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# CORRELATION BETWEEN ELECTRICAL AND MECHANICAL CHARACTERISTICS OF CABLES WITH RADIATION-MODIFIED INSULATION ON THE BASIS OF A HALOGEN-FREE POLYMER COMPOSITION

*Introduction. The high saturation of the cable routes of nuclear and thermal stations, wind parks and solar power plants, on-board systems imposes stringent requirements in the field of fire safety of cables, which makes it necessary to use highly flame retardant halogen-free compositions. The introduction of flame retardants causes the mandatory modification (crosslinking) of the polymer matrix. Purpose. Determination of the optimal radiation dose based on the correlation between the mechanical and electrical characteristics of a radiation-modified halogen-free ethylene vinyl acetate copolymer with high-strength flame retardant insulation cables. Methodology. Mechanical and electrical tests of samples of radiation-modified cables with a copper conductor cross section of 1.0 mm$^2$ and a halogen-free filled insulation based on an EVA copolymer with a thickness of 0.7 mm have been performed. Results. A strong correlation is established between the elongation at break and the tensile strength, between the insulation resistance and the breakdown voltage. It is shown that at the optimum value of the irradiation coefficient in the range from 7 to 5, the insulation resistance increases more than twice, and the breakdown voltage at the direct current is increased by 1.3 times. The elongation at break is within the allowed values.* References 12, figures 3.
*Key words:* **halogen-free composition, radiation modification, irradiation coefficient, mechanical and electrical characteristics, correlation coefficient.**

***Исследовано влияние коэффициента облучения ускоренных электронов с энергией 0,5 МэВ на механические и электрические характеристики кабельной высоконаполненной антипиренами изоляции из не распространяющей горение безгалогенной композиции на основе сополимера етиленвинилацетата. Установлена сильная корреляционная связь между относительным удлинением при разрыве и прочностью при растяжении, между сопротивлением изоляции и пробивным напряжением. Показано, что при оптимальном значении коэффициента облучения в диапазоне от 7 до 5, сопротивление изоляции возрастает более чем в два раза, а пробивное напряжение на постоянном токе – в 1,3 раза. Относительное удлинение при разрыве остается в пределах допустимых значений.*** Библ. 12, рис. 3.
*Ключевые слова:* **безгалогенная композиция, радиационное модифицирование, коэффициент облучения, механические и электрические характеристики, коэффициент корреляции.**

**Introduction.** High saturation of the cable routes of nuclear and thermal stations, wind parks and solar power stations, on-board systems makes stringent requirements in the field of fire safety of cables [1]. All this necessitates the use of new class materials, such as halogen-free compositions, for the insulation and sheath of cables. The term «halogen-free composition» is not a strict designation of the polymer from a technical point of view, such as polyethylene or polyvinyl chloride. However, this term is used in the cable industry and in fact is a separate class of materials [1]. Halogen-free compositions are polymeric materials that do not contain or contain very little (less than 0.5 % by weight) halogens, and which do not spread combustion under the influence of fire. The absence of halogens in insulation, filling and sheathing of cables is one of the most important characteristics of their fire safety. To ensure high resistance to the spread of combustion, the polymer is filled with a large amount (up to 70 % by weight) of inorganic flame retardants (mainly aluminum or magnesium hydroxides). However, the introduction of fire retardants necessitates a mandatory modification (crosslinking) of the polymer matrix, which leads to the creation of a spatial structure. The most preferred method of crosslinking is radiation modification [2-4], in which the probability of formation of low-molecular products, including moisture, is significantly lower in comparison with the chemical method [5].

Sources of ionizing radiation for modifying the polymer insulation of cables and wires with conductor cross-section up to 240 mm$^2$ are electron accelerators with energies (0.3-5) MeV and power up to hundreds of kW [6, 7].

The required dose for polyethylene crosslinking is 20-40 Mrad [5, 8-11]. For fluoropolymers – from (0.5-2) to (20-30) Mrad [5]. Crosslinking of polymers allows to significantly increase their mechanical strength, heat resistance, resistance to the action of chemically active substances, cracking [8-11].

The most interesting as halogen-free compositions are compositions based on copolymers of ethylene (ethylene-vinyl acetate, ethylene-acrylate, ethylene-propylene, etc.) with the introduction of flame retardants and other additives in the polymer matrix that increase the resistance of the material to the spread of combustion, as well as better dispersion of fillers in the polymer [12].

The presence in the macromolecule of ethylene units, as well as double bonds, provides a polymer composition based on an ethylene-vinyl acetate copolymer, as well as polyethylene, crosslinking under the influence of ionizing radiation. The dose of irradiation is determined at the stage of investigation of the cable composition and cable development.

**The goal of the paper** is determination of the optimal radiation dose based on the correlation between the mechanical and electrical characteristics of a radiation-modified halogen-free ethylene vinyl acetate copolymer high-strength flame retardant cable insulation.

**Technological parameters of radiation modification.** When irradiated as a result of the ionization of molecules and the disruption of C-H bonds, free macroradicals and atomic hydrogen are formed in the polymer. As a result of further recombination of macroradicals and the formation of crosslinks between macromolecules, the polymer acquires a three-dimensional (spatial) structure. However, at irradiation, not only the process of crosslinking of macromolecules proceeds, but also the process of their destruction, caused by the rupture of valence bonds in the macromolecule. The possibility of carrying out the radiation crosslinking of a polymer is determined by the ratio of the rates of the «crosslinkage – destruction» processes and depends on which of these processes prevails.

The technological parameters of radiation modification and, as a consequence, the dose of irradiation, have a significant influence on the ratio of the processes of crosslinking and degradation.

At a fixed voltage of the electron accelerator, the technological dose of irradiation is directly proportional to the current of the electron beam and inversely proportional to the transmission speed of the cable under this beam [5]: $D = \frac{120 \cdot I \cdot N}{L\,V}$, Mrad, where $I$ is the electron beam current (mA), $N$ is the number of wire passes under the electron beam, $L$ is the length of the beam scan perpendicular to the direction of the workpiece pulling, $V$ is the velocity of the passage under the electron beam (m/min).

In practice, at the radiation modification of insulation and cable sheaths, the irradiation factor ($K$) is used, which is controlled by the change in the cable passage velocity under the electron beam at the electron beam current unchanged: the higher $K$, the less the irradiation of the material [5]. The radiation factor is the result of a compromise between the mechanical and electrical properties of the insulation and the technical requirements imposed on the finished cable.

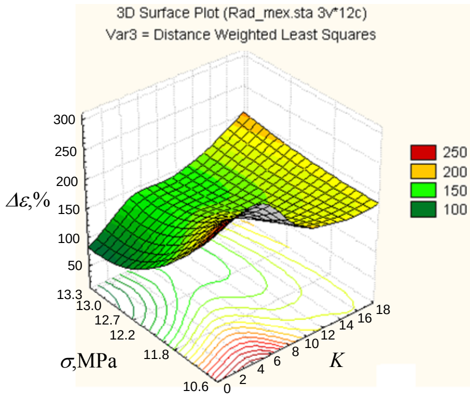
To ensure uniform crosslinking over the entire volume of insulation, the stability of the accelerator operation is a prerequisite, which makes the parameters of the electron beam constant.

**Test samples and parameters of irradiation.** On an industrial accelerator of charged particles ЕЛВ-1 radiation modification of samples of insulated wire 5 m long with copper cores of 1.0 mm$^2$ cross section has been carried out (Fig. 1). Insulation of 0.7 mm thickness is halogen-free composition based on ethylene-vinyl acetate copolymer, highly filled to 70 % by mass with flame retardants. The wire samples are irradiated with different irradiation factors $K$: 17; 15; 13; 11; 10; 9; 8; 7; 6; 5 and 4 at accelerated electron energy of 0.5 MeV. One sample is control one (not exposed to radiation). The electron beam current is 10 mA. The number of wire passes under the electron beam is 80.

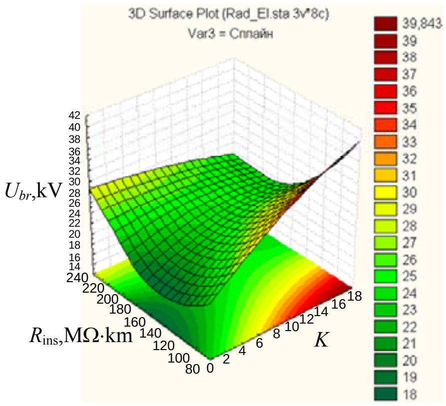
**Correlation between the electrical and mechanical characteristics of radiation-crosslinked insulation.** In the initial state (before irradiation) and after exposure, mechanical and electrical tests of wire samples were carried out.

Fig. 2 shows the correlation dependences of the mechanical (Fig. 2,*a*) and electrical (Fig. 2,*b*) characteristics on the irradiation factor: mechanical elongation at break $\Delta\varepsilon$ and the tensile strength $\sigma$ (Fig. 2,*a*); insulation resistance $R_{ins}$ and breakdown voltage $U_{br}$ (Fig. 2,*b*), respectively.

Fig. 1. The layout of the electron accelerator for irradiating insulation of cables and wires




*a*




*b*

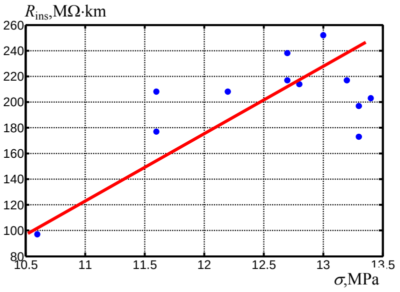
Fig. 2. To establish the correlation dependence between the mechanical (*a*) and electrical (*b*) characteristics of radiation-crosslinked insulation

A strong correlation is observed for mechanical and electrical characteristics. Here, between the relative elongation at break and the tensile strength this is negative; between the resistance of insulation and breakdown voltage this is positive. The correlation coefficients are 0.9189 and 0.8045, respectively. At decrease in the irradiation coefficient, i.e. with increasing radiation dose, tensile strength, insulation resistance and breakdown voltage at constant current increase to a certain value, after which they begin to decrease; the relative elongation at mechanical break decreases monotonically.

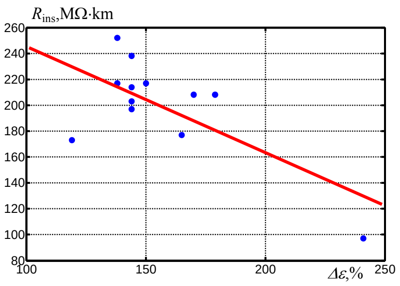
For mechanical characteristics, the correlation is more pronounced, which is also confirmed by the Spearman rank correlation analysis: a significance test for 100 % of the data at a *p*-level of 0.001496. For electrical characteristics, the significance test is only for 25 % of the measured values at a *p*-level of 0.617075.

Such a difference is due to the sample size of the samples measurements for each dose of radiation: the mechanical characteristics are averaged for 5 measurements, electrical – for the 1st one.

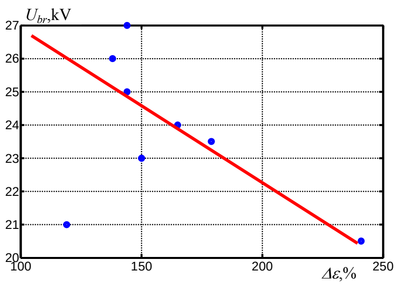
Between the mechanical and electrical characteristics there is also a correlation relationship (Fig. 3).



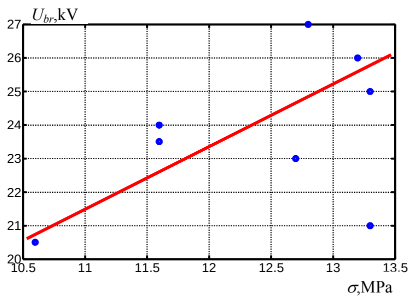

*a*




*b*




*c*




*d*

Fig. 3. Correlation dependence between mechanical and electrical characteristics of radiation-crosslinked insulation

The correlation coefficient between the insulation resistance and the tensile strength is positive and equal to 0.6253 (Fig. 3,*a*), between the insulation resistance and the relative elongation (Fig. 3,*b*) is negative and equal to **-0.7105**. The correlation between the breakdown voltage and the relative elongation (Fig. 3,*c*), between the breakdown voltage and the tensile strength (Fig. 3,*d*) is weak: the Pearson pair correlation coefficients are **–0.4980** and **0.4964**, respectively.

Considering that the resistance to radiation of materials is determined by the radiation index (RI) according to [2] as the logarithm of the absorbed dose in Grays, at which the relative elongation decreases by no more than 50 % (twice) relative to the initial value, the optimum value of the irradiation coefficient lies in the range from 7 to 5. In this range of values of the irradiation coefficient, the maximum value of tensile strength (see Fig. 2), insulation resistance and breakdown voltage at constant current is observed (see Fig. 3). The insulation resistance increases more than twofold, the breakdown voltage at constant current is 1.3 times that of the unirradiated state, which is associated with an increase in the homogeneity and orderliness of the molecular structure of the polymer after crosslinking. With a decrease in the irradiation coefficient, i.e. an increase in the irradiation dose, a trend is observed toward a reduction in electrical characteristics due to the accumulation in the polymer of charge carriers and free radicals formed during irradiation.

**Conclusions.**

The influence of the coefficient of irradiation of accelerated electrons with an energy of 0.5 MeV on the mechanical and electrical characteristics of a cable high-fire-retardant insulation made of a non-halogen composition based on an ethylene-vinyl acetate copolymer is investigated and a strong correlation relationship between the relative elongation at mechanical break and tensile strength, between insulation resistance and breakdown voltage is determined.

For the first time, the optimal range of the insulation coefficient of insulation of cables, ranging from 5 to 7, has been determined, with which the electrical insulation resistance increases more than twice, the breakdown voltage at constant current increases by 1.3 times, and the elongation at mechanical break remains within the permissible values.

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