina State University, 2016.
5. ALONGI, Jenny, BOSCO, Federico, CAROSIO, Federico, DI BLASIO, Alessandro, MALUCELLI, Giulio. New era for flame retardant materials? *Materials Today,* 2014, **17**(4), 152–153, doi. 10.1016/j.mattod.2014.04.005.
6. McCARTHY, Brian J. *Polymeric protective technical textiles*. Shawbury : Smithers Rapra Technology, 2013, p. 152.
7. KOLOSNICHENKO, Olena, OSTAPENKO, Nataliia, LUTSKER, Tatiana, RUBANKA, Alla. Обґрунтування вибору термостійких текстильних матеріалів для захисного одягу (Substantiation for the choice of heat-resistant textile materials for protective clothing). *Bulletin of Kyiv National University of Technologies and Design,* 2017, **3**, 209–215.
8. MCQUERRY, Meredit, DENHARTOG, Emiel, BARKER, Roger. Garment ventilation strategies for improving heat loss in structural firefighter clothing ensembles.*AATCC Journal of Research,* 2016, **3**(3), 9–14, doi: 10.14504/ajr.3.3.2.
9. TRETIAKOVA, Larisa, OSTANENKO, Nataliia, KOLOSNICHENKO, Marina, PASHKEVICH, Kalina. Designing of rational structure of range of insulating protective clothing on the basis of the principles of transformation. *Fibres and Textiles,* 2016, **23**(4), 27–36.
10. ALONGI, Jenny, HORROCKS, Richard, CAROSIO, Federico, MALUCELLI, Giulio. *Update on flame retardant textiles : state of the art, environmental issues and innovative solutions*. Shawbury : Smithers Rapra Technology, 2013, p. 320.
11. ISO 13688:2013 *Protective clothing – general requirements*. Geneva : International Organization for Standardization, 2013.
12. GUTSKOVA, S. Метод экспертных оценок. *(Method of expert judgments)*. Moscow: Litagenstvo, 2011, p. 254.
13. ADLER, YU., MARKOVA, E., GRANOVSKY, YU. *Планирование эксперимента при поиске оптимальных условий*. (Planning an experiment in the search for optimal channels). Moscow : Science, 1976.
14. YASHKINA, Olga I. Statistical tools of expert opinion consistency in marketing research. *Economic bulletin national technical university of Ukraine »Kyiv polytechnical institute«*, 2013, 10, 442–449, http://economy.kpi.ua/en/node/524.
15. RUBANKA, Alla I., OSTAPENKO, Nataliia V., RUBANKA, M.M., KOLOSNICHENKO, Olena V., PASHKEVICH, Kalina L. Experimental researches on determination of reliability indexes of heat-protective materials. *Fibres and Textiles,* 2017, **24**(4), 22–29, http://vat.ft.tul.cz/2017/4/VaT_2017_4_4.pdf.
16. ISO 13938-1:2019. *Textiles – Bursting properties of fabrics Part 1: Hydraulic method for determination of bursting strength and bursting distension*. Geneva : International Organization for Standardization, 2019.
17. ISO 139:2005/AMD 1:2011. *Textiles – Standard atmospheres for conditioning and testing – amendment 1*. Geneva : International Organization for Standardization, 2011.
18. KOLOSNICHENKO, Olena, OSTAPENKO, Nataliia, KOLOSNICHENKO, Marina. The development of new forms of special clothes by design projecting methods. *Textile fibres and Textiles*, 2016, 18(2), 3–8.
19. ANSI/ASHRAE Standard 55-2017. *Thermal environmental conditions for human occupancy*. Standard by ANSI/ASHRAE: American Society of Heating. Refrigerating and Air-Conditioning Engineers, 2017, p. 62.
20. TRETIAKOVA, Larisa, BILAN, Vadim. *Експериментально-розрахункове дослідження теплового стану гірника*. (Experimental-calculated study of the miner's thermal condition). *Coal of Ukraine*, 2011, **1**(649), 41–45.
21. PREK, Matjaz. Thermodynamic analysis of human heat and mass transfer and their impact on thermal comfort. *International Journal of Heat and Mass Transfer*, 2005, **48**(3–4),731–739, doi: 10.1016/j.ijheatmasstransfer.2004.09.006.
22. MCQUERRY, Meredith, DENHARTOG, Emiel, BARKER. Roger. Evaluating turnout composite layering strategies for reducing thermal burden in structural firefighter protective clothing systems. *Textile Research Journal*, 2017, **87**(10), 1217–1225. doi: 10.1177/0040517516651101.
23. WALKER, Marika, Ayana. From sweating plates to manikins: evaluating the role of *clothing in reducing the risk of heat stress in wildland firefighting*. Raleigh, North Carolina : Textile Engineering, 2013, p. 229.