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ELECTROSTATIC PROPERTIES OF SELECTED PERSONAL PROTECTIVE EQUIPMENT REGARDING EXPLOSION HAZARD

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Abstract
In industries such as the mining, petrochemistry or power industries, personal protective equipment is often used in explosive atmospheres. What causes the occurrence of explosive hazards is ever-present in the work environment they include, electrostatic phenomena as well as the build-up of electrical charges on the surface of the protective equipment used. This paper presents the results of studies which were aimed at determining the fundamental electrostatic parameters of protective helmets as well as eye and face protection, surface resistance and the voltage of electrostatic fields. Examinations on the typical structure of the above mentioned equipment was conducted including the variable values of ambient humidity, which can occur in the working environment and with the use of various types of materials used to generate a charge. The adopted methods and testing equipment have been presented. Using the current, general requirements regarding the electrostatic properties of materials, the examined helmets and eye protection were assessed for their use in explosive atmospheres.

Keywords
electrostatics, protective helmets, eye and face protection, resistance, electrostatic field voltage, individual protection equipment, zone of explosion hazard

1. INTRODUCTION

Static electricity is a common phenomenon commonly observed both in natural conditions as well as workstations in the industry.

State of being charged with static electricity arises in most cases as a result of physical and chemical changes or pro-cesses of dynamic nature, and can be a direct effect of hu-man activity. The resulting electrostatic charge generally builds up on the materials of low electrical conductivity or conductive objects, isolated with dielectric materials of leakage resistance $R_u > 10^6$ Ω (Wytyczne… 1984; PN-E--05200:1992). It can cause a number of various disturbances in the working environment, and above all: fire-explosion hazard, technological disturbances in the course of the production processes and disruptions in the functioning of measurement and control equipment.

The occurrence of static electricity – especially in areas where explosive mixtures may be present – is especially dangerous from the point of view of potential consequences to employees. Therefore, in accordance with the ATEX directive (Directive 1999) in an explosive atmospheres, all potential sources of ignition must be eliminated. Personal protective equipment such as garments, industrial safety helmets, eye and face protection, footwear – mostly made of plastic with low electrical conductivity may contribute to the development of dangerous spark discharge or brush discharge (Kowalski, Wróblewska 2002; Vogel et. al 2002; Domaradzka-Nicińska, Wróbel 2002). In a situation when the energy of a discharge is greater than the minimum ignition energy of an explosive atmosphere (PN-E-05201:1992), these materials may be a source of ignition. Therefore, in areas of explosion risk, personal protective equipment should be used which has been verified in terms of electrostatic properties. During the verification, special attention ought to be paid to:

- materials, from which elements of personal protective equipment are made can be subject to dangerous charge with static electricity in conditions of their use
- wearing personal protective equipment (putting it on and taking it off) can cause dangerous electrification

Specific requirements for some of the products are contained in the relevant harmonized standards with Directive 89/686/EWG (Directive 1989). Currently, there are three standardized test methods. Two of them – PN-EN 1149--1:2008 and PN-EN 1149-2:1999 – refer to determining the surface and volume resistance of materials, and the third – PN-EN 1149-3:2007 – is for determining the charge decay time and shielding ratio for clothing materials. To date, however, no established standards have been developed to provide detailed requirements and test methods for industrial protective helmets and eye protection to enable the assessment of their suitability in explosive atmospheres. It has not been clearly established if these products pose a potential hazard in these areas. Due to this fact, the Central Institute for Labour Protection-National Research Institute (CIOP-PIB), undertook the task of developing testing methods and testing standards for protective helmets and eye protection, to assess their suitability in hazardous areas.

2. ELECTROSTATIC PHENOMENA

Static electricity is treated as a set of phenomena associated with the formation and accumulation of electrostatic charges on materials with low electrical conductivity and on conductive objects isolated from the ground. Electrostatic charges are created as excess electrical charges.

In most cases, one has to deal with "contact" electrification, i.e. a situation in which an electrostatic charge is formed as a result of affecting the electrical equilibrium on the surface of two bodies (materials) at their mutual contact. If, in the system of bodies in contact (materials), one of them is a grounded conductor, then the charge remains on the non-conductive material only. Due to the limited mobility of this type of charge, it is referred to as an "electrostatic" charge. The size and the sign of the resulting electrostatic charge depends on such factors as the chemical composition, the physical state and structure of the material, type and the amount of admixtures of foreign substances in the electrifying bodies and the electrical conductivity of the material. The electrostatic properties of the materials to the greatest extent determine the following parameters:

Leakage resistance R_u, which primarily determines the possibility for the accumulation of an electrostatic charge on the material. This refers to the total electrical resistance, measured between the surface of the object in question and the ground. It is therefore a transition resistance to the ground, the value of which, in addition to the conductivity of the material of a given object, is also affected by the resistance of separating it from ground construction materials. An electrostatic charge cannot be accumulated on objects where leakage resistance fulfils the condition $R_u \leq 10^6\ \Omega$.

Permittivity is the ability of a material to produce and maintain an electrostatic charge. Knowledge of the relative permittivity ε facilitates approximately assessing the expected electrification of a given material. In particular, the degree of its static electricity charge, achieved in contact with different materials, is greater the bigger the difference between the electrical permeability of this material and the permeability of the material in contact with it.

The relaxation time of an electrostatic charge τ, determines the rate of removal of the electrified material or object. This is the time during which the degree of static electricity in the material is reduced to about 27% of the initial value of the generated charge. It can be expressed as the product of the permittivity $\varepsilon_0\varepsilon$ and volume resistance ς_v of a given material ($\tau = \varepsilon_0\varepsilon\varsigma_v$) or the product of leakage resistance R_u and electric capacity C, if the electrostatic charge is accumulated in isolated form with a ground conductive object ($\tau = R_uC$). The above takes place when a loss of charge takes place through leakage resistance R_u, a situation is not taken into account when a dominating part plays the process of discharging conditions e.g. by the depolarization of a material or the desorption of ions. It is accepted (Wytyczne 1984; Directive 1999), that the total disappearance of electrostatic charge takes place after the passage of the so-called time of complete discharge t_w ($t_w = 5\ \tau$).

The electrical conductivity of materials, which plays a decisive part in maintaining the electrified state of an object is expressed by the value of volume resistance ς_v and surface resistance ς_s (Wytyczne 1984; Directive 1999; Pidoll 2002). It is accepted that:

1) Materials that become electrified share the following characteristics:
   - small electrical conductivity, for which volume resistance is $\varsigma_v > 10^4\ \Omega$m or surface resistance is $\varsigma_s > 10^7\ \Omega$,
   - conductivity, these are materials for which volume resistance is $\varsigma_v \leq 10^4\ \Omega$m or surface resistance is $\varsigma_s \leq 10^7\ \Omega$, and are isolated from the ground with non-conductive materials, for which volume resistance is $\varsigma_v > 10^7 \Omega$m or surface resistance is $\varsigma_s > 10^{10}\ \Omega$.
2) For permanent electrification to occur, volume resistance of $\varsigma_v > 10^7\ \Omega$m, surface $\varsigma_s > 10^{10}\ \Omega$ in cases of solid bodies and volume resistance of $\varsigma_v > 10^8\ \Omega$m in case of liquids must be present; the electrification of such materials generally results in disturbances in the environment surrounding it or production processes have been carried out with their participation.
3) Materials of volume resistance $10^4\ \Omega\text{m} < \varsigma_v \leq 10^7–10^8\ \Omega$m or surface resistance $10^7\ \Omega < \varsigma_s \leq 10^{10}\ \Omega$ generally show a slight capability of electrification and in contact with the grounded, conductive elements of the production equipment, quickly lose its generated charge.
4) Materials with volume resistance $\varsigma_v \leq 10^4\ \Omega$m and surface resistance $\varsigma_s \leq 10^7\ \Omega$ are considered to be conductive, i.e. unable to accumulate an electrostatic charge, under the condition that they are not isolated from the ground with non-conductive materials.

Electrostatic discharge is dangerous, when its energy W_w reaches the value of the so-called minimum energy of ignition W_{zmin} of combustible material, it is possible to be within the range of this discharge, i.e. when $W_w \geq W_{\text{zmin}}$, where $W_{z\text{min}}$ is understood as the lowest energy of electrostatic discharge, which in determined conditions is still sufficient to cause ignition of a given combustible or explosive medium.

3. PROTECTIVE HELMETS

Protective helmets differ in purpose and design, but three elements that they do have in common can be identified: a shell, a harness and a main strap.

The shell is the outer part of the helmet which gives it a basic shape. Its primary objective is to take an impact, partially absorb its energy and transfer its remaining part to the harness. Due to the size of the surface it has the greatest impact on electrical properties of protective helmets. The most commonly used today for the production of shells are polythene, ABS and glass mat composite cured with synthetic resins (Table 1).

Table 1. Selected properties of plastic used more frequently for the production of protective helments (Szlezyngier 2001)

Material	Density g/cm^3	Volume resistance Ω*m*	Dielectric constant for *f* = 50 Hz	Dielectric strength, kV/mm
Polythene	0.92–0.96	$10^{12}–10^{17}$	2.2–2.4	15–25
Polystyrene	1.0–1.1	$10^{11}–10^{17}$	2.4–3.4	18–30
ABS	1.01–1.2	$10^{12}–10^{17}$	2.6–3.6	17–30
Epoxide resin	1.1–1.9	$10^{10}–10^{15}$	3.1–6.5	16–25
Polyurethane resin	1.15–1.22	$10^{11}–10^{13}$	3.5–5.0	15–28

A harness and a main strap make up the inside of the helmet, linked with appropriate hooks with the shell. It has the form of a strap system made of polyamide textile tapes or low-pressure polyethylene. Their main task is to keep the helmet stable on the head of the user, absorb impact energy and distribute, in such a case, forces acting on a large surface area of the head. This is the element that electrically connects the helmet shell with the head and hair of the wearer. At this point, owing to the friction of the harness elements with hair, an electric charge can be generated. An example of helmet structure is shown in Photo 1.

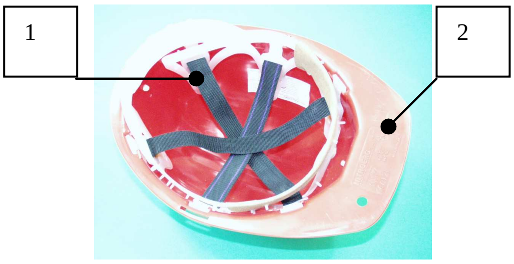

Photo. 1. Example of protective helmet structure: 1 – harness, 2 – shell

The object of the study held in CIOP-PIB of electrostatic properties were helmets presented in Table 2.

Table 2. Protective helmets selected for the study

Helmet marking	Material of shell		Material of harness	No. of samples
A	homogeneous materials	ABS – poly(acrylonitrile-co-butadiene-co-styrene	PE – polythene	**5**
B		HDPE – high density polythene	PE – polythene PA – polyamide	**5**
C		PE – polythene	PE – polythene PA – polyamide	**5**
D	heterogeneous materials	glass fibres, carbon and epoxy resin	PA – polyamide	**5**
E		glass fibres and polyester resin	PE – polythene PA – polyamide, aramid	**5**

4. EYE AND FACE PROTECTION

Personal protective equipment designed to protect the eyes and face from four basic categories:

- safety glasses
- safety goggles
- face shields
- welding shield (this category of eye protection includes welding shields, helmet shields, goggles and hoods).

In the enumerated categories of eye protection visors, protective shields, mesh or filters are mounted. Eye protection can also be part of respiratory protective equipment or head protection. All categories of eye protection consist of a transparent part and the frame or body with a harness.

The most important common element in most of the above categories of eye protection is the protective shield. Its main task is to protect against impact. It is made of polymethyl methacrylate, cellulose acetate, and (predominantly) polycarbonate with a thickness from 0.25 to 3 mm. This material is characterized by its very high mechanical strength, and the natural ability to absorb ultraviolet radiation and the ability to colour the material in mass. The main disadvantage of polycarbonate – mainly due to the electrostatic properties such as high resistance, limited possibilities of discharge or easiness of introducing charges on the surface – is the possibility of bringing about hazards in areas where there is an explosive atmosphere. In addition, it has a relatively low resistance to scratching. This disadvantage is eliminated by applying hardening layers to the surface. It is also common to apply an anti-fog layer on the internal part of shield. All applied coatings can have a significant impact (both positive and negative) on the electrostatic properties of eye and face protection.

For this study, personal protective equipment for the eyes and face were selected and are presented in Table 3.

Table 3. Personal protective equipment selected for the study

No. of sample	Name of the product	Photograph	Materials used for construction: visor/frame
1	Protective glasses		PC/PE
2	Protective goggles		PC/PCV
3			PC/PCV
4	Face protection		PC/PE

5. METHODOLOGY OF THE STUDY

Today there are several methods adopted to assess the suitability of products for use in explosive areas. Among them, there is a group of methods including the ignition ability of explosive mixtures by electrification of samples of materials or entire products (Ptasiński, Żegleń 2001). Another group of methods for such an assessment is based on measurements of the charge transferred in an electric discharge. These methods result from the thesis that there is a correlation between the charge displaced in an electrostatic discharge and the probability of the ignition of flammable or explosive mixture (von Pidoll, Brzostek, Froechtenigt 2002; von Pidoll 2002; Ebadat 2002). The next group of methods is based on studying the electrostatic properties of materials used in their manufacture. According to the currently applicable standards (PN-EN-05200:1992), a product is anti-electrostatic if it is made of a material which in conditions of use, does not electrify or electrifies to an acceptable level. Due to the specific design of the equipment, which is the subject of this study and the materials used to produce them, it was decided in order to assess electrostatic properties, to choose methods based on the measurement of surface resistance and the voltage value of any charge accumulated on the surface. To take into account the actual conditions that would prevail in the workplace, it was decided to pre-condition tested products within 24 hours. The adopted conditions are summarized in Table 4.

Table 4. Adopted conditioning

Conditioning	Conditioning (ambient air)
X	temperature 21°C, humidity 53%
Y	temperature 21°C, humidity 65%
Z	temperature 21°C, humidity 95%

6. SURFACE RESISTANCE OF HELMETS

To determine the resistance it was necessary to apply an appropriate system of electrodes. Due to the complicated shape of helmets and eye protection, and the lack of flat elements on their structures and to facilitate the use of standard electrodes (EN1149-1:2006) it was decided to apply electrodes (Photo 2) using an electrically conductive coating with the addition of silver – ELECTRONE 40AC. Geometrical parameters of used strap electrodes (the length and the distance between them) were selected so that the geometric ratio of electrodes necessary to determine the resistance was 10, i.e.:

$$\varsigma_s = kR_s$$

where:

k – geometric ratio of measurement electrodes
R_s – surface resistance
ς_s – surface resistivity

The diagram of the measuring system is shown in Figure 1.

The electrodes (3) have been connected to high resistance meter type TO-3 (Germany) (1) to measure the resistance in the range from 10 TΩ to 160 TΩ while measuring voltage between 100 and 500 V. The measurement sample was placed in a Faraday cage (2) during the measurement. When a voltage was applied, resistance of the sample was recorded every 1 second. Measurements were performed under conditions labelled as X after previous conditioning (Table 4).

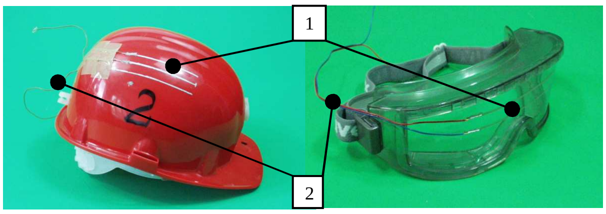

Photo. 2. The electrodes with an electrically conductive coating: 1 – applied electrodes, 2 – connection cables

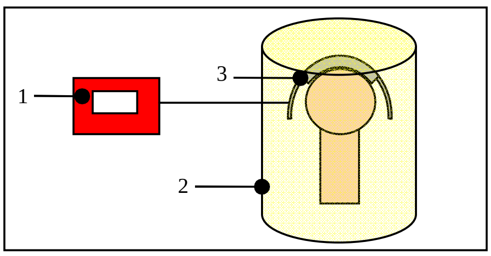

Fig. 1. Scheme of measuring system: 1 – high resistance meter, 2 – Faraday cage, 3 – tested product

7. ELECTROSTATIC VOLTAGE

In actual conditions, when in use, helmets and eye protectors are usually electrified by friction. Therefore, the measurement of electrostatic voltage, generated on the surface of products, was made after prior electrification by rubbing them. For this purpose, the samples were rubbed by hand with a frequency of 1 Hz for 30 seconds. Three types of materials were used for this purpose:

- bristle (brush)
- plastic material (fleece)
- human hair (wig).

The diagram of the measuring system is shown in Figure 2.

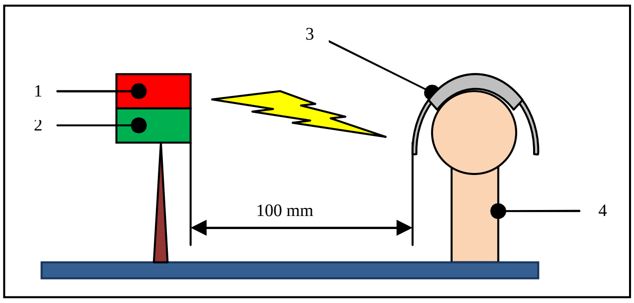

Fig. 2. Scheme presenting the way of electrostatic charge measurement: 1 – voltage meter box, type JCI 140 (USA), 2 – laser distance meter, 3 – examined product, 4 – model of the head

Voltage measurement was performed using voltage electrostatic field meter type JCI 140 (USA) and placed – in accordance with the instructions – in a distance of 100 mm from the electrified product located on the model of the head. Measurements regarding distance were made using a laser distance meter.

8. RESULTS OF THE STUDY AND DISCUSSION

The following analysis of the results did not take into account the measurement uncertainty resulting from the metrological properties of the equipment used, since on the basis of the calibration certificates held it was decided that it is considerably small in comparison with the standard deviation values obtained.

8.1. Surface resistance

All tests of resistance were carried out under conditions specified in Table 4 as X, Y, Z. Just before measurements were taken, the samples were conditioned as specified in the same Table. The results of the helmet tests of are shown in Table 5.

Table 5. Test results of surface resistance of protective helmets

Marking of sample (according to Tab. 2)	Conditioning (according to Tab. 4)	Average value of resistance, Ω		Standard deviation	
		voltage, V			
		100	500	100	500
A	X	7.18E+13	6.56E+13	2.39E+12	1.33E+12
	Y	1.95E+14	1.78E+14	1.05E+13	7.53E+12
	Z	1.16E+13	2.06E+12	7.53E+10	5.16E+09
B	X	8.06E+12	9.61E+12	9.33E+10	2.59E+10
	Y	1.59E+12	8.90E+11	4.17E+09	1.68E+10
	Z	4.46E+11	1.02E+11	4.17E+09	9.83E+07
C	X	9.30E+13	3.35E+13	1.58E+12	3.70E+11
	Y	2.72E+12	1.65E+12	6.53E+09	8.94E+09
	Z	6.20E+11	1.13E+12	1.17E+09	9.52E+09
D	X	1.04E+11	1.01E+11	2.41E+08	3.49E+08
	Y	1.80E+11	2.80E+11	1.38E+09	2.64E+09
	Z	1.75E+11	1.64E+10	7.53E+08	2.80E+08
E	X	5.81E+09	5.43E+09	7.07E+06	1.67E+06
	Y	1.60E+08	1.32E+08	3.27E+05	3.78E+05
	Z	5.90E+07	3.51E+07	5.75E+05	1.05E+05

Results of testing eye protection are presented in Table 6.

Table 6. Results of testing surface resistance of eye protection

Marking of the sample (according to Tab. 3)	Conditioning (according to Tab. 4)	Average value of resistance, Ω		Standard deviation	
		voltage, V			
		100	500	100	500
1	X	8.49E+11	8.37E+11	1.52E+10	2.65E+10
	Y	7.995E+11	6.475E+11	2.34E+11	3.27E+11
	Z	7.67E+11	6.34E+11	3.66E+10	1.34E+11
2	X	8.7E+11	8.72E+11	1.28E+09	3.16E+09
	Y	8.7E+11	8.7E+11	7.55E+08	7.94E+08
	Z	8.31E+11	8.29E+11	1.00E+11	9.91E+10
3	X	1.34E+12	1.28E+12	3.67E+11	5.14E+10
	Y	1.27E+12	1.29E+12	9.24E+10	3.72E+11
	Z	1.28E+12	9.27E+11	3.47E+10	2.38E+11
4	X	3.52E+12	3.62E+12	2.59E+11	2.64E+11
	Y	2.237E+12	2.082E+12	2.03E+12	6.25E+11
	Z	1.77E+12	3.23E+12	1.32E+12	2.80E+12

After analysing the results of the surface resistance of helmets, it can be said that:

- During measurements carried out on the same helmet, satisfactory concurrence of results was visible, since the standard deviation was within the range from 1.05E5 for the value of 3.51E7 Ω to 1.05 Ω E13 for the value of 6.56E13 Ω, thus from 0.3 to 16% in relation to the average value.
- The highest resistance was displayed by helmets made of ABS – 1.95E14 Ω and helmets B and C made of polythene – 9.30E13 Ω, the lowest resistance was found in helmets E, it was made of heterogeneous materials, i.e. glass fibre and polyester resin – 3.51E7 Ω, the resistance values obtained were close to the theoretical resistance value of any other given material.
- With the increase in the ambient humidity (from 53, through 65, to 95%) and the decreased surface resistance of the helmet, the greatest differences were seen in the case of helmet B – from 9.61E12 to 9.02E10 Ω, C, – from 9.3E13 to 6.2E11 Ω and E – from 5.43E9 to 3.51 E7 Ω.
- Differences in resistance, due to the voltage used for the tests, only exceeded 10% in two cases, that is for helmet B after conditioning Z and for helmet C after conditioning X.

Analysing the results of the surface resistance of eye and face protection, it can be said that:

- The values of surface resistance obtained during tests using strip electrodes in most cases showed a large analogy with the theoretical values of resistance of given materials. Small differences are due only to differences of polycarbonate composition, the method of its preparation and processing by individual manufacturers and any additional coating changing the properties of the base material (coating to prevent fogging – Antifog).
- The results from the standpoint of prior conditioning show very slight decreases in the resistance with increasing ambient humidity. The largest differences were for sample no. 1 – from 8.37E+11 to 6.34 E+11 and for sample no. 4 – from 3.52E+ to 1.77E +12.
- Differences in resistance, resulting from the voltage used for the measurement, in some cases exceeded 20%, e.g. for sample no. 1 after conditioning Y, for sample no. 3 after conditioning Z and for sample no. 4 and after conditioning Z.

8.2. Electrostatic voltage

All tests concerning electrostatic voltage were carried out under the conditions described in Table 3 as X. Immediately before performing the measurements the samples were conditioned under X as shown in Table 4 for 24 hours. The results concerning helmets are shown in Table 7.

Table 7. Results of testing voltage of electrostatic filed for protective helmets

		Voltage *U*, kV					
		Materials for rubbing, by means of which the sample was charged with static electricity					
		bristle (brush)		artificial material (fleece)		human hair (wig)	
		1 – right side of the helmet, 2 – left side of the helmet					
Marking of sample (according to Tab. 2)		1	2	1	2	1	2
A	mean value	2.54E-01	3.53E-01	9.78E-01	4.70E-01	1.29E+00	1.16E+00
	standard deviation	7.26E-03	5.00E-03	6.67E-03	2.45E-02	6.72E-02	5.01E-02
B	mean value	2.40E+00	2.37E+00	5.56E+00	4.49E+00	5.57E+00	5.44E+00
	standard deviation	6.73E-02	3.50E-02	1.03E-01	3.93E-01	1.29E-01	1.64E-01
C	mean value	1.07E+00	1.07E+00	1.51E+00	1.45E+00	4.46E+00	4.37E+00
	standard deviation	4.69E-03	1.03E-02	6.40E-03	3.34E-03	2.37E-02	3.69E-02
D	mean value	3.80E-02	1.28E-01	5.01E-01	2.76E-01	6.10E-02	1.76E-01
	standard deviation	4.22E-03	4.22E-03	1.29E-01	1.30E-01	6.64E-02	6.42E-02
E	mean value	5.21E-01	5.29E-01	5.09E-01	4.89E-01	5.83E-01	4.92E-01
	standard deviation	3.16E-03	3.16E-03	3.16E-03	3.16E-03	4.83E-03	4.22E-03

The results of eye and face protection are shown in Table 8.

Table 8. The results for voltage electrostatic field of eye and face protection

		Voltage *U*, kV					
		Materials for rubbing, static electricity with which the sample					
		bristle (brush)		artificial material (fleece)		human hair (wig)	
		Another series of measurements		Another series of measurements		Another series of measurements w	
Sample marking (according to Tab. 3)		1	2	1	2	1	2
1	mean value	1.72E+00	2.51E+00	1.27E+00	3.10E+00	3.88E+00	2.84E+00
	standard deviation	7.78E-02	3.04E-02	5.77E-02	3.75E-02	1.76E-01	3.50E-02
2	mean value	6.93E-01	6.11E-01	7.53E-01	4.43E-01	2.20E+00	1.94E+00
	standard deviation	7.78E-03	3.96E-02	8.46E-03	2.87E-02	2.47E-02	1.26E-01
3	mean value	8.00E-01	8.64E-01	8.51E-01	9.81E-01	2.49E+00	2.34E+00
	Standard deviation	6.49E-03	6.07E-03	6.90E-03	6.90E-03	2.01E-02	1.64E-02
4	mean value	7.05E+00	9.22E+00	4.83E+00	1.36E+01	9.14E+01	1.01E+02
	standard deviation	6.51E-01	3.74E-01	4.46E-01	5.50E-01	8.44E+00	4.12E+00

By analysing the results of electrostatic voltage on helmets, it can be said that:

- The values of the voltage are greatly dependent on the material with which the surface was electrified – for a given helmet within the range of:
  helmet A: 0.1–1.2 kV,
  helmet B: 0.25–5.6 kV,
  helmet C: 0.28–4.46 kV,
  helmet D: 0.04–0.5 kV,
  helmet E: 0.49–0.76 kV.
- Helmets D and E, made of laminate, were characterized with the smallest change of values of measured voltage due to changes of material, by means of which they were electrified, that is from 6.1E-2 kV to 1.28E-1 kV for helmet D and from 7.59E-1 kV to 4.89 E-1 kV for helmet E. In other cases, the highest efficiency was obtained for the electrification of natural hair, when the values of voltage of the electrostatic field for helmet A came to 1.29 kV, the helmet B – to 5.57 kV and for a helmet C – up to 4.46 kV.
- The highest repeatability while changing the place of measurement was obtained for products made of homogenous material injection. In only one case he difference of the measured values exceeded 5% – for helmet B during electrification with fleece it was 1.07 kV, or 19%. For helmets made of heterogeneous materials, such as in the case of helmet E, during electrification with bristle brush, the difference exceeded 70%.

The results of electrostatic voltage for each type of eye and face protection, depending on the material with which they were electrified, fall into the range:

- product no. 1: 1.27–3.88 kV,
- product no. 2: 0.61–2.2 kV,
- product no. 3: 0.8–2.49 kV,
- product no. 4: 4.83–1.01 kV.

In this case, the face protection equipment marked in Table 3, product no. 4 showed the greatest susceptibility to the way (material) of electrification.

The above data shows that with the increase of the surface area of eye and face protection, on which a charge was introduced, the value of electrostatic voltage increases.

9. SUMMARY

Summing up the results obtained in this study and applying it to the existing criteria for evaluating materials from the point of view of the possibility of their use in potentially explosive atmospheres (Directive 1999; PN-E-05201:1992), the following conclusions can be drawn:

- Criterion of resistance

This specifies the minimum value of the critical resistance to materials from the point of view of the possibility of their use in explosive areas. For all explosive mixtures:

- surface resistance of $\varsigma_s \leq 10^7$ Ω,
- with ignition energy of 10^{-4} J < $W_z \leq 0.1$ J, it can be allowed to use the materials with surface resistance of 10^7 Ω < $\varsigma_s \leq 10^{10}$ Ω.

Therefore, the surface resistance criterion was met only for helmet E, at ambient air above 65%.

- Voltage criterion

It specifies the maximum value of the critical surface potential of materials from the point of view of the possibility of their use in explosive areas. Surface potential at a time when the product is in use and in the presence of flammable material should have a minimum ignition energy of:

- $W < 0.1$ mJ should be less than 1 kV,
- 0.1 mJ < W < 0.5 J should be less than 3 kV.

This criterion for combustible materials of minimum ignition energy $W_z < 0.1$ mJ was met only by two types of protective helmets, and only one protective helmet and safety goggles for substances of ignition energy of 0.1 mJ < W_z < 0.5 J – was found. All of the tested protective goggles and face shield exceeded the established threshold.

The obtained results indicate that the products analysed, despite their relatively small size, are able to accumulate an electric charge in environments where explosive mixtures are found. This means that in the case of helmets and eye and face protection – as in the context of protective garments – in explosive atmospheres, equipment having laboratory-confirmed anti-static properties must be used.

It is necessary to conduct further research in this area so as to improve the method of evaluating and selecting personal protective equipment for zones where explosions may occur.

Of course, there are other criteria that can serve to assess the electrostatic properties of materials. As presented in this article, the methods and results of the study, according to the author, are characterized by the highest repeatability, and conducted tests have confirmed the correctness of the selection of the equipment and the methods used to determine the surface resistance and voltage of the electrostatic field in materials of uneven shape, such as shells of protective helmets and visors. Therefore, it can be assumed that they can be regarded as reliable tools for the evaluation of electrostatic properties.

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