UDC 538.971

# CALCULATION OF THE FREQUENCY ELECTRONIC TRANSMISSION FACTORS AT THE PASSAGE THROUGH THE POLYMERIC POLYIMIDE COMPOSITE MATERIAL FILLED BY BISMUTH SILICATE


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On this paper, a theoretical evaluation of the interaction of fast electrons with a polymer polyimide composite filled with bismuth silicate was carried out, calculations were carried out for the specific energy losses of electrons and transmission coefficients. It is shown that the Bi, C, and O atoms contribute well to the ionization losses, and the radiation losses are practically due only to the Bi atoms. It has been established that at the electron energies from 1 to 6 MeV, interesting from the point of view of electronic protection of equipment in outer space, the losses are mainly determined by the ionization of atoms, and not by the radiation losses. It is established that for an electron energy of 6 MeV with a composite thickness of up to 0.8 cm, the transmittance by the number of electrons predominates, and with a composite thickness of more than 0.8 cm, the transmission coefficient of electrons over the energy begins to predominate. The high stability of the developed composite according to the flux of fast electrons is shown in the general case of their fall at different angles to the normal of the target surface.


## INTRODUCTION

The development of nuclear power for the production of electricity, the use of energy and research reactors, radionuclides and other sources of ionizing radiation in various fields of the national economy, science, technology and medicine is inextricably linked with the problem of ensuring radiation safety [1–3], with the limitation of the radiation effect on humans And objects of the environment, as well as the tasks of designing and creating new types of highly effective radiation-protective materials [4–5]. Hence, it is necessary to study the effect of ionizing radiation of various natures on various materials and composites, with the aim of developing completely new radiation shielding screens that are highly effective with a minimum thickness of protection.

At present, the silicate systems of the sillenite class are of considerable interest to scientists and practitioners. These are complex oxygen compounds of the type ($mBi_2O_3 \cdot nSiO_2$), which have electrooptical and magneto-optical properties, which, in combination with photoconductivity, puts them among the promising materials for the creation of laser radiation modulators, PROM memory (Programmable Read-Only Memory). In addition, bismuth silicates have photocatalytic properties [6].

According to the symmetry of the crystal lattice, the sillenites belong to the class of cubic oxides of the type $Bi_{12}MO_{20}$ (where M: Si, Ti, Ge). The most widely used bismuth silicates, for which the technology of growing large single crystals has been developed.

Silicates of bismuth of the syllenite class, possessing a number of unique properties, have not yet been used in the design of new types of radiation protection. Their use requires a deep scientific and practical study of their physical and technical characteristics under the influence of radiation fields of different nature, as well as the harsh conditions of outer space.

In this paper, a theoretical evaluation of the interaction of fast electrons with a polymer composite filled with bismuth silicate was carried out, calculations were carried out for the specific energy losses of electrons and transmission coefficients.

## EXPERIMENTAL TECHNIQUE

As radiation-protective filler, bismuth silicate has been studied. The authors synthesized the sillenite of $Bi_{12}SiO_{20}$ by chemical precipitation of a water-soluble organosilicon oligomer (MSN) and bismuth salt solution followed by heat treatment at 773 K.

As a binder for the synthesis of radiation-protective composites, a thermoplastic polyimide press powder of the PR-20 grade with a density of 1,42 g/cm$^3$ was used. The choice of polyimide as a binder is due to its unique properties. So the radiation resistance is $10^8$Gy, the heat resistance is up to 773 K, the cryogenic stability is up to 77 K, the mechanical tensile strength is 100 MPa.

Analysis of the effect of fast electrons on the composite in question was carried out by mathematical modeling using standard formulas and techniques. For this purpose, the elemental composition of the composite was calculated (Table), whose density is 2.9 g/cm$^3$.

The elemental composition of the proposed radiation-protectivecomposite

| Content in the composite, wt.% | | | | | | |
|---|---|---|---|---|---|---|
| Bi | Na | Si | O | C | N | H |
| 48 | 4.2 | 4.5 | 18 | 23.2 | 3,4 | 0.7 |

The ionization losses of the electron energy arecalculated by the formula:

$$\left(-\frac{dE}{dx}\right)_{col}=K\rho\frac{Z}{A}\frac{1}{2\beta^2}\left[\ln\left(\frac{m_ec^2E_k}{I^2}\frac{\beta^2}{2(1-\beta^2)}\right)-\left(2\sqrt{1-\beta^2}-1+\beta^2\right)\ln 2+1-\beta^2+\frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right], \quad (1)$$

where A is the atomic mass of the element, Z is the atomic number (the ordinal number of the element in the periodic table)

$$K=4\pi r_e^2m_ec^2N_A=0.307\frac{MeV}{g/cm^2},$$

$m_ec^2=0.511$ MeV – therestof the energy of an electron, $r_e=\frac{e^2}{m_ec^2}=2.8\cdot10^{-13}$ cm – classical radius of an electron, $N_A=6\cdot10^{23}\frac{1}{mol}$, $\rho$ – density of matter, $I$ – average ionization potential of the medium atom of the medium, $\beta=\sqrt{1-\frac{(m_ec^2)^2}{(m_ec^2+E_k)^2}}$ – Lorentz factor of electron with kinetic energy $E_k$.

Since the investigated composite consists of atoms of 7 different chemical elements (Bi, Na, Si, O, C, N, H), each of them will contribute to ionization losses of electron energy. We use the composition law of Bragg:

$$\left(-\frac{dE}{dx}\right)_{col}=\sum_i\rho_i\left(-\frac{dE}{dx}\right)_i, \quad (2)$$

where $\rho_i$ and $\left(-\frac{dE}{dx}\right)_i$ – density and contribution of the i-thelement in the complex depends on the ionization losses of the electron. We rewrite expressions (2) in a more convenient form for analysis:

$$\left(-\frac{dE}{dx}\right)_{col}=\rho\frac{Z}{A}F(E_k,I), \quad (3)$$

$$F(E_k,I)=\frac{K}{2\beta^2}\left[\ln\left(\frac{m_ec^2E_k}{I^2}\frac{\beta^2}{2(1-\beta^2)}\right)-\left(2\sqrt{1-\beta^2}-1+\beta^2\right)\ln 2+1-\beta^2+\frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2\right]. \quad (4)$$

Starting from the composition law of Bragg (2), the ionization energy losses of electrons in the studied polymer composite are written in the form:

$$\left(-\frac{dE}{dx}\right)_{col}=\rho_{Bi}\frac{Z_{Bi}}{A_{Bi}}F(E_k,I_{Bi})+\rho_{Na}\frac{Z_{Na}}{A_{Na}}F(E_k,I_{Na})+\rho_{Si}\frac{Z_{Si}}{A_{Si}}F(E_k,I_{Si})+\rho_O\frac{Z_O}{A_O}F(E_k,I_O)+\rho_C\frac{Z_C}{A_C}F(E_k,I_C)+\rho_N\frac{Z_N}{A_N}F(E_k,I_N)+\rho_H\frac{Z_H}{A_H}F(E_k,I_H). \quad (5)$$

The radiative energy losses during the passage of electrons through the substance are found from the formula:

$$\left(-\frac{dE}{dx}\right)_{rad}=\rho\frac{Z^2}{A}\frac{K\alpha}{4\pi}\frac{\varepsilon}{m}G(E_k), \quad (6)$$

where

$$G(E_k)=\frac{K\alpha}{4\pi}\frac{\varepsilon}{m}\left[\frac{12\varepsilon^2+4m_e^2c^4}{3\varepsilon p}\ln\left(\frac{\varepsilon+p}{m_ec^2}\right)-\frac{(8\varepsilon+6p)m_e^2c^4}{3\varepsilon p^2}\times\left(\ln\left(\frac{\varepsilon+p}{m_ec^2}\right)\right)^2-\frac{4}{3}+\frac{2m^2c^4}{\varepsilon p}F\left(\frac{2p(\varepsilon+p)}{m^2c^4}\right)\right] \quad (7)$$

$\varepsilon=E_k+m_ec^2$ – Totalof the electron energy, $\alpha=\frac{1}{137}$ – fine structure constant.

$$F\left(\frac{2p(\varepsilon+p)}{m^2c^4}\right)=\int_0^{\frac{2p(\varepsilon+p)}{m^2c^4}}\frac{\ln(1+y)}{y}dy, \quad (8)$$

p – electron momentum.

Since the investigated polymer composite consists of atoms of different chemical elements, it is necessary to take into account the contribution of each to the radiative losses of a fast electron. Therefore, the radiative energy loss by radiation is determined by the expression:

$$\left(-\frac{dE}{dx}\right)_{rad}=\left(\rho_{Bi}\frac{Z_{Bi}^2}{A_{Bi}}+\rho_{Na}\frac{Z_{Na}^2}{A_{Na}}+\rho_{Si}\frac{Z_{Si}^2}{A_{Si}}+\rho_O\frac{Z_O^2}{A_O}+\rho_C\frac{Z_C^2}{A_C}+\rho_N\frac{Z_N^2}{A_N}+\rho_H\frac{Z_H^2}{A_H}\right)G(E_k). \quad (9)$$

The total energy losses in the polymer composite studied were determined by the sum of the ionization and radiation losses of the electron energy in the substance.

To calculate the transmission coefficients for the number of particles and for energy, the following formulas were used:

$$T_N(x) = \frac{N(x)}{N_0}, \quad (10)$$

$$T_{E_k}(x) = \frac{E(x)}{N_0 E_0}, \quad (11)$$

where $N_0$ and $E_0$ are the number of incident electrons and their kinetic energy.

In addition, the angle of incidence of the electrons was taken into account φ (the angle between the normal to the surface of the composite and by the electron) to the studied polymer composite.

To calculate the transmission coefficients of the number of electrons, an empirical formula was used:

$$T_N(x) = \exp\left[-\beta\left(\frac{x}{R_{ex}}\right)^{\alpha}\right], \quad (12)$$

where

$$R_{ex}(E_0, Z, \phi) = \cos^2\frac{\phi}{2}\left(\begin{array}{l}\frac{107,2 - Z}{5.442Z - 1312} + \\ \frac{292.7 - Z}{4.163Z + 561.3}E_0 + \\ \frac{Z - 2.797}{83.86Z + 587.5}E_0^2\end{array}\right)\frac{1}{\rho}, \quad (13)$$

where $R_{ex}$ is the extrapolated range of electrons.

$$\alpha = 1 + \frac{5.5 - 0.1(3.4 - E_0)^2}{\frac{0.398 - 0.032E_0}{Z}}\left(\cos\phi - 0.1564\right) + \quad (14)$$
$$+0.0125(E_0 - 2)(50 - Z)(\cos\phi - 0.1564)^3,$$

for Z < 50, E >2 MeV,

$$\alpha = 1 + \frac{5.5 - 0.1(3.4 - E_0)^2}{\frac{0.398 - 0.032E_0}{Z}}\left(\cos\phi - 0.1564\right), \quad (15)$$

– in other cases,

$$\beta = 2.59 - 0.0076(Z - 6). \quad (16)$$

The energy transmission coefficient has the following form:

$$T_E(x) = \exp\left[-\beta_E\left(\frac{x}{R_{ex}}\right)^{\alpha_E}\right], \quad (17)$$

$$\alpha_E = 0.78 + \frac{Z + 24}{0.93Z + 13.7}\left(\cos\phi - 0.1564\right), \quad (18)$$

$$\beta_E = \frac{Z + 32.6}{0.524Z + 10.8}. \quad (19)$$

Expressions $T_N(x)$ and$T_E(x)$ can be used to accurate calculations at electron energies of 0.4…6 MeV and angles of incidence 0…45°, if these conditions are violated, the error will be 20…30%.

Since the investigated polymer composite consists of atoms of different types, instead of Z and A it is necessary to use effective values, which are determined by formulas:

$$Z_{eff} = \sum_i \frac{\rho_i}{\rho} Z_i, \quad (20)$$

$$A_{eff} = \frac{Z_{eff}}{\sum_i \frac{\rho_i}{\rho}\frac{Z_i}{A_i}}. \quad (21)$$

## RESULTS AND DISCUSSION

In Fig. 1 shows the curves showing the ionization losses of the polyimide composite under consideration (the fat curve) and the individual contribution of each element to the ionization losses. From Fig. 1 it follows that the Bi, C, and O atoms have a greater contribution to the ionization losses. The contribution of the remaining atoms is very small, so the curves practically lie on the abscissa axis.

Also the analysis of Fig. 1 shows that an increase in the energy of fast electrons from 1 to 6 MeV leads to an insignificant increase in the specific ionization losses in the polyimide composite.

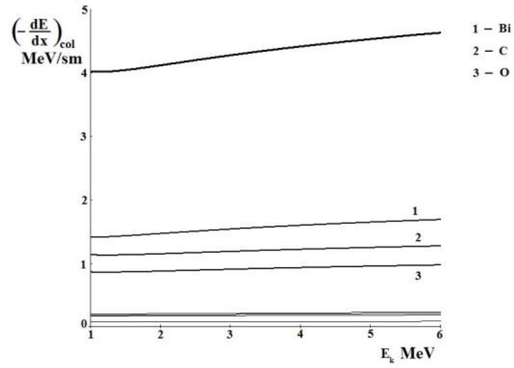


*Fig. 1. Specific ionization losses of fast electrons in a polyimide composite*

In Fig. 2 shows curves plotted using formulas (6) and (9), which show the radiation losses due to fast-electron radiation in a polyimide composite (bold curve) and the individual contribution of each composite material to these losses

From Fig. 2 it follows that Bi contributes to the radiation losses, while taking into account the low density of the composite (2.9 g /sm$^3$), the energy losses are rather high, but small in comparison with the ionization losses at the considered electron energies (3-4 times in Dependence on energy).

Also the analysis of Fig. 2 shows that when the energy of fast electrons increases from 1 to 6 MeV, the specific radiation losses in the polyimide composite increase significantly.

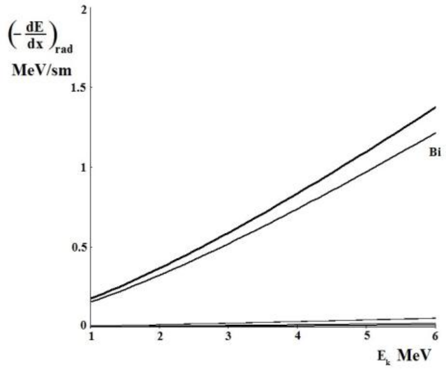


*Fig. 2. Specific radiation losses of fast electrons in a polyimide composite*

The total energy losses in the polyimide composite studied are shown in Fig. 3. It follows from the figure that for the electron energies from 1 to 6 MeV, which are of interest from the point of view of electronic protection of equipment in outer space, the losses are mainly determined by the ionization of theatoms.

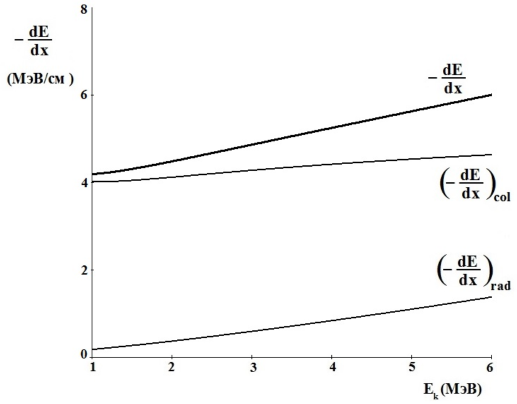


*Fig. 3. Dependence of the total specific energy losses of fast electrons in the polyimide composite studied*

Since the loss of energy of the electron in the composite leads to its deceleration, we find the mean range that determines the average path length that the particle would pass through in the process of deceleration in an unbounded and homogeneous medium, provided that it continuously loses energy along the entire path in accordance with the stopping power. True runs are random and distributed near the mean run.

In Fig. 4 shows a curve showing the dependence of the mean free path of an electron in a composite as a function of its initial kinetic energy. It can be seen that in the obtained composite the average path of an electron is sufficiently small in a wide range of initial electron energies, which indicates the prospect of its use for protection against the effect of electrons in outer space.

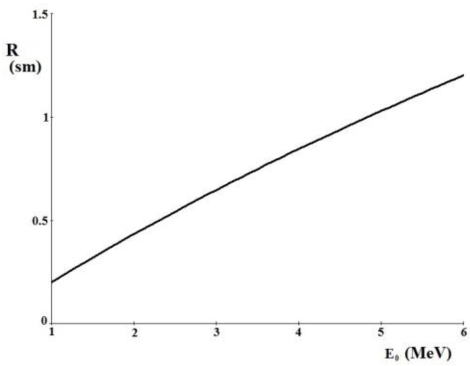


*Fig. 4. The dependence of the mean free path of an electron in a polyimide polymer composite on its initial kinetic energy*

Since fast electrons in outer space have a wide energy range and a different directionality of the initial velocity, it is also necessary to investigate the transmission coefficients of electrons by the developed polyimide composite.

The process of electron transmission through the developed polymer composite was modeled in the work by the Monte Carlo statistical method. In Figs. 5–9 graphically shows the results of modeling the dependence of the transmittance coefficients on the number of particles and energy, depending on the thickness of the developed composite, for the angles and initial energies presented in the figures.

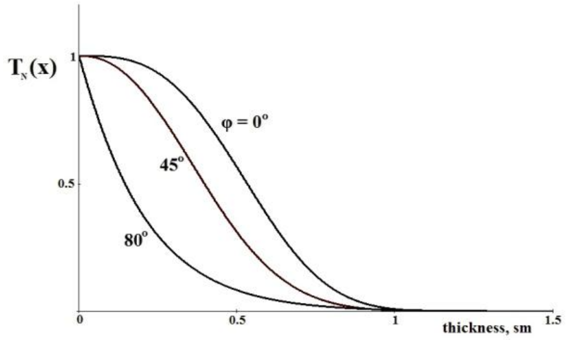


*Fig. 5. Dependence of the transmission coefficient of the number of electrons on the thickness of the polyimide composite at an energy of 6 MeV and different angles of incidence*

Analysis of the data in Fig. 5 shows that as the angle of incidence of the electron is increased, the transmission coefficient of the number of electrons is significantly reduced. Also, the data in Fig. 5 show that as the thickness of the polyimide composite increases, the transmittance of the number of electrons at all considered angles of incidence decreases and tends to zero. At a thickness of 1.2 cm, electrons with an energy of 6 MeV are completely absorbed by the proposed composite and the transmittance at high energies is simply absent.

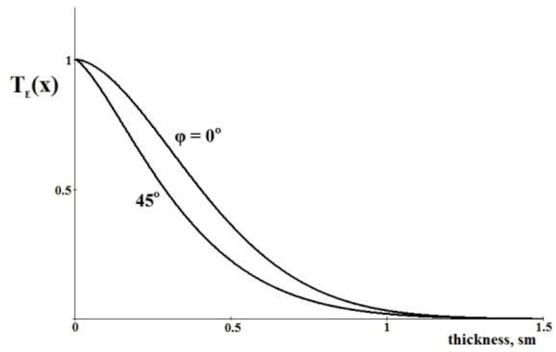


*Fig. 6. Thetransmission of the coefficient for the electron energy from the thickness of the polyimide composite at an energy of 6 MeV and different angles of incidence*

Analysis of the data in Fig. 6 shows that when the angle of incidence of an electron increases, the electron energy transmission coefficient decreases. As well as in Fig. 5, the transmission coefficients for the electron energy are noticeably lower, the thickness of the composite is increasing and the curve tends to the abscissa axis.

In Fig. 7 shows curves of the dependence of the transmission coefficients of the number of electrons at normal incidence on the composite for different initial energies of the electron. It is noticeable that as the electron energy increases from 1 to 6 MeV, the transmission of coefficients of the number of electrons with the same thickness of the composite also increases. It is also observed in Fig. 8.

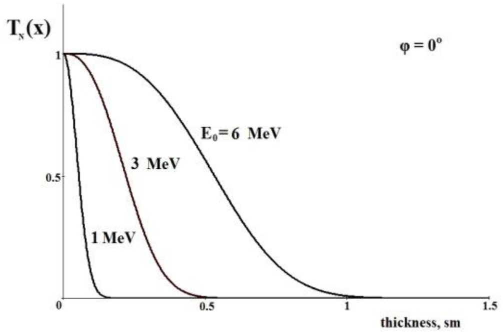


*Fig. 7. The transmission coefficient of the number of electrons at normal incidence on the composite for different initial electron energies*

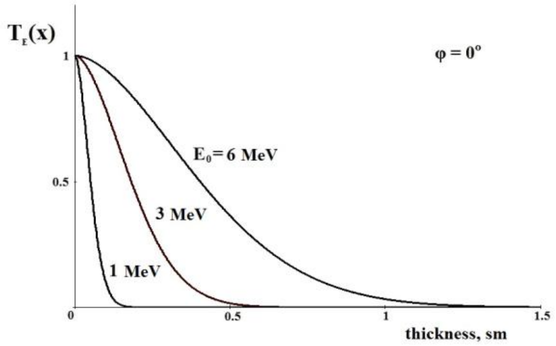


*Fig. 8. The transmission coefficient for the electron energy at normal incidence on a polyimide composite for different initial electron energies*

In Fig. 9 shows two curves that allow one to estimate the transmission coefficients with respect to the number of particles and energy at normal incidence on a polyimide composite and electron energies of 6 MeV. The analysis presented in Fig. 9 of the data indicates that with a composite thickness of up to 0.8 cm the transmittance by the number of electrons predominates, and with a composite thickness of more than 0.8 cm, the transmission coefficient of electrons over the energy begins to predominate.

On the basis of the data obtained, it can be concluded that the developed composite is highly stable with respect to the flow of fast electrons in the general case of their incidence at different angles to the normal of the target surface.

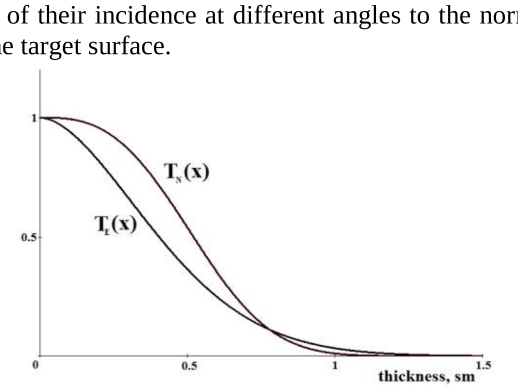


*Fig. 9. Comparison of the transmittance coefficients for the number of particles and energy at normal incidence on a polyimide composite and electron energies of 6 MeV*

## CONCLUSION

The process of passage of fast electrons through the developed composite material is studied; the process of passage of fast electrons through the composite material is simulated. The total energy losses of electrons in the composite are calculated. It is shown that the Bi, C, and O atoms make a greater contribution to the ionization losses, and the radiation losses are practically due only to the Bi atoms.

The dependence of the mean free path of fast electrons in the polymer composite on their initial kinetic energy is investigated. It is shown that at an electron energy of 6 MeV, the range in the composite is 1.2 cm. The transmission coefficients for the number of particles and energy in the composite are modeled and investigated, depending on the angle of incidence to the normal of the composite and the initial energy of the incident electrons. It is established that for an electron energy of 6 MeV at a composite thickness of up to 0.8 cm, the transmittance by the number of electrons predominates, and at a composite thickness of more than 0.8 cm, the transmission coefficient of electrons over the energy begins to predominate.

The high stability of the developed composite with respect to the flux of fast electrons is shown in the general case of their fall at different angles to the normal of the target.

***The article was prepared within a development program of the Base University on the basis of BSTU named after V.G. Shukhov.***

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*Article received 28.04.2017*

# РАСЧЕТ КОЭФФИЦИЕНТОВ ПРОПУСКАНИЯ БЫСТРЫХ ЭЛЕКТРОНОВ ПРИ ПРОХОЖДЕНИИ ЧЕРЕЗ ПОЛИМЕРНЫЙ ПОЛИИМИДНЫЙ КОМПОЗИЦИОННЫЙ МАТЕРИАЛ, НАПОЛНЕННЫЙ СИЛИКАТОМ ВИСМУТА

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Проведены теоретическая оценка взаимодействия быстрых электронов с полимерным полиимидным композитом, наполненным силикатом висмута, и расчеты по удельным потерям энергии электронов и коэффициентам пропускания. Показано, что больший вклад в ионизационные потери вносят атомы Bi, C и O, а радиационные потери практически обусловлены только атомами Bi. Установлено, что при рассматриваемых энергиях электрона от 1 до 6 МэВ, интересных с точки зрения электронной защиты аппаратуры в космическом пространстве, потери в основном определяются ионизацией атомов, а не радиационными потерями. Также определено, что для энергии электронов 6 МэВ при толщине композита до 0,8 см преобладает коэффициент пропускания по числу электронов, а при толщине композита более 0,8 см начинает преобладать коэффициент пропускания электронов по энергии. Показана высокая стойкость разработанного композита по отношению к потоку быстрых электронов в общем случае их падения под разными углами к нормали поверхности мишени.

# РОЗРАХУНОК КОЕФІЦІЄНТІВ ПРОПУСКАННЯ ШВИДКИХ ЕЛЕКТРОНІВ ПРИ ПРОХОДЖЕННЯ ЧЕРЕЗ ПОЛІМЕРНИЙ ПОЛІІМІДНИЙ КОМПОЗИЦІЙНИЙ МАТЕРІАЛ, ЩО НАПОВНЕНИЙ СИЛІКАТОМ ВІСМУТУ

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Проведено теоретична оцінка взаємодії швидких електронів з полімерним поліімідним композитом, наповненим силікатом вісмуту, і розрахунки за питомими втратами енергії електронів і коефіцієнтам пропускання. Показано, що найбільший внесок у іонізаційні втрати вносять атоми Bi, C і O, а радіаційні втрати практично обумовлені тільки атомами Bi. Встановлено, що при розглянутих енергіях електрона від 1 до 6 МеВ, цікавих з точки зору електронного захисту апаратури в космічному просторі, втрати в основному визначаються іонізацією атомів, а не радіаційними втратами. Встановлено, що для енергії електронів 6 МеВ при товщині композиту до 0,8 см переважає коефіцієнт пропускання по числу електронів, а при товщині композиту більше 0,8 см починає переважати коефіцієнт пропускання електронів по енергії. Показано високу стійкість розробленого композиту по відношенню до потоку швидких електронів у загальному випадку їх падіння під різними кутами до нормалі поверхні мішені.