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An investigation of gamma ray mass attenuation from 80.1 to 834.86 keV for fabric coating pastes used in textile sector

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Abstract In the present study, we investigate several textile coating pastes used in the market based on their radiation protection capability for gamma rays. The gamma ray mass absorption coefficients of some coating pastes doped with antimony, boron and silver elements have been investigated. It has been determined that the gamma ray mass attenuation coefficient decreases rapidly as the energy of the gamma rays increases. It was determined that the doping of the main printing paste with silver and antimony considerably increased the gamma ray absorption capability of main paste. However, the doping of the paste with boron reduces the mass absorption of gamma rays. In particular, the gamma ray mass absorption power of the main paste doped with silver and antimony was determined to be useful in the gamma energy range from 80 to 140 keV. This indicates that the newly doped textile material may be considered for radiation protection in the case of low-energy gamma rays .

Keywords Gamma ray absorption · Radiation protection · Printing pastes · antimony · silver

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1 Introduction

Radiation is present in nature in various forms, and we are continuously exposed to this source of energy. The term radiation is a broad term. It can exist in either a particle-like or wave-like form. Protons, electrons, neutrons, and energetic ions radiation are in the form of particle. X-rays and gamma rays are in the form of waves. Particle-like radiation can be easily stopped by a material compared to gamma and energetic X-rays. Gamma rays and X-rays have the same from but their origins are different. It is well-known that gamma rays are directly emitted from nuclei, whereas X-rays are emitted from atomic level transitions of an atom. As such, gamma rays are more energetic than X-rays in general. It is also a well-known fact that radiation with high ionizing power can damage living cells [1, 2]. However, radiation can be exploited in the fields of energy, industry, technology and medicine. Currently, there are 442 operable nuclear reactors [3] and 1427 nuclear medicine centers in the world [4]. There are also many nuclear units to meet the needs of scientific research, agriculture and industry. Radiation is used in medicine for treatment and diagnosis processes in radiation oncology and nuclear medicine units [5–9]. However, most radiation applications in radiology and nuclear medicine units use gamma rays and X-rays with a wide range of energies.

Individuals that work with high energy radiation sources should be mindful of radiation exposure. However, the basic principle of radiation protection is to minimize radiation dose [10]. This principle is called ALARA (As Low As Reasonably Achievable). The use of protective materials for radiation reduces the radiation dosage when handling radioactive materials, and assist in the application of the ALARA principle. Several recent studies related to investigations into various radiation protective materials have been published Ref. [11–15] and references therein.

Individuals who work in the field of nuclear medicine or radiation oncology wear radiation protective aprons, goggles, gloves and textile materials such as thyroid protective neck collar. These shield materials generally contain lead and are not ergonomic materials. Therefore, research into alternative materials that provide reliable radiation protective are still under investigation. In particular, most radioisotopes used in nuclear medicine for diagnostic purposes emit low energetic gamma rays. As such, the aim of the present study is to investigate the application of coating pastes used in the textile sector as radiation protective material for low-energy gamma rays.

In this context, we have reviewed several studies in the literature related to radiation shielding using textile. Two different fabrics were plastered with barite and their X-ray absorptions were investigated by Molla [5]. The results revealed that the barite coated fabric absorb more radiation than the uncoated fabric. Müjde investigated the X-ray radiation absorption coefficients of products used in the textile industry in Turkey produced from different types of fibers [16]. Samples were irradiated with X-ray photons in the energy range of 16–362 keV, which were emitted from ^{241}Am and ^{133}Ba radioactive point sources. When the results obtained for the samples were compared, it was determined that polyester and polyester doped products were superior for radiation shielding compared to the other samples. In addition, it has been concluded that polyamide, acrylic and polyamide-acrylic doped textile products are more radiation protective materials compared to polyester and polyester doped products. It was observed that wool and cotton products had a lower radiation absorption [16].

The X-ray stopping capacity of samples at the 100 keV level to covered cotton fabrics with silicone rubber containing tungsten, bismuth and barium sulfate powders were measured by Aral et al. [17]. The best results were obtained for bismuth coating. Maghrabi et al. investigated the X-ray protection ability of bismuth oxide, and the X-ray protection ability of polyester fabrics coated with bismuth oxide was determined [18]. Qu et al. measured the X-ray radiation stopping power of woven fabrics that were weaved from fibers produced via regenerated cellulose spinning solution by the addition of sub-micron barium sulfate particles [19]. The X-ray attenuation rate of the samples tended to increase with the increase in the amount of barium sulfate. Demirkurt examined the electromagnetic shielding property of boron carbide appliqued to fabrics and found that boron carbide application increased the electromagnetic shielding property, but not sufficiently [20]. In the study of Emikönel [21], the radiation absorbency was examined for gamma ray absorption of tericoton, cotton and cotton/polyester blended fabrics coated with different ratios of barite. It was determined that the barite coating process significantly contributes to the radiation absorption properties of the fabric. Özdemir and Camgöz tested and compared the gamma ray protection of woven fabrics that are woven for different constructions [22]. They investigated the gamma ray shielding properties of different fabric types and the effect of the structural properties of the fabric such as the weaving pattern, fabric thickness, porosity and conductive weft yarn density on the gamma radiation shielding efficiency based on gamma radiation shielding physics and statistics. They observed that diced woven fabrics exhibited superior gamma radiation shielding efficiency compared to 1/3 twill woven fabrics [23].

Based on the literature summarized above, it is evident that most research focus on X-rays and electromagnetic (EMG) shielding, and that there are very few studies on gamma ray shielding regarding textile materials. As such, this study focuses on gamma ray attenuation of coated textile materials to address this deficiency. In this context, the aim of this study is to determine the gamma ray protection capability of several coating pastes that are commonly used in the textile market. It may be possible to design new radiation shielding materials by considering some special circumstances, depending on the area of application. It is a well-known fact that as the gamma ray energy increases, the stopping power decreases [24]. The use of lead as radiation protective material is more appropriate in the case of high energetic gamma rays. However, there are alternative materials for low energetic gamma rays. In particular, radioisotopes with gamma ray energy in the range of 80 keV and 140 keV (i.e., ^{99m}Tc and ^{201}Tl) are widely used for diagnostic purposes in nuclear medicine applications. Most technicians in nuclear medicine units are exposed to gamma rays with an energy of 80–140 keV. As such, we have investigated the possible usage of coating pastes doped with different elements to produce radiation protective textile material for low-energy gamma rays. The gamma ray mass attenuation coefficients of coating pastes produced in this work were determined for gamma energy ranges between 80.1 and 834.86 keV. Their half value layer thickness and tenth value layer thickness were calculated. In addition, the effective atomic number of coating pastes was calculated as a function of the gamma energy.

The report is organized as follows: Sect. 2 describes the preparation of the coating pastes and the experimental framework used to determine the gamma ray mass attenuation coefficients for the considered materials. The experimental gamma ray mass attenuation coefficients of the coating pastes used in this work are provided and compared with theoretical results. In addition, the radiation protective characteristics of the new coating pastes are discussed in Sect. 3. Finally, a summary is presented in Sect. 4.

2 Material and method

In this study, standard printing paste that is generally used in the textile market was selected as the main paste that consists of a binder and a thickener. The main paste fixes different chemicals to a fabric. This paste was prepared by following the procedure as described in Table 1.

Special-purpose ready-made printing pastes are available from textile markets that introduce different properties to the fabric. In this study, we considered three special-purpose ready-made printing pastes. Their properties are listed in Table 2. These ready-made printing pastes were chosen, because their antimony (Sb), silver (Ag) and boron (B) content can affect the gamma ray mass attenuation of coating pastes. In particular, these special-purpose ready-made printing pastes that contain antimony and silver were chosen, because they can increase the stopping power of the main paste against gamma rays, given that antimony and silver have high mass numbers and densities.

In the present study, new coating pastes were obtained by the mixing of the main paste and 3 different coating pastes containing B, Sb and Ag. The main paste + silver paste, main paste + boron paste and main paste + antimony paste were produced using a mass ratio of 1:1, as listed in Table 3. The density of main paste was determined to be 1.45 g/cm^3.

The samples were prepared in the form of plates instead of coating onto the fabric by considering the experimental setup for gamma ray mass attenuation measurements. After the coating pastes were prepared, they were poured into rectangular molds and dried in an oven at 150°C for 120 min. Later, the samples were maintained at room temperature for 24 h. The plate thicknesses were set to approximately 4 mm, which is suitable for gamma ray mass attenuation measurements. As will be explained later, the thickness of the material cannot contribute to the experimental results, because the mass attenuation coefficient is represented in units of cm^2/g. Several views of the sample plates are presented in Fig. 1.

Table 1 Details of the preparation of the main paste

Material	Value (g/l)
Binder	160
Thickener	20
Distilled water	820

Table 2 Properties of printing pastes used in this investigation

Paste	Name	Properties	Company
Silver paste	Pigmacolor glitter Silver	Water based Ready-to-use	Kemiteks
Antimony paste	Pigmacolor metallic	Water based Ready-to-use	Kemiteks
Boron paste	Tubicoat CRO	Acrylic based Ready-to-use Waterproofing	CHT

Table 3 The rates and densities of the mixtures

Sample	Density (g/cm^3)
200 g main paste + 200 g antimony paste	1.65
200 g main paste + 200 g boron paste	1.43
200 g main paste + 200 g silver paste	1.56

The gamma ray attenuation experiments involving the samples were performed using an AMATEK-ORTEC brand HPGe (High Purity Germanium) detector system at Karadeniz Technical University. To acquire the experimental data during the measurement process, the GammaVision (Ortec, USA, Version: 6.07) computer program was used. In the experiments, a collimator was utilized to collimate the incident gamma rays on the sample. This instrument is an important tool in the acquisition of reliable experimental results. In the present study we used a collimator and its schematic overview is shown in Fig. 2.

In this study, the absorption measurements of the materials were conducted in the energy range of 80.1–834.86 keV. For this purpose ^{133}Ba (80.1 keV and 356 keV), ^{57}Co (134 keV), ^{137}Cs (661.7 keV) and ^{54}Mn (834.86 keV) radioactive sources were used. Each measurement was conducted for 5000 s. To eliminate unwanted background radiation, measurements were also performed without a sample. The obtained gamma spectra were analyzed using the GammaVision Software. For each gamma energy, the area of peaks was determined.

The gamma ray is stopped in matter mainly via the photoelectric effect, Compton scattering and electron-positron pair production. Their contribution depends on the gamma energy. Up to a few hundred keV of gamma energy, the most dominant interaction of gamma rays with matter is the photoelectric effect [7]. Gamma ray attenuation in matter can be determined using the formula,

Fig. 1 (Color online) The pictures of sample plates

$$I = I_0 e^{-\mu x}, \quad (1)$$

where I_0 is the intensity of the incident gamma beam on the sample, x is the thickness of material, I is the intensity of the gamma beam after traversing through a distance x in the sample, and μ is the linear attenuation coefficient of the absorbing material [25]. The μ term can be divided into three components as follows:

$$\mu = \mu_f + \mu_C + \mu_p, \quad (2)$$

where μ_f, μ_C and μ_p are the linear attenuation coefficient of the photoelectric effect, Compton scattering and electron-positron pair production, respectively. We are interested in the total linear attenuation coefficient (μ) in this investigation. It should be noted that gamma ray attenuation of any material depends on the density of the material. This dependence is revealed by dividing the linear absorption coefficient by the material density (μ/ρ), and this is called the mass attenuation coefficient. To determine the gamma ray mass attenuation coefficient of a sample, information on the surface area and the mass of the sample is sufficient, without considering the density of the sample. Therefore, the mass and surface area of each sample were measured and the mass attenuation coefficient were determined in units of cm^2/g.

The half value layer (*HVL*) and tenth value layer (*TVL*) thickness provide useful information about the penetration depth of a specific radiation in a given material. *HVL* is the half value layer thickness of the absorbing material i.e., this thickness reduces the initial intensity of the gamma beam by 50%. The equation for *HVL* is given as follows:

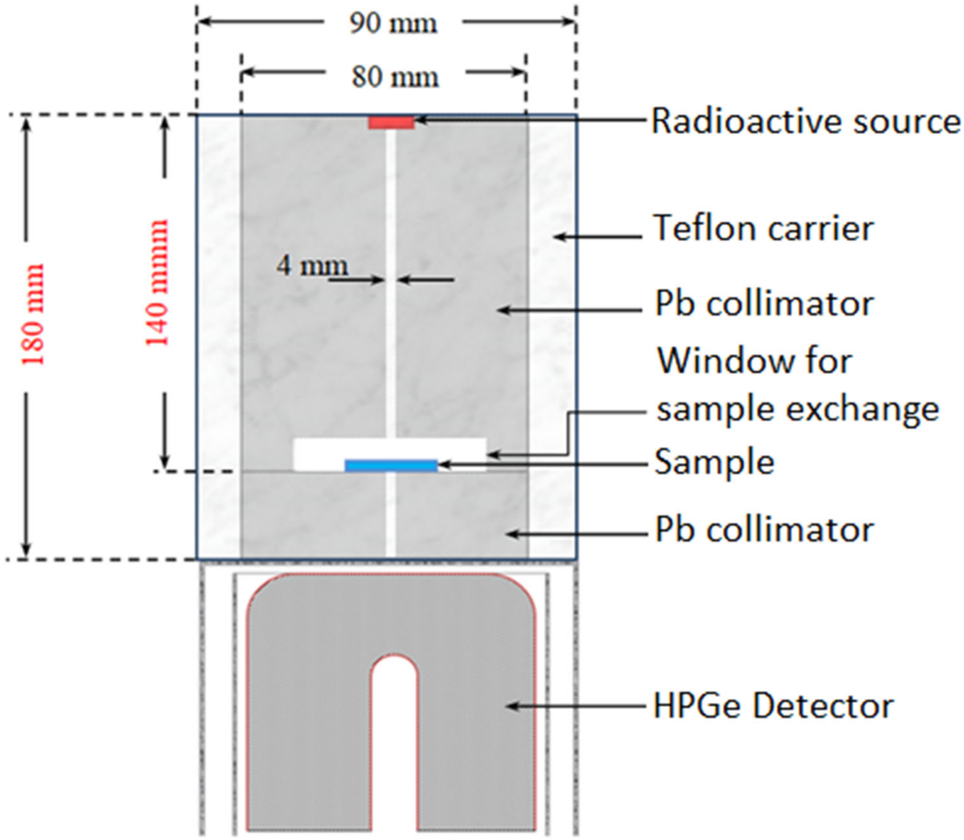
$$HVL = \ln 2/\mu, \quad (3)$$

where μ is the linear attenuation coefficient [25]. *TVL* is the thickness of a given material for which 10% of the incident gamma beam intensity is attenuated. This parameter can be determined as follows:

$$TVL = \ln 10/\mu\,. \quad (4)$$

The *HVL* and *TVL* values of each sample as a function of the incident gamma energy have were also determined in the present study.

Fig. 2 Schematic representation of the collimator used for gamma ray mass attenuation absorption measurements



3 Results and discussion

In this study, the investigated samples consist of many elements. Therefore, we checked the validity of our experimental setup for the determination of the mass attenuation of various coating pastes. For this purpose, we used high purity antimony (> 99.9%) as one of the elements in the preparation of the coating paste. The determined mass attenuation coefficients of antimony for 80.1 keV, 134 keV, 356 keV, 661.7 keV, and 834.86 keV gamma energies are shown in Fig. 3, together with the NIST-XCOM data taken from Ref. [26]. It is evident in Fig. 3 that the determined mass attenuation coefficients of antimony are in agreement with the NIST-XCOM data. The mass attenuation coefficient decreases with an increase in the gamma ray energy, because energetic gamma rays penetrate further into the material.

The determined mass attenuation coefficients of the main paste and the three coating pastes doped with Sb, B and Ag for 80.1 keV, 134 keV, 356 keV, 661.7 keV, and 834.86 keV gamma energies are shown in Fig. 4. In addition, we performed energy-dispersive X-ray spectroscopy (EDX) analysis on the materials. Based on EDX results we calculated the molar ratio of the elements including in each material. Using the molar ratio, we calculated the theoretical total gamma ray mass attenuation

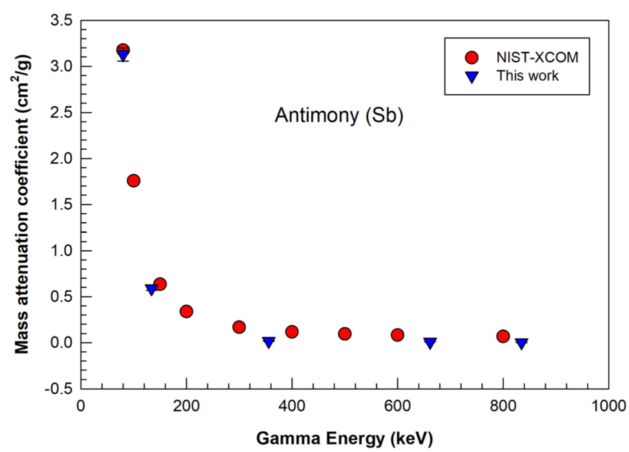


Fig. 3 (Color online) Determined mass attenuation coefficients of high purity antimony and NIST-XCOM data

coefficients. For this task, we used the NIST-XCOM database [26]. The calculated total gamma ray mass attenuation coefficients are shown in Fig. 4 together with the experimental values for comparison. As expected, the mass attenuation coefficient of each material decreases dramatically, whereas the gamma energy increases. It should be noted that the experimental values for each material are lower than the calculated values. However, the general tendency of the experimental mass attenuation

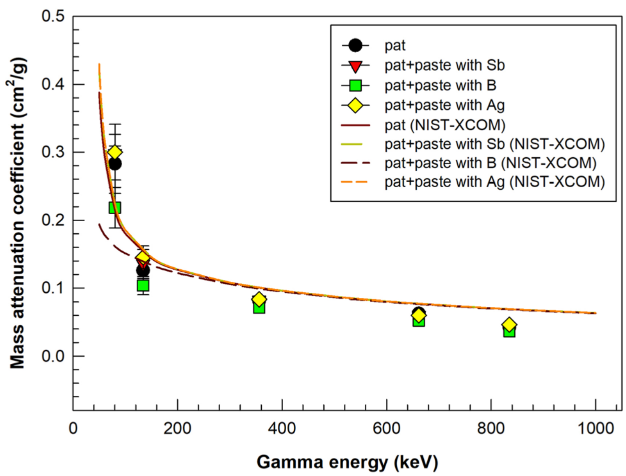


Fig. 4 (Color online) Determined mass attenuation coefficients of the main paste and coating pastes with Sb, B and Ag

coefficients as a function of the gamma energy is in agreement with the theoretical results. The mass attenuation coefficient of the coating pastes doped with silver and antimony are in agreement for each gamma energy. Moreover, their values are greater than those of the main paste and the coating paste doped with boron. In particular, the lowest mass attenuation coefficient was obtained for the coating paste doped with boron. Furthermore, the mass attenuation coefficients of the coating paste doped with boron are lower than those obtained for the main paste. This result is likely due to the small mass number and low density of boron. Therefore, doping of the main paste with elements such as Ag and Sb with high mass numbers and densities can potentially be used to obtain superior coating pastes with higher stopping power against gamma radiation.

From Fig. 4, it is evident that the mass attenuation coefficient value of coating pastes doped with antimony and silver are high for low gamma energies of 80.1 keV and 134 keV. This indicates that these coating pastes are possible candidates for usage in nuclear medicine application for gamma ray protective material, given that the radioisotopes (i.e., ^{99m}Tc and ^{201}Tl are mostly used) used in nuclear medicine for diagnostic purposes emit low-energy gamma rays. The calculated *TVL* and *HVL* values of samples investigated in the present study using the determined mass attenuation coefficient of the main paste and the coating pastes doped with Sb, B and Ag can provide more information on their possible use as radiation protective material. In Fig. 5, the calculated *HVL* (upper panel) and *TVL* (lower panel) values for the samples obtained from the experimental gamma ray mass attenuation coefficients for exact gamma energies are shown together with their theoretical predictions obtained from the NIST-XCOM database [26].

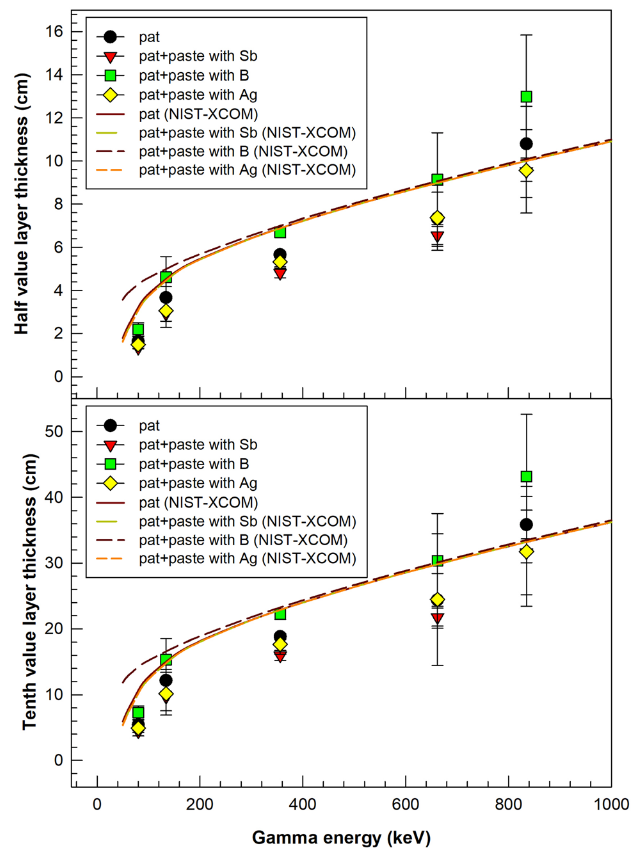


Fig. 5 (Color online) The calculated HVL and TVL values of the main paste and coating pastes doped with Sb, B and Ag

In Fig. 5, it is evident that the calculated values of the *HVL* and *TVL* thickness values obtained using the experimental gamma ray mass attenuation coefficients for each material are close to the theoretical values. However, the calculated values of the *HVL* and *TVL* thickness at a gamma energy of 834.86 keV are far from the theoretical results for the coating paste doped with boron. The calculated values of the *HVL* and *TVL* thickness for the coating paste doped with antimony and silver are lower than those obtained for all the others gamma energies ranging from 80.1 to 834.86 keV, as shown in Fig. 5. The *HVL* value of lead for 120 keV gamma ray is 0.12 cm [26]. This value is significantly larger than those of the coating pastes doped with antimony and silver. This indicates that unlike lead, they cannot stop gamma rays. However, the fabrication of protective materials using coating pastes doped with antimony by increasing the coating thickness is an alternative.

Another important parameter for radiation shielding of material is the effective atomic number Z_{eff}. It can be calculated directly using the following equation [25, 27]:

$$Z_{\text{eff}} = \frac{\sum_i f_i A_i (\mu/\rho)_i}{\sum_j f_j \frac{A_j}{Z_j} (\mu/\rho)_j}, \tag{5}$$

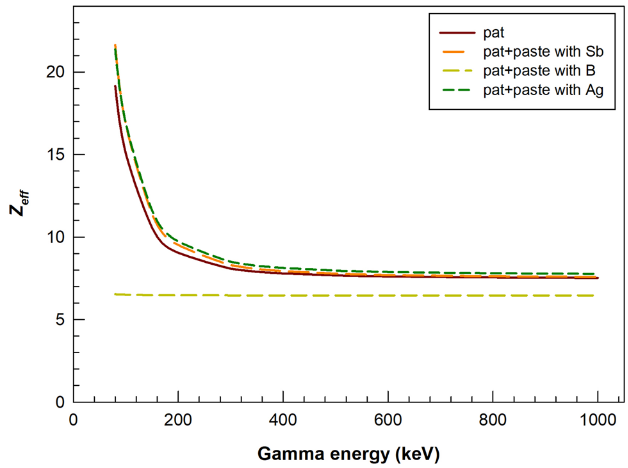


Fig. 6 (Color online) The calculated Z_{eff} values for the main paste and coating pastes doped with Sb, B and Ag

where f is the molar fraction, A is the atomic weight, Z is the atomic number, and (μ/ρ) is the mass attenuation coefficient.

We calculated Z_{eff} values for the main paste and coating pastes doped with antimony, boron and silver in the present study. The atomic weight values are obtained from Ref. [28]. The total mass attenuation coefficients of elements present in the materials were obtained from the NIST-XCOM database [26]. The calculated Z_{eff} values for our materials in the present study are shown in Fig. 6. In Fig. 6, it is evident that the Z_{eff} values for the mixture of the main paste and coating paste with Sb and Ag are higher than those of the main paste. In particular, contributions of As and Sb to Z_{eff} are evident for gamma energies between 80 and 400 keV. It should be noted that the boron content of a mixture reduces Z_{eff} in the same energy range.

4 Summary

The mass attenuation coefficients of coating pastes doped with antimony, boron and silver for 80.1 keV, 134 keV, 356 keV, 661.7 keV and 834.86 keV gamma energies were determined using an HPGe gamma ray detector system, and the results were compared to theoretical values obtained from the NIST-XCOM database. The determined attenuation coefficients were used to obtain HVL and TVL values of the investigated coating pastes. The addition of boron to the main paste decreases the attenuation coefficient of the coating paste, because this element decreases the effective atomic number of the coating paste. However, the addition of antimony and silver to the main paste increases the gamma ray mass attenuation coefficient of the coating paste. This study demonstrates that the doping of main paste using elements with a high mass number and density can be useful in the development of textile coating materials for radiation protective purposes for low-energy gamma rays that are typically used in diagnostic nuclear medicine applications.

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