New approaches to the design of composite materials for shielding from ionizing radiation

V Glyva[1], B Khalmuradov[1], I Matvieieva[2] and N Kichata[1,3]

[1] Department of Civil and Industrial Safety**,** National Aviation University, 1 Liubomyra Huzara ave., Kyiv 03058, Ukraine
[2] Department of Ecology, National Aviation University, 1 Liubomyra Huzara ave., Kyiv 03058, Ukraine

[3] E-mail: naturly@ukr.net

Abstract. Based on an analysis of the scattering mechanisms of ionizing electromagnetic radiation and the dependence of radiation attenuation on the index number of the element and its density, it is concluded that it can be shielded by materials containing iron. The foundations of designing a composite metal-polymer material are proposed for reducing the intensity of x-ray and gamma radiation. It is shown that a change in the ionizing radiation absorption with a change in the radiation wavelength occurs non-monotonically. Therefore, for the design of the material, it is necessary to find out the preferred wavelengths (frequencies) of radiation that require shielding. It has been established that for effective screening of radiation there is a critical concentration of metal particles in the polymer matrix. This occurs at the threshold of the flow of electric current when the content of the shielding substance is 11-12% (by weight). This is consistent with the electrodynamic ratios of continuous media. When designing a material using iron ore concentrate, its various properties should be taken into account, depending on the manufacturer. The design of the protective material should be preceded by laboratory studies to determine the overwhelming fraction of iron ore particles by the size and content of iron and its compounds in the feedstock.

1. Introduction

Protection against the influence of physical factors of man-made origin is one of the priority areas of research in the field of civil security. The most critical of these factors is ionizing radiation. Constant growth the electromagnetic load on the environment caused by the development of energy infrastructure, networks of wireless communications, radio technical equipment of civil aviation, etc., requires determining the values of electromagnetic fields and radiation of individual objects, evaluating of their impact on the public, staff and different buildings, allocating the areas of restrictions of people stay.

Protection against its effects is usually provided by rubber and polymeric materials containing lead. But such materials are very heavy, and lead is toxic, which limits the use of these products. Therefore, it is advisable to consider the possibility of manufacturing protective materials without the use of lead while maintaining sufficient shielding coefficients of harmful radiation.

An increase in the operating frequencies of radio equipment - sources of non-ionizing radiation can be observed in modern conditions. At the same time, these frequencies gradually move into the region of extremely high. Taking into account, that ionizing gamma radiation is also electromagnetic radiation, it is rational to consider the possibility of developing a composite material for simultaneous shielding of ionizing and non-ionizing radiation of different origins. This possibility is due to the presence of well-developed technologies for the production of composite metal-polymer materials for protection against electromagnetic influences with controlled protective properties. Therefore, it is advisable to consider the possibility of development of protective structures, based on such materials for shielding ionizing radiation of various origins.

2. Materials and Methods

Designing and studying protective screens have been paid much attention to. However, development of technologies for electromagnetic and acoustic screens is a separate direction. The field of materials fabrication for protection against electromagnetic fields has two areas – the screens to reduce the levels of fields of ultra-low frequencies and those to reduce the levels of electromagnetic radiation at very high and highest frequencies. Low-frequency screens are made mostly of metals.

The main direction of research and applied developments in the protection of personnel of enterprises and institutions that work with sources of ionizing radiation is the creation of protective materials without lead. It is known, that the absorption properties of elements for all types of radioactive radiation increase with increase of ordinal number in the periodic table, namely the charge number Z. Therefore, the most acceptable and common metal for shielding radiation is lead ($N = 82$).

In works [1, 2] the possibility of using bismuth as a shielding element ($N = 83$) was considered. This metal has poor physical and mechanical properties, so it was used in an oxide form as a filler in nano-composite materials, based on polymers. With acceptable X-ray shielding coefficients, such materials have high costs due to the complexity of manufacturing technologies.

The article [3] presents the results of the development of a composite material with use of dysprosium and gedolinium as shielding elements. Their charge numbers are quite large, but these metals have an extremely high cost, so it is impractical to produce large volumes of protective coatings, made from them (even with a small content in the polymer matrix).

The article [4] considers the possibilities of manufacturing the composites using compounds of elements with a small charge number - boron and alkali metals.

These shielding efficiencies are small. In addition, the boron carbide, which was used, is very expensive to manufacture.

Many studies have been devoted to determining the protective properties of materials containing tungsten. Thus, in the work [6] we proposed a composite material of ethylene-vinyl acetate with a tungsten filler, and in the study [7] with a filler of tungsten oxide. The same article compares the properties of composite materials based on barium sulfate, bismuth trioxide and tungsten oxide with lead. It is shown that their protective properties are only 10-15% worse than the properties of pure lead, which is quite satisfactory for most of real production conditions. In this case, as shown in the work [8], as a matrix it is possible to use epoxy materials that do not degrade under the influence of ionizing radiation.

In the work [9] the results of development and research of protective properties of electromagnetic metal-polymer screens in the high-frequency area of the spectrum are given. The material is made with use of an enriched iron ore as a filler of the polymer matrix. The shielding coefficients of ultrahigh frequency electromagnetic fields with a metal substance content of 5–20% are 3.3–44. It is rational to consider the possibility of using such materials for shielding ionizing radiation. The filler from iron ore has a low cost and is perspective for shielding surfaces of large areas, so it is important to evaluate its effectiveness for ionizing radiation.

The purpose of the work is to determine the possibility of use of iron and iron-containing fine substance to create composite materials for protection against the effects of ionizing radiation.

3. Results

Analysis of studies on the shielding of ionizing radiation by elements with charge numbers smaller than the charge of the lead nucleus, shows that this direction is perspective for reducing the level of radiation, at least with low intensities. Such radiations are, for example, parasitic radiation of medical equipment, radiation of equipment in the hardware of civil aviation, and so on.

The most important component of such radiation is gamma radiation. The attenuation of the gamma radiation in the layer of material is determined by the dependence:

$$\varphi = \varphi_o \cdot \varepsilon^{-\mu\partial} \qquad (1)$$

where φ is the flux density γ of the quanta after passing the absorbing material;
φ_o is the flux density γ of quanta in front of the absorbing material;
d is the thickness of the absorbing layer;
μ is the linear attenuation coefficient.

The mass attenuation coefficient $\mu_M = \mu/\rho$ (m^2/kg), is the coefficient, related to the linear attenuation coefficient. The decrease in the intensity of gamma radiation occurs by three mechanisms. The photoeffect predominates at energies $E_\gamma < 0.5$ MeV. The mass attenuation coefficient of the photoeffect τ/ρ increases with increase of ordinal number (charge number) of the element Z and decreases with decrease of photon energy:

$$\frac{\tau}{\rho} = \frac{Z^4}{(h\nu)^3} \qquad (2)$$

where *h* is the Planck constant, *v* is the photon frequency.

At energies greater than 1 MeV (up to about 5 MeV), the mechanism of electron-positron pair formation predominates. The mass attenuation coefficient of the formation of pairs k/ρ is defined as:

$$\frac{k}{\rho} \approx Z \cdot \ln(h\nu). \qquad (3)$$

At photon energies of 30 keV – 5 MeV, the Compton effect prevails (scattering of photons by free electrons):

$$\frac{\delta}{\rho} = \frac{1}{h\nu} \qquad (4)$$

The total attenuation coefficient μ is defined as:

$$\mu = \tau + k + \sigma \qquad (5)$$

The linear attenuation coefficient μ′ (m^{-1}) is defined as:

$$\mu' = \mu \cdot \rho \qquad (6)$$

The above relations for the three types of photon energy scattering are not strict, but are sufficient to estimate the absorption efficiency. For lead, the data on linear coefficients are known, so it is rational to compare them with iron, which was used as a shielding substance in a metal-polymer composite for shielding electromagnetic non-ionizing fields [9] (Table 1).

Table 1. Dependence of the magnetic attenuation coefficients of lead and iron on the energies of gamma radiation

E, MeV	0.50	1.0	1.5	2.0	3.0	4.0	5.0	10,0
μ_{Pb}, cm^{-1}	1.80	0.80	0.60	0.52	0.48	0.47	0.48	0.55
$\mu_{,Fe}$, cm^{-1}	0.66	0.50	0.38	0.34	0.30	0.26	0.25	0.23

These data indicate that the attenuation coefficients of iron comparing with lead are not so low, that they cannot be compensated, for example, by some increase of the thickness of the protective layer. The nonmonotonicity of the change of the attenuation coefficient for lead obtained experimentally is noteworthy. This fact indicates the resonant phenomena in the absorption of photons at certain frequencies for a particular material. This is confirmed by data on the mass attenuation coefficients of X-rays (Table 2).

Table 2. Dependence of the mass attenuation coefficient of lead and iron from the wavelengths of X-rays

Element	λ, nm									
	0.02	0.04	0.06	0.08	0.10	0.12	0.14	0.16	0.18	0.20
μ / ρ, m^2 / kg, Pb	46	330	770	1470	770	1280	1800	2580	3600	3820
μ / ρ, m^2 / kg, Fe	11	71	235	507	950	1700	2700	3900	610	780

The presented results show, that for some wavelengths the efficiency of iron is higher than the efficiency of lead, and this occurs at the conditional limit of "soft" X-rays, inherent to the side (parasitic) radiation of the hardware for various purposes.

Our choice of the iron-ore dust as a filler for the polymeric matrix was predetermined by the following considerations. Iron-ore dust was selected from the dust-absorbing screens in an aspiration system at the iron ore crushing station. This predetermines the high enough dispersion of the material and large percentages of iron and its compounds in the products of ore enrichment.

This discovers the possibility of using composite metal-polymeric materials, based on fine iron, as a shield from ionizing electromagnetic radiation. In the work [9], manufacturing technologies and data on shielding of ultrahigh-frequency electromagnetic radiation with a composite of latex and iron-containing filler from iron ore concentrate are presented. The main problem, considering the short wavelengths of ionizing radiation, is the selection of the concentration of fine metal substance, which provides the minimum and needed levels of attenuation of radiation. For this purpose the metal parts must be evenly and tightly distributed in the polymer body.

The size factor (shielding particle size) is the most important. Photons, multiply scattered in the material, are taken into account by introducing into the law the attenuation of radiation - the accumulation factor. The accumulation factor characterizes the deviation of the detector readings in the wide beam geometry to the detector readings in the narrow beam geometry. Thus, for iron the accumulation factor (dose factor) at photon energies of 0.5 MeV and change of μd from 1 to 20 varies from 1.98 to 55.6, and at energies of 10 MeV from 1.2 to 13.0. These indicators directly depend on the size of the shielding particles on which the scattering of photons occurs due to Raman scattering. The preferred dispersion of iron ore concentrate, determined by the sedimentation method (sedimentation method), is 12 μm. When delivered from the ore processing plant, the concentrate particles are tightly packed by adhesion during the drying process of raw materials, which is obtained by the flotation method. For their separation and grinding it is possible to apply processing of dry concentrate in a ball mill. But this process is long and costly. To obtain the material of the desired dispersion and isotropy, it is advisable to use the ultrasonic method of mixing and grinding. The method is as follows: the required amount of iron ore concentrate is added to the liquid polymer. After mechanical stirring, the ultrasonic wave emitter is immersed in the initial mixture and the mixture is processed.

Laboratory studies have shown that during the pre-treatment of the metal-polymer mixture with ultrasonic radiation at frequencies of 23-25 kHz with amplitudes of 40-45 microns for 0-15 minutes (volume of the mixture - 1 dm^3) there is grinding of particles and their uniform distribution in the mixture. This is confirmed by the results of metallographic studies of the surface of the finished material after drying.

However, significant coefficients of reflection of electro-magnetic radiation with ultra-high frequency under actual industrial conditions could become critical in the presence of internal sources of radiation. It is possible that there is an increase in the electromagnetic background through the repeated reflection of external radiation from shielding surfaces, for instance at equipment facilities at enterprises of civil aviation.

The developed method allows to obtain a material with the required (predicted) protective properties and to minimize the cost of its manufacture.

To scatter radiation from the material, the metal particles must form an almost solid structure. Namely, it is necessary to determine the concentration of metal particles sufficient to shield ionizing radiation. This can be realized by measuring the electrophysical properties of the material at different concentrations of the shielding substance - fine iron ore concentrate. The determination of specific conductivity was carried out by measuring the inverse value - the resistivity of the material by the method of a double bridge (Figure 1).

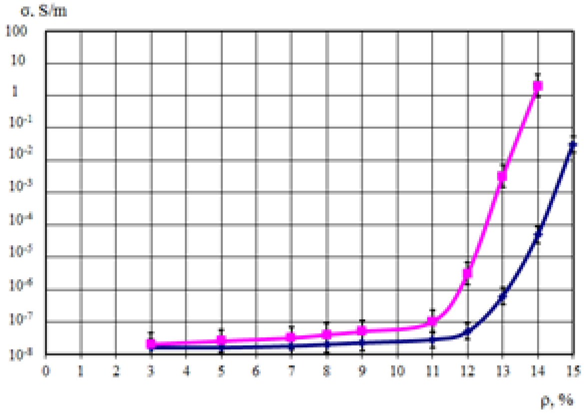

Figure 1. Dependence of specific conductivity of metal-polymeric material on concentration of fine metal substance ■ – 5–10 microns, ◆ – 15–25 microns.

The graphical data show that the sharp increase in the conductivity occurs at the concentration of metal particles of 11-12% (by weight). This indicates, that at these concentrations the material reaches the threshold of electrical conductivity, i.e. the conductive particles form conduction circuits and begin to contact each other. This agrees well with the ratios of the electrodynamics of continuous environments. At iron particle concentrations of 15–20%, the composite material has conductive properties and is suitable for shielding both non-ionizing and ionizing electromagnetic radiation.

The advantage of such materials is the possibility of manufacturing shielding surfaces of large areas, which is due to the low cost of iron ore concentrate. In provided example the latex was used as a polymer matrix, that is not the essential and it can be replaced by any polymer. The only condition is the absence of degradation of mechanical properties under the influence of radiation. This approach allows you to design materials with predictions (necessary) protective properties by changing the concentration of iron-containing substance and the thickness of the material.

Difficulties of using iron-ore dust for the manufacture of protective materials refer to the difference in characteristics of iron ore at different deposits and enterprises, and its enrichment stations. Thus, at the previous stages of the development and production of screens, it is necessary to determine the chemical composition and dispersion of the chosen iron dust.

To improve it, there should be techniques to enhance the uniformity of distribution of shielding particles in the polymer. Such a technique could involve a preliminary preparation, on the base of iron-ore dust, of a magnetic or a rheological fluid, which could be used in the technological process for manufacturing protective materials.

During the creation of such materials, it should be taken into account that the iron ore concentrate of different manufacturers has different dispersion and content of iron and magnetite. These parameters must be pre-determined due to the dependence of the protective properties from the size of the shielding particles and the conductivity of the material from the iron content.

Conclusion

1. It is shown that for soft ionizing radiation it is possible to use iron and its compounds contained in iron ore concentrate as a substance, that provides its shielding.

2. For some wavelengths of ionizing radiation, the shielding properties of iron exceed this figure for lead. The protective properties of metallic materials change non-monotonically, with a change in the wavelength of radiation, which must be taken into account when performing design work.

3. For shielding of ionizing radiation it is rational to use composite metal-polymeric material on the basis of iron ore concentrate. Changing the concentration of the shielding substance allows developing protective materials of the desired efficiency and certain geometric characteristics.

4. To improve the quality of the shielding material, it is necessary to pre-determine in the laboratory the dispersion of the initial shielding raw material and the content in the iron concentrate and its compounds at the laboratory.

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