EXPERIMENTAL RESEARCHES ON DETERMINATION
OF RELIABILITY INDEXES OF HEAT-PROTECTIVE MATERIALS

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Abstract: *The article presents the results of the experimental researches on determination of dependency of the breaking stress and the elongation at the moment of abruption on the number of washing cycles and the temperature for heat-resistant textile materials. Results, obtained after the experiments, provided the opportunity to predict the behavior of the selected materials, depending on the operating loads.*

Keywords: *heat-resistant materials, breaking stress, elongation at the moment of abruption, washing.*

1   INTRODUCTION

Manufacturing of modern ergonomic and reliable protective clothing primarily depends on the materials used. The range of modern heat-resistant textile materials is quite wide. Nowadays they are distinguished by raw materials composition, type of processing, interweaving and so on. Natural fabrics are used preferably, but the share of synthetic and mixed fabrics increases annually.

Among the natural fabrics cotton is used most often for making emergency-rescue clothing. Also linen is well known, which is used mainly in manufacturing of suits for welders in lower economic segment of the market. The main reason for the rejection from linen is its high surface density and rigidity, so its use in working conditions is ergonomically inadvisable because of the dynamic discrepancy of the clothes. The advantage of the synthetic fabrics for manufacturing of heat-resistant clothing

is their durability. Reduced hygienic characteristics can be considered as a main disadvantage.

We analyzed the existing market materials and proposed their classification based on the method of provision of heat resistance (Figure 1). So, we can underline several ways of heat resistance provision, namely:

- application of substances on the fabric, which break up at burning with bleeding of incombustible gases (impregnation of fabrics);
- formation of incombustible film (membrane) on the fabric that protects the fiber from the contact with air during the combustion (fabric covering);
- chemical transformation of functional groups of fibers to increase the stability of macromolecular chains to thermal splitting (heat-resistant fibers);
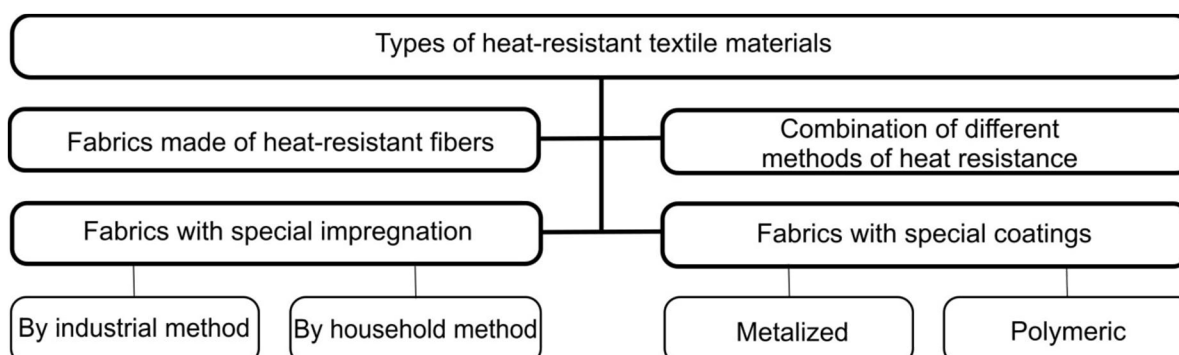- combination of two or more of the abovementioned methods [1].

Figure 1 Types of heat-resistant materials by means of provision of heat resistance

Among the fabrics with special processing the Proban® technology is the most popular. It is fireproof chemical processing, developed in the 1950s, by which fabrics and knitted cotton or mixed with cotton fabrics are impregnated at the final stages of their production. Proban is a polymer chemical substance with a low molecular weight used for impregnation of fabrics. The fabric is dried in an environment with specified moisture content, then in the high concentration of gaseous ammonia, is oxidized by hydrogen peroxide, washed, dried and soften again by polyethylene fabric softener. The heaviness of the fabric ignition is achieved through the inert polymer, which is located in fiber and isn`t washed out from the fabric during the washing. When heating, fire retardant (antipyrene) breaks down to form acids in the fabric and catalyzes the formation of carbon. Carbon prevents the oxidation of potassium. That is, when the fabric, processed by the Proban, is exposed to the flame, the localized area is formed, which acts as an insulating layer. So, Proban provides comfortable, reliable and economically efficient solution for the fire safety at the workplace. Fabric with Proban does not "support" the combustion and smolder processes, does not affect the original properties of cotton and does not washed away during the washings and dry cleanings (up to 50 cycles).

Famous Pyrovatex is a fire-resistant material with processing, which is applied on the cotton fabric or on the fabric containing synthetic fibers in the amount no more than 25%. The attention is on keeping fabric soft and breathable while keeping a high level of protection after several washing cycles. Pyrovatex is a chemical product that contains organic compounds of phosphorus. Cotton fabrics are processed with this substance on a molecular level. Fireproof properties remain stable after repeated washing or dry cleaning in case if all recommendations on care are the subject to compliance. Under the action of the flame "carbonic scaffold" of dehydrated cellulose is produced, which stops the flame spreading and its penetration into the fabric. Thus there is no risk of melting and after removal of flame source the fabric does not burn or smolder. The relative simplicity of creation of such a fabric makes it one of the most economical heat-protective solutions. Unlike the Proban technology, Pyrovatex is not washed off from the fabric that does not limit the time of its use.

Nomex fabric is a synthetic polyamide, developed in the early 1960s by DuPont Company. Nomex fiber is the aramid polymer (class of heat-resistant fibers), which has a chemical added aromatic base that has a man-made chemical formula that provides the fiber with additional rigidity and strength. This combination of the unique elements creates a fiber with high thermal, chemical and radiation resistance and is used for environments with a high level of risk. Nomex can be manufactured in the form of fiber or sheet, which further increases its use. Suits, helmets, gloves, pads, underwear etc. are made from the Nomex fibers [2].

The question about the change of characteristics specified by the manufacturer as a result of operating loads remains poorly known. Such operating loads for heat-resistant clothing primarily include the impact of the increased temperature. Also these clothes are the subjects to washing from time to time, which could affect negatively on their protective properties. That is why we conducted the experimental researches on determination of dependency of the breaking stress and the elongation at the moment of abruption on the temperature of the heat chamber and the number of washing cycles. The temperature of the heat chamber varied from 0 to 150°C. The full washing cycle was made using standard detergents at the temperature 60±5°C.

2   EXPERIMENT PLANNING

A number of experimental researches of heat-resistant textile materials were made in an accredited analytical and experimental testing laboratory "Textiles – TEST" of KNUTD with the aim of determination and prediction of reliability indexes. As the object of the experimental researches, the following fabrics of foreign production with different ways of heat resistance provision were selected, namely:

- suiting fabric Nomex BV-120 (100% metaaramid Nomex fibers) with a surface density of 265 g/m^2, production of "Ten Cate Protect", The Netherlands;
- suiting fabric XB 9340 (75% cotton, 25% Kevlar, Proban impregnation, anti-static) with a surface density of 340 g/m^2, production of "Ten Cate Protect", The Netherlands;
- suiting fabric FlameStat Lite (100% cotton, Proban impregnation, anti-static) with a surface density of 250 g/m^2, production of "Carrington", The United Kingdom;
- suiting fabric RigChief (100% cotton, Pyrovatex impregnation, anti-static) with a surface density of 370 g/m^2, production of "Daletec", Norway.

During the study of the processes and systems with two factors the plan of regular hexagon type was chosen as a rational one, namely noncomposite rototable plan of second order [3], which provides for 10 tests, six of which are performed at levels of factors, indicated at the tops of hexagon, and four tests - at levels of factors that correspond to the center of the plan. The advantage of the chosen plan is that for the factor x_1 it requires the use of five levels (+1; +0.5; 0; -0.5; -1), and for the factor x_2 - just the use of three levels (+0.866; 0; -0.866). The matrix of the plan presented in the Table 1.

Table 1 The matrix of experiment planning

No. of experiment	x_0	x_1	x_2	$x_1 x_2$	x_{12}	x_{22}	y
1	+1	+1	0	0	+1	0	y_1
2	+1	-1	0	0	+1	0	y_2
3	+1	+0.5	+0.866	+0.433	+0.25	+0.75	y_3
4	+1	+0.5	-0.866	-0.433	+0.25	+0.75	y_4
5	+1	-0.5	+0.866	-0.433	+0.25	+0.75	y_5
6	+1	-0.5	-0.866	+0.433	+0.25	+0.75	y_6
7	+1	0	0	0	0	0	y_7
8	+1	0	0	0	0	0	y_8
9	+1	0	0	0	0	0	y_9
10	+1	0	0	0	0	0	y_{10}

Table 2 The values of the factors at levels of variation

Name of the factor	No. of experiment									
	1	2	3	4	5	6	7	8	9	10
Number of washings n	12	0	9	9	3	3	6	6	6	6
Temperature of the heat chamber t [C]	75.0	75.0	139.95	10.05	139.95	10.05	75.0	75.0	75.0	75.0

In order to ensure the reliability of the obtained results, during the realization of the experiment plan in every experiment and during the test of reproducibility of the process by Cochran criterion it was found that the number of repeats (duplications) of every experiment should be not less than six.

The values of the factors at appropriate levels of variation according to the matrix of experiment planning are presented in the Table 2.

3 RESULTS AND DISCUSSION

It was determined the regression dependencies of breaking stress P [N] in warp $\rightarrow Y_1$ and in weft $\rightarrow Y_2$, elongation at the moment of abruption L [mm] in warp $\rightarrow Y_3$ and in weft $\rightarrow Y_4$, on the number of washings $n \rightarrow X_1$ and on the temperature of the heat chamber t [°C] $\rightarrow X_2$.

For two factors the equation of regression will be the following one:

$$y = b_0 + b_1 x_1 + b_2 x_2 + b_{12} x_1 x_2 + b_{11} x_1^2 + b_{22} x_2^2 \qquad (1)$$

Coefficients of equation (1) were obtained using the below formulas:

$$b_0 = \frac{1}{4} \sum_{u=1}^{4} y_{0u} \; ; \quad b_1 = \frac{1}{3} \sum_{j=1}^{10} x_{1j} y_j \; ;$$

$$b_2 = \frac{1}{3} \sum_{j=1}^{10} x_{2j} y_j \; ; \quad b_{12} = \frac{4}{3} \sum_{j=1}^{10} x_{1j} x_{2j} y_j$$

$$b_{11} = \frac{3}{4} \sum_{u=1}^{4} x_1^2 y_j + \frac{1}{12} \sum_{j=1}^{10} x_2^2 y_j + \frac{1}{4} \sum_{j=1}^{10} y_j$$

$$b_{22} = \frac{3}{4} \sum_{u=1}^{4} x_2^2 y_j + \frac{1}{12} \sum_{j=1}^{10} x_1^2 y_j + \frac{1}{4} \sum_{j=1}^{10} y_j$$

(2)

where y_{0u} - the value of the response function in the u-th experiment at the center of the plan; x_{1j}, x_{2j} – coded values of the factors in the j-th experiment; y_j – the value of the response function in the j-th experiment.

The obtained values of the regression coefficients are presented in the Tables 3 - 6.

As a result of the check it was found that for the equations of regression coefficients are insignificant; such coefficients are marked with gray in Tables 3 - 6.

Using the obtained equation of regression (1) the graphic dependencies were built, which are presented on the Figures 2 - 17.

Table 3 Coefficients of the equation of regression, obtained as a result of data processing after tests of suiting fabrics Nomex BV-120

Coefficient	Breaking stress P [N]		Elongation at the moment of abruption L [mm]	
	in warp	in weft	in warp	in weft
b_0	1670.0	1465.0	44.5	41.0
b_1	-10.5	-3.150	0.525	1.042
b_2	31.465	46.793	-0.488	0.038
b_{12}	0.577	-0.520	-1.576	-2.327
b_{11}	-12.525	-1.022	4.999	2.899
b_{22}	7.613	22.438	2.444	1.644
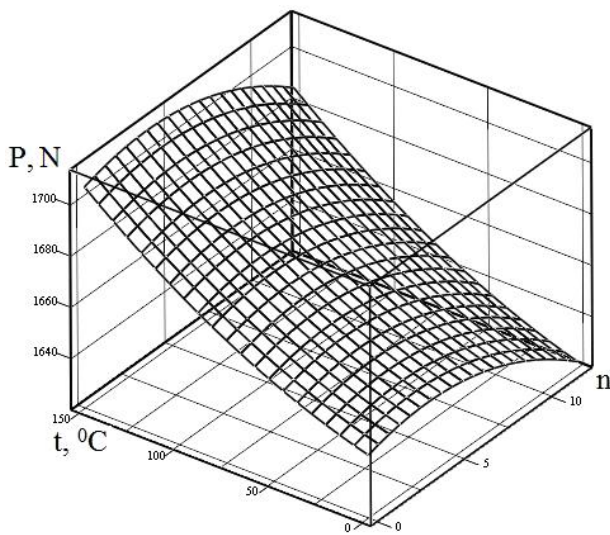
Figure 2 The diagram of dependency of the breaking stress *P* for the Nomex BV-120 material in warp on the number of washings *n* and on the temperature of the heat chamber *t*
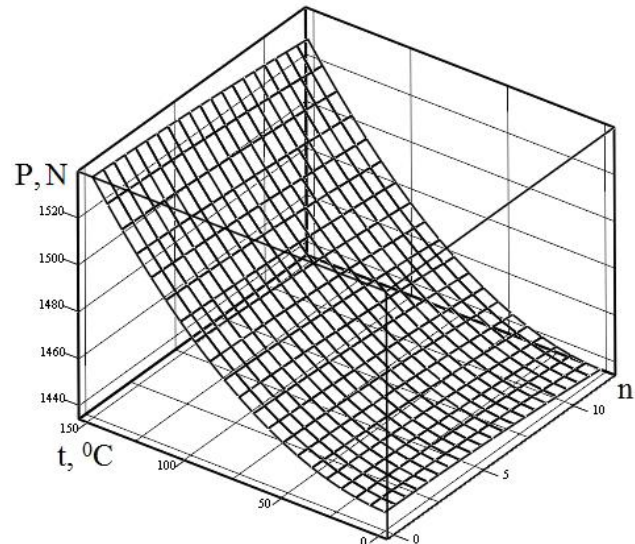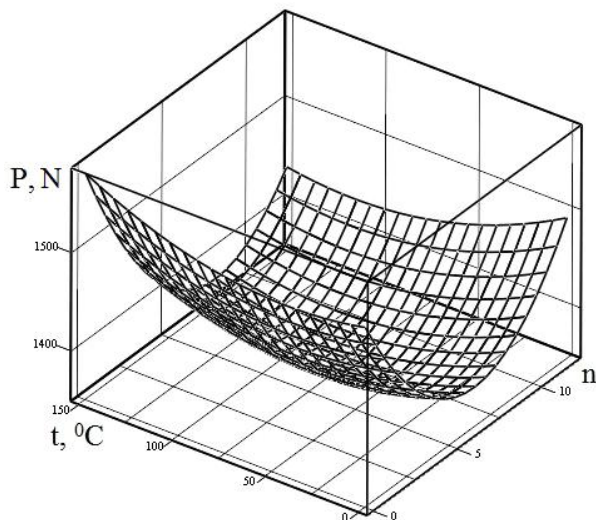

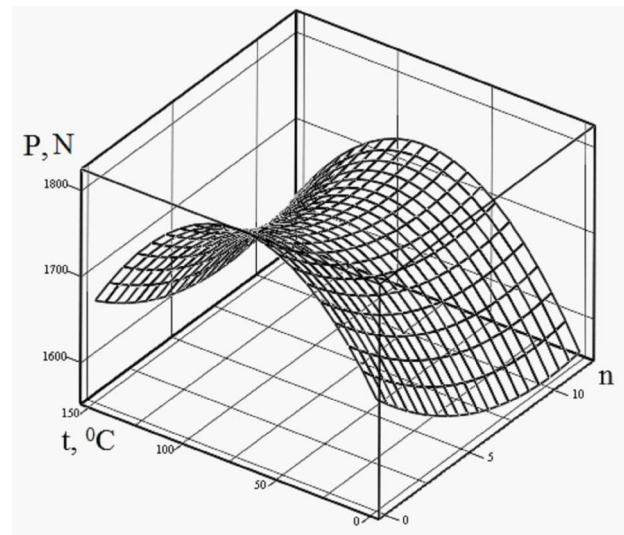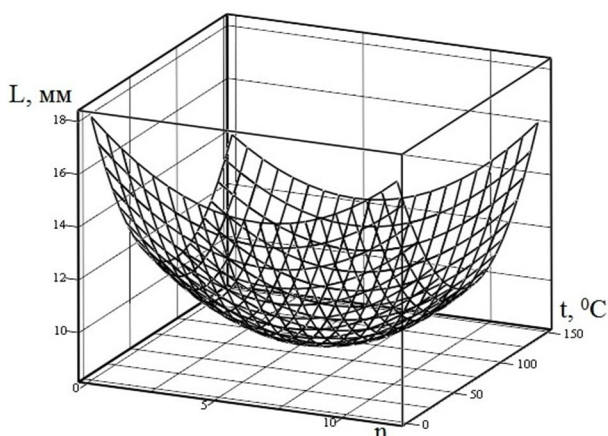**Figure 3** The diagram of dependency of the breaking stress *P* for the Nomex BV-120 material in weft on the number of washings *n* and on the temperature of the heat chamber *t*
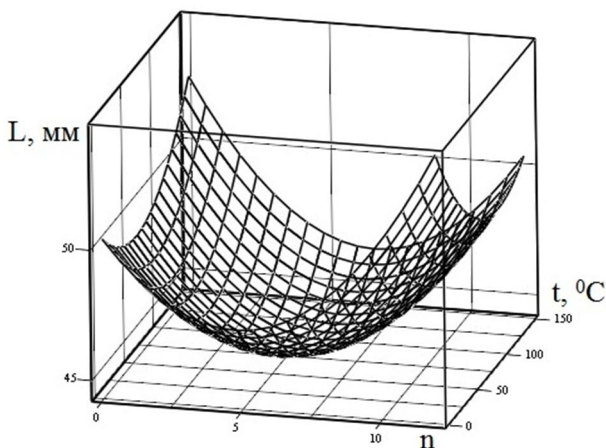
Figure 4 The diagram of dependency of the elongation at the moment of abruption *L* for the Nomex BV-120 material in warp on the number of washings *n* and on the temperature of the heat chamber *t*
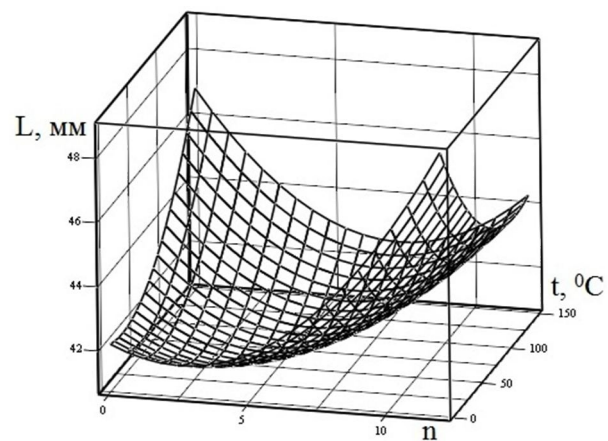
Figure 5 The diagram of dependency of the elongation at the moment of abruption *L* for the Nomex BV-120 material in weft on the number of washings *n* and on the temperature of the heat chamber *t*

Table 4 Coefficients of the equation of regression, obtained as a result of data processing after tests of suiting fabrics XB 9340

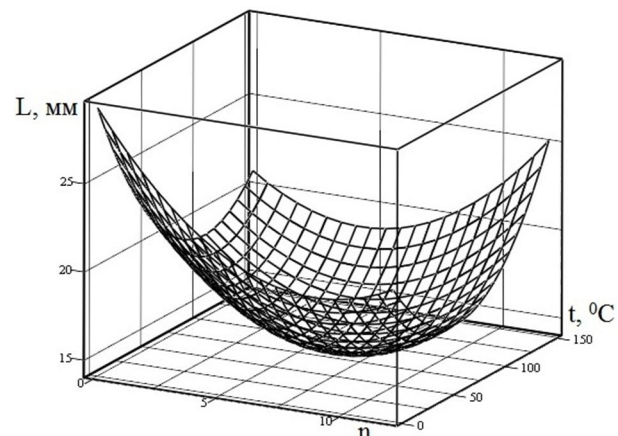| Coefficient	Breaking stress P [N]		Elongation at the moment of abruption L [mm]	
	in warp	in weft	in warp	in weft
b_0	1360.0	1732.5	8.5	14.5
b_1	-46.083	-42.25	0.290	-0.867
b_2	-2.627	11.633	-1.340	-1.201
b_{12}	-26.269	17.262	0.727	3.002
b_{11}	122.229	42.226	2.70	4.10
b_{22}	27.231	-141.133	5.152	5.564

Figure 6 The diagram of dependency of the breaking stress P for the XB 9340 material in warp on the number of washings n and on the temperature of the heat chamber t

Figure 7 The diagram of dependency of the breaking stress P for the XB 9340 material in weft on the number of washings n and on the temperature of the heat chamber t

Figure 8 The diagram of dependency of the elongation at the moment of abruption L for the XB 9340 material in warp on the number of washings n and on the temperature of the heat chamber t

Figure 9 The diagram of dependency of the elongation at the moment of abruption L for the XB 9340 material in weft on the number of washings n and on the temperature of the heat chamber t

Table 5 Coefficients of the equation of regression, obtained as a result of data processing after tests of suiting fabrics FlameStat Lite

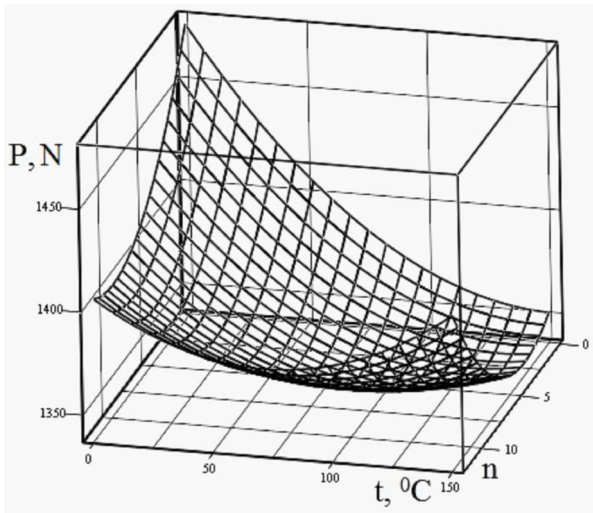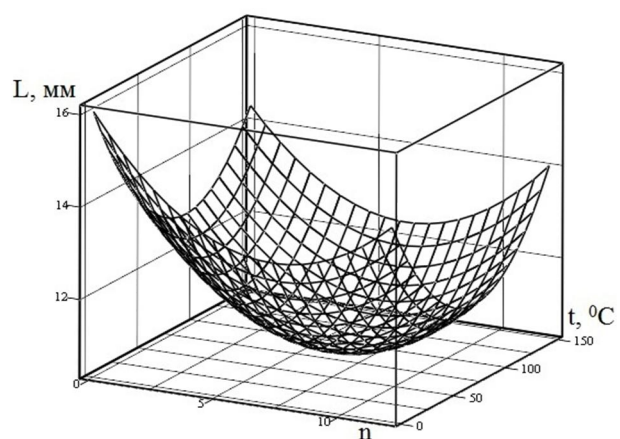| Coefficient	Breaking stress P [N]		Elongation at the moment of abruption L [mm]	
	in warp	in weft	in warp	in weft
b_0	1350.0	630.0	10.0	10.5
b_1	-3.333	11.50	0.565	-0.467
b_2	-30.021	-7.505	-1.602	-0.548
b_{12}	33.024	33.023	1.403	0.30
b_{11}	30.980	-13.759	3.550	1.850
b_{22}	30.151	-59.493	5.218	2.375

Figure 10 The diagram of dependency of the breaking stress *P* for the FlameStat Lite material in warp on the number of washings *n* and on the temperature of the heat chamber *t*
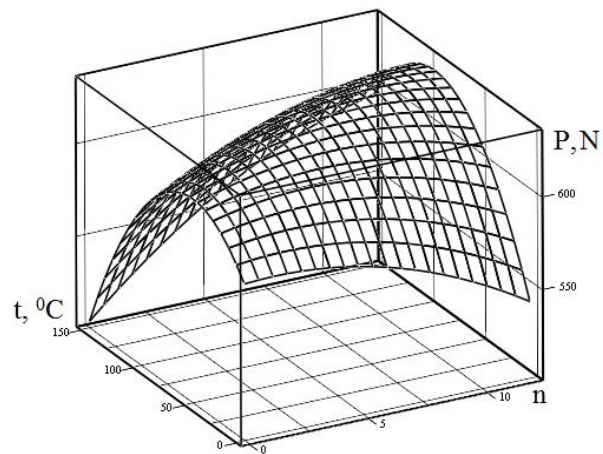
Figure 11 The diagram of dependency of the breaking stress *P* for the FlameStat Lite material in weft on the number of washings *n* and on the temperature of the heat chamber *t*
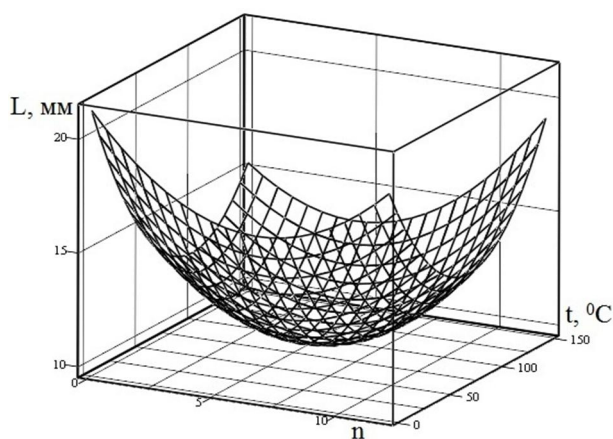
Figure 12 The diagram of dependency of the elongation at the moment of abruption *L* for the FlameStat Lite material in warp on the number of washings *n* and on the temperature of the heat chamber *t*

Figure 13 The diagram of dependency of the elongation at the moment of abruption *L* for the FlameStat Lite material in weft on the number of washings *n* and on the temperature of the heat chamber *t*

Table 6 Coefficients of the equation of regression, obtained as a result of data processing after tests of suiting fabrics RigChief

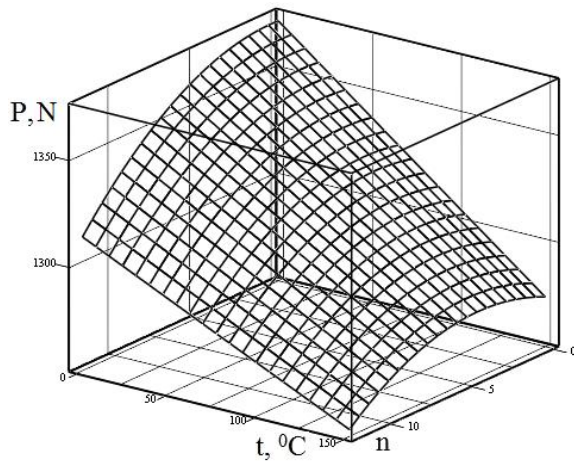| Coefficient	Breaking stress P [N]		Elongation at the moment of abruption L [mm]	
	in warp	in weft	in warp	in weft
b_0	1320.0	797.5	10.5	16.0
b_1	-19.783	37.417	0.90	-0.20
b_2	-39.403	-61.168	-1.501	-1.201
b_{12}	9.757	113.330	0.60	1.201
b_{11}	-16.019	-4.261	2.650	4.20
b_{22}	0.060	-66.515	5.115	6.730

Figure 14 The diagram of dependency of the breaking stress P for the RigChief material in warp on the number of washings n and on the temperature of the heat chamber t
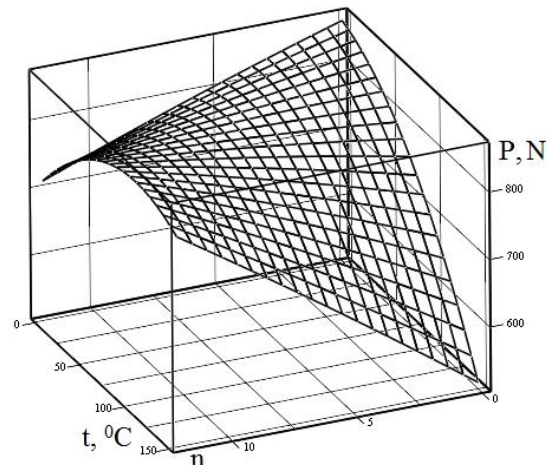

Figure 15 The diagram of dependency of the breaking stress P for the RigChief material in weft on the number of washings n and on the temperature of the heat chamber t
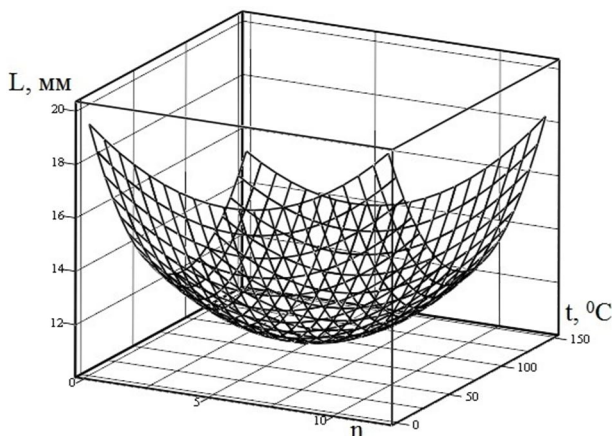

Figure 16 The diagram of dependency of the elongation at the moment of abruption L for the RigChief material in warp on the number of washings n and on the temperature of the heat chamber t
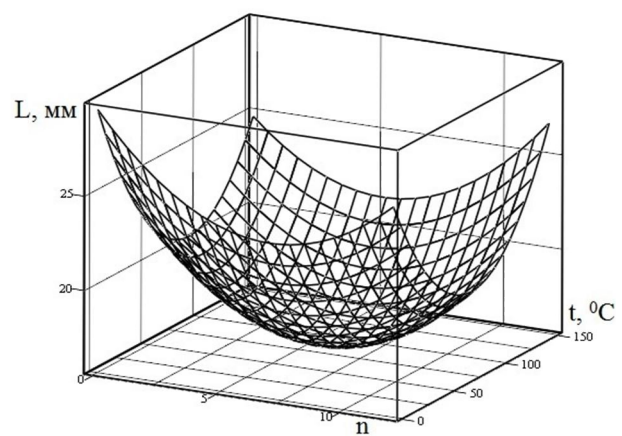

Figure 17 The diagram of dependency of the elongation at the moment of abruption L for the RigChief material in weft on the number of washings n and on the temperature of the heat chamber t

The significance of the factors was tested using the Student criterion and the adequacy of equations of regression during the experiment – using the Fisher criterion [4].

The insignificant coefficient b_2 of the equation of regression, obtained as a result of data processing after tests of suiting fabrics Nomex BV-120 in weft, since its absolute value is less than the value of the confidence interval, that is, $b_2 = 0.038 < \Delta b_i = 0.4652$. Also, the insignificant coefficient b_{22} of the equation of regression, obtained as a result of data processing after tests of suiting fabrics RigChief in warp, since $b_{22} = 0.060 < \Delta b_i = 0.5442$. Estimated value of the Fischer criterion F_{rozr} of the obtained test model of suiting fabrics Nomex BV-120 in warp – 3.1762, in weft - 3.1134; suiting fabrics XB 9340 in warp - 3.0263, in weft - 3.1074; suiting fabrics FlameStat Lite in warp - 2.9874, in weft - 2.9713; suiting fabrics RigChief in warp - 3.2571, in weft - 3.2144. Table value of Fisher's criterion F_{tabl} is 4.03. Since $F_{rozr} < F_{tabl}$ has no reason to reject the hypothesis of the adequacy of models.

Some graphic dependencies show that breaking stress (Figures 6, 7, 11) and elongation at the moment of abruption (Figures 4, 8, 9, 12, 13, 16, 17) have pronounced extreme character because of the number of washings and the temperature of the heat chamber. We can talk about the existence of optimal number of washings and temperature of the heat chamber.

The limits of variation of the factors of full-scale experiment are technologically grounded because they cover a wide range of operational characteristics of heat-resistant textile materials.

Results of the obtained graphical dependencies provide us with opportunity to make a conclusion about the existence of points that correspond to the rational choice of parameters, which can be found by the way of determination of the function extremum, differentiating the equation of regression (1) for each of the varied factors.

4   CONCLUSIONS

As a result of the experimental researches, the dependencies of changes in reliability indexes were determined. Experimentally obtained equations of regression provide with the opportunity to predict the behavior of the materials as a result of operating loads, such as the breaking stress and the elongation at the moment of abruption on the number of washings and the temperature of the heat chamber.

Experiments proved that selected materials change their properties after 12 washing cycles within acceptable limits. Conducted experimental researches on determination of dependencies of changes in the breaking stress and the elongation at the moment of abruption after the wet processing

(washings) allow to state that all selected materials can be used in manufacturing of protective clothing for rescue operations. It was found that that material Nomex BV-120 met all the requirements the best.

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