The heterogeneous anti-radiation shield for spacecraft

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Abstract. The paper deals with modeling of elemental composition and properties of heterogeneous layers in multilayered shields to protect spacecraft onboard equipment from radiation emitted by the natural Earth’s radiation belt. This radiation causes malfunctioning of semiconductor elements in electronic equipment and may result in a failure of the spacecraft as a whole. We consider four different shield designs and compare them to the most conventional radiation-protective material for spacecraft - aluminum. Out of light and heavy chemical elements we chose the materials with high reaction cross sections and low density. The mass attenuation coefficient of boron-containing compounds is 20% higher than that of aluminum. Heterogeneous shields consist of three layers: a glass cloth, borated material, and nickel. With a protective shield containing heavy metal the output bremsstrahlung can be reduced. The amount of gamma rays that succeed to penetrate the shield is 4 times less compared to aluminum. The shields under study have the thicknesses of 5.95 and 6.2 mm. A comparative analysis of homogeneous and multilayered protective coatings of the same chemical composition has been performed. A heterogeneous protective shield has been found to be advantageous in weight and shielding properties over its homogeneous counterparts and aluminum. The dose characteristics and transmittance were calculated by the Monte Carlo method. The results of our study lead us to conclude that a three-layer boron carbide shield provides the most effective protection from radiation. This shield ensures twice as low absorbed dose and 4 times less the number of penetrated gamma-ray photons compared to its aluminum analogue. Moreover, a heterogeneous shield will have a weight 10% lighter than aluminum, with the same attenuation coefficient of the electron flux. Such heterogeneous shields can be used to protect spacecraft launched to geostationary orbit. Furthermore, a protective boron-containing and nickel coating can be deposited onto a finished housing frame of space equipment.

Introduction.

When on orbit, satellite onboard electronic units require protection from space radiation causing malfunctioning of the spacecraft (SC) navigation and telecommunication systems [1-

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A subsection of the Federal State Program "Space apparatus for fundamental space research" provides for elaboration of "space complexes and instruments to investigate Phobos, Mars, Venus, the Moon". European countries and the USA and China have intensified their activity on preparation for manned flights to the Moon, Mars and subsequent exploration and exploitation of these cosmic bodies. Modeling the effect of ionizing radiation on various materials is one of the important preparation stages aimed at development of new compositions for protective shields [3-8].

Most often protection is provided by the aluminum or aluminum-alloy housing of an electronic unit. The challenging research task in spacecraft protection from ionizing radiation is to come up with a shield that would offer better protective qualities and weigh less than its aluminum counterpart [9]. Properties of the materials are analyzed based on the following characteristics: the absorbed doze, mass thickness, mass attenuation coefficient, and the number of penetrated particles.

**Experimental procedure.**

Heterogeneous shields made of materials capable of absorbing or scattering hazardous radiation prove to be the most effective protective means to ensure reliable functioning of the control system of a satellite [10]. The ionizing radiation of an electron flow emitted by natural radiation belts of the Earth is the most dangerous on a geostationary orbit [11]. The number of solar and galaxy particles is grossly less, therefore modeling radiation as an electron beam with the energies of 0.04-5 MeV yields plausible results.

The choice of materials should rely on their physical properties, the reaction cross-section being one of them [12]. The higher is the atomic number of a chemical element, the more severe is the loss of energy by primary electrons; however, increasing the thickness induces brake radiation in heavy-element materials. So, it would be reasonable to consider using elements of different groups when modeling a protective shield [13]. A heterogeneous shield with layers of different density offers advantages that will be illustrated for the two models discussed below.

The protective shield consists of three layers (Table 1) arranged according to the growing atomic number of the basic absorbing substance of the layer. The first layer is a boron compound (boron carbide and sodium tetraborate shields have been considered). The second (structural) layer is a T-10 glass fabric containing aluminum, silicon and boron oxides and having a higher attenuation coefficient than aluminum. The last layer is nickel, having the highest atomic number. The choice of these materials is due to the reaction cross-sections in these media. Boron has the largest photon trapping - \((0.0092 \cdot 10^{-24} \text{ cm}^2)\) and scattering \((3.6 \cdot 10^{-24} \text{ cm}^2)\) cross-sections among the inexpensive, light and commercially available materials [12]. Nickel possesses the best characteristics such as \(4.43 \cdot 10^{-24} \text{ cm}^2\) trapping cross-section and \(17.3 \cdot 10^{-25} \text{ cm}^2\) scattering cross-section, which is an order of magnitude higher than the reaction cross-sections of other heavy elements, for instance, copper, their density being about the same. So nickel is a good material to protect against gamma-radiation and therefore it is efficient as the last protective layer [14].

| Shield/Layer | 2.75/2.5 mm | 1.7 mm | 1.75 mm |
|-------------|-------------|--------|--------|
| 1           | B\(_4\)C    | Glass fabric | Ni    |
| 2           | B\(_4\)Na\(_3\)O\(_7\) | Glass fabric | Ni    |
Thicknesses of the layers obey the half-attenuation rule and are 2.75/2.5 mm for the boron-containing coating, 1.75 mm for the nickel layer, and 1.7 mm for the glass fabric.

Epoxy resin, which is 20-30% of the shield, was chosen as a binder.

**Results and discussion.**

The shielding qualities of the materials under study are summarized in Table 2. The data for nickel and boron-containing substances take into account the weight content of epoxy resin (25% in boron and 20% in nickel layers). The number of particles having penetrated the shield is normalized to one particle.

The mass attenuation coefficient decreases with growing density of the material and increases as the number of penetrated particles goes down. Boron-containing materials and glass fabric have a higher electron flow mass attenuation coefficient compared to aluminum, which supports the preferred choice of these materials for protective shields. Although nickel is not so good in interacting with electrons, it is advantageous in other aspects, which will be discussed further down.

A comparative analysis of the materials has also revealed that a homogeneous shield with a chemical composition identical to a heterogeneous shield has a 20% higher mass attenuation coefficient compared to aluminum.

**Table 2. Comparing properties of the materials**

| Material                  | Density, kg/m³ | Thickness, m | Mass thickness, kg/m² | Amount of penetrated electrons | Mass attenuation coefficient, m²/kg |
|---------------------------|----------------|--------------|------------------------|--------------------------------|-----------------------------------|
| B₄Na₂O₇                  | 1904           | 0.001        | 1.90                   | 0.0069                          | 2.6088                           |
| B₄C                      | 1881           | 0.001        | 1.88                   | 0.0079                          | 2.5684                           |
| T-10                     | 1596           | 0.001        | 1.60                   | 0.0071                          | 3.0270                           |
| Ni                       | 3898           | 0.001        | 3.90                   | 0.0006                          | 1.9044                           |
| Al                       | 2700           | 0.001        | 2.70                   | 0.0031                          | 2.1384                           |
| Homogeneous shield with B₄Na₂O₇ | 2156.4         | 0.001        | 2.16                   | 0.0044                          | 2.5146                           |
| Homogeneous shield with B₄C           | 2134.4         | 0.001        | 2.13                   | 0.0032                          | 2.6873                           |

To understand the contribution of each layer to the radiation attenuation, we studied the amount of penetrated particles (electrons) depending on the shield thickness (Fig.1). The angle of inclination of the sections corresponding to different layers being about the same is an indication of the proper choice of thicknesses of the layers.
Numerical estimates of the amount of penetrated electrons (normalized to one particle) and mass attenuation coefficients for each layer are given in Table 3. Also given are the calculated characteristics of homogeneous shields. The mass attenuation coefficients appear to be close to each other, therefore our choice of the structure will be based on technological considerations. Boron-containing and nickel coatings can be deposited onto a finished housing of spacecraft equipment, which makes the heterogeneous shield more universal. In terms of the shield characteristics, all the discussed compounds are advantageous over aluminum.

Table 3. Layer-by-layer comparison of material properties in heterogeneous shields

| Shield | Material       | Density, kg/m³ | Thickness, m | Mass thickness, kg/m² | Amount of penetrated electrons | Mass attenuation coefficient, m²/kg |
|--------|----------------|----------------|--------------|-----------------------|--------------------------------|-----------------------------------|
| 1      | B₄Na₂O₇        | 1904           | 2.50E-03     | 4.76                  | 6.62E-02                       | 1.54                              |
|        | Glass fabric   | 1596           | 1.70E-03     | 2.71                  | 1.09E-01                       | 0.82                              |
|        | Ni             | 3898           | 1.75E-03     | 6.82                  | 1.82E-02                       | 1.66                              |
|        | Entire shield  | 2156.4*        | 5.95E-03     | 12.83*                | 1.31E-06                       | 1.06*                             |
| 2      | B₄C            | 1881           | 2.75E-03     | 5.17                  | 5.87E-04                       | 1.44                              |
|        | Glass fabric   | 1596           | 1.70E-03     | 2.71                  | 1.07E-01                       | 0.82                              |
|        | Ni             | 3898           | 1.75E-03     | 6.82                  | 1.68E-06                       | 0.60                              |
|        | Entire shield  | 2134.4*        | 6.20E-03     | 13.23*                | 1.06E-06                       | 1.04*                             |
When studying parameters of the protective shields under equally attenuated electron flow, we also calculated the secondary emission ratio (the amount of gamma-ray photons penetrated through all the layers) and the absorbed dose ratio. A $10^6$ times attenuation of the electron flow is achieved with a 6 mm-thick aluminum shield. The absorbed dose for this shield thickness is 1.55E-11 µGy while this parameter for heterogeneous shields is an order of magnitude less. Table 4 gives the ratio of respective parameters between heterogeneous and aluminum shields.

We also analyzed the situation with homogeneous shields. A sodium tetraborate shield exhibits a 10% lower attenuation of the absorbed dose than aluminum, whereas heterogeneous shields are twice as efficient.

Table 4. Comparison of secondary emission and absorbed dose

| Material                        | Thickness, mm | Amount of penetrated gamma-ray photons | Absorbed dose, µGy | Secondary emission ratio | Absorbed dose ratio |
|---------------------------------|---------------|----------------------------------------|--------------------|-------------------------|--------------------|
| Aluminum                        | 6             | 1.46E-3                                | 1.55E-11           | 1                       | 1                  |
| B$_4$Na$_2$O$_7$+T10+Ni         | 5.95          | 2.26E-4                                | 7.89E-12           | 6.46                    | 1.97               |
| B$_4$C+T10+Ni                   | 6.2           | 1.13E-4                                | 6.60E-12           | 12.89                   | 2.35               |
| Homogeneous shield with B$_4$Na$_2$O$_7$ | 5.95    | 3.15E-4                                | 1.65E-11           | 4.63                    | 0.94               |
| Homogeneous shield with B$_4$C  | 6.2           | 2.49E-4                                | 6.06E-12           | 5.85                    | 2.56               |

*– the mean value

The shields under consideration let 4 to 5 times less gamma-ray photons resulting from Bremsstrahlung penetrate the shield, which is due to the heavy metal – nickel present in their composition. In Fig. 2 one can see that the amount of secondary emission particles drastically decreases in the interval from 4.2 mm, which corresponds to the nickel layer.
Figure 2. The amount of gamma-ray photons depending on the thickness of the B$_4$C heterogeneous barrier. Normalization to one particle. The Y-axis scale is logarithmic.

To compare the shields in terms of the amount of penetrated electrons, we calculated the real thickness of the aluminum layer (Table 5). It equals the mass thickness of a multilayered shield. A 5.3 mm-thick aluminum shield is 2 times less effective in trapping electrons than the heterogeneous shields under study.

Table 5. Finding the ratio of penetrated electrons

| Material          | Thickness, m | Amount of penetrated electrons | Mass attenuation coefficient, m$^2$/kg | Protection ratio |
|-------------------|--------------|---------------------------------|---------------------------------------|------------------|
| Aluminum          | 5.29E-03     | 2.64E-06                        | 0.90                                  | 2.02             |
| B$_4$Na$_2$O$_7$+T10+Ni | 5.95E-03     | 1.30E-06                        | 1.06                                  |                  |
| B$_4$C+T10+Ni     | 6.2E-03      | 1.06E-06                        | 1.04                                  | 1.97             |
| Aluminum          | 5.45E-03     | 2.10E-06                        | 0.89                                  |                  |

The mass of a protective shield is an important consideration as it affects the cost of satellite launching to orbit and as a consequence the market demand for this material. To make our estimates more specific, we adopted a model in the form of a 5 mm-radius cylinder. The cylinder height was as shown in Table 5. Comparison was carried out for the shields with the same amount of penetrated electrons (10$^{-6}$ particles). The mass ratio between the heterogeneous and aluminum shields was 0.9 (Table 6). That is, on top of all the advantages discussed above, the shields under study are lighter than aluminum shields.
Table 6. Comparison of masses for the same amount of missed electrons, $N=10^{-6}$

| Material             | Mass, g | Mass ratio |
|----------------------|---------|------------|
| Aluminum             | 127.23  | 1          |
| $B_4Na_2O_7$+T10+Ni  | 112.27  | 0.88       |
| $B_4C$+T10+Ni        | 115.51  | 0.91       |

We have considered and calculated using the "Computer laboratory" program [15] five different combinations of protective shields made of materials with high shielding quality and mass attenuation coefficient. Homogeneous and heterogeneous shields are advantageous over aluminum in lower bremsstrahlung and smaller weight. The boron carbide shields outmatch aluminum shields in all studied characteristics.

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