BRAZILIAN JOURNAL OF RADIATION SCIENCES

doi.org/10.15392/2319-0612.2024.2460
2024, 12(2) | 01-14 | e2460
Submitted: 2024-03-19
Accepted: 2024-06-04

Polymer-based shielding approaches as a practical solution reducing radiological risks in field operations

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Abstract: The objective of this research is to evaluate various polymeric materials that have the potential to serve as substitutes or supplements to heavy vehicle structures for radiation-intensive environments. The materials under investigation include Nylon 6 (PA-6, $C_6H_{11}NO$), polyethylene (PE, C_2H_4), polypropylene (PP, C_3H_6), polyvinyl chloride (PVC, C_2H_3Cl), and polymethylacrylate (PMMA, $C_5H_8O_2$). This study's primary aim is to determine each material's effectiveness in shielding against radiation and reducing exposure to vehicle occupants. As a new approach, this research examines the impact of utilizing polymeric materials and the potential health hazards for young drivers of both sexes, such as developing solid cancers from radiation exposure. According to the study, PVC was the most efficient polymer with a Transmission Factor (TF) of 0.44, leading to a 56% decrease in the relative risk estimate for the maximum thickness evaluated (20 cm). On the other hand, PP was identified as the least efficient, with a TF of 0.65, resulting in a 35% reduction in the relative risk estimate for the same thickness. The study concludes that each polymer has varying degrees of attenuation and that combining their properties is essential to achieving the desired level of risk reduction.

Keywords: polymeric materials, radiation shielding, radiological risk.

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Abordagens de blindagens baseadas em polímeros como uma solução prática na redução dos riscos radiológicos em operações de campo

Resumo: O objetivo deste estudo é avaliar diversos materiais poliméricos que têm o potencial de servir como substitutos ou complementares para estruturas de veículos pesados em ambientes de intensa radiação. Os materiais em investigação incluem Nylon 6 (PA-6, $C_6H_{11}NO$), polietileno (PE, C_2H_4), polipropileno (PP, C_3H_6), cloreto de polivinila (PVC, C_2H_3Cl) e polimetilmetacrilato (PMMA, $C_5H_8O_2$). O principal objetivo deste estudo é determinar a eficácia de cada material na proteção contra radiação e na redução da exposição dos ocupantes do veículo. Como uma nova abordagem, esta pesquisa examina o impacto do uso de materiais poliméricos e os potenciais riscos à saúde para motoristas jovens de ambos os sexos, como o desenvolvimento de cânceres sólidos devido à exposição à radiação. De acordo com o estudo, o PVC foi o polímero mais eficiente com Fator de Transmissão (FT) de 0,44, levando a uma diminuição de 56% na estimativa de risco relativo para a espessura máxima avaliada (20 cm). Por outro lado, o PP foi identificado como o menos eficiente, com FT de 0,65, resultando em redução de 35% na estimativa de risco relativo para a mesma espessura. O estudo conclui que cada polímero apresenta graus variados de atenuação e que combinar suas propriedades é essencial para alcançar o nível desejado de redução de riscos.

Palavras-chave: materiais poliméricos, blindagem das radiações, risco radiológico.

1. INTRODUCTION

Research on using polymeric materials for shielding against radiological exposure is not a new concept. However, it has gained increasing attention in recent years due to its versatility, ease of production, and lower density than heavy metallic materials traditionally used for radiation shielding [1]. This type of shielding is particularly relevant for terrestrial and aerial manned vehicles, which require protection for crews in radioactive environments. While the initial focus is on shielding for land vehicles used in radioactive environments, this concept can be extended to other modes of transportation, such as submarines, aircraft, and spacecraft [2]. By enhancing the protective capacity of vehicles operating in radioactive environments, this preliminary study is expected to reduce health risks such as cancer development among those transported.

This investigation explores the potential application of polymers as a viable alternative for safeguarding manned vehicles intended to enter radioactive areas with perilously high radiation levels deemed hazardous to human life. Polymers, which consist of low-atomic number elements, could potentially replace high-density materials such as iron and lead that are commonly used in industry. Five different types of polymers were examined in the study, namely nylon 6 (PA-6, $C_6H_{11}NO$), polyethylene (PE, C_2H_4), polypropylene (PP, C_3H_6), polyvinyl chloride (PVC, C_2H_3Cl), and polymethylacrylate (PMMA, $C_5H_8O_2$). The study focused on the ability of polymers to attenuate gamma radiation beams, as well as the production of factors that have a buildup effect on transmission factors (TF) and the associated risks to human health. The study proposes a methodology incorporating innovative polymeric materials. The study also highlights the significance of practical tests in radioactive environments typical of aerospace activity. Evaluating radiological risk for crews at high altitudes, within radioactive plumes, or even in space zones beyond the Earth's magnetosphere is paramount [3]. The polymers classified in this study are candidates for use as vehicle shielding elements for radioactive energy fields up to 1 MeV [4].

2. MATERIALS AND METHODS

The Transmission Factor (TF) for the studied gamma radiation beams is a property of each polymer used. TF is defined as the ratio between transmitted and incident radiation intensity. The calculation considered the source-detector direction and the Beer-Lambert attenuation effect [5]. The transmission factors were calculated following four main steps: (a) exponential attenuation (XCOM/NIST); (b) equivalent atomic number (Z_{eq}) [6]; (c) G-P Geometric Progression tuning parameters [7], e (d) buildup factors (BF) based on G-P parameters [8]. The calculations made it possible to correlate each polymer's transmission factors (TF) as a function of the thicknesses for 1 MeV photon energy field.

The development of radiation protection methods heavily relies on the buildup factor (BF). These factors are a correction factor in radiation-matter interaction calculations, performed using the Geometric Progression (G-P) fitting method for energies ranging from 0.015 to 15 MeV. To determine the exponential attenuation of gamma rays, the transmitted radiation's intensity (I) passing through a thickness (x) is compared with the incident radiation's intensity (I_0). The exponential Beer-Lambert law [9] represented by Equation 1 gives the linear attenuation ($e^{-\mu x}$).

$$I = I_0 e^{-\mu x} B(\mu x) \tag{1}$$

I is the radiation intensity after interacting with the material medium, while I_0 represents the incident radiation intensity. B is the buildup factor, and $e^{-\mu x}$ represents exponential attenuation. The value of the exponential attenuation coefficient (μ) can be determined using the values provided by NIST/XCOM.

The exponential attenuation coefficient (μ) provided by NIST/XCOM determines exponential attenuation. However, the calculation of the equivalent atomic number (Z_{eq}) is of utmost importance as it must fall within a designated energy range between atomic numbers Z_1 and Z_2 (where $Z_1 < Z_{eq} < Z_2$). This requirement is expressed in Equation 2 [6].

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \qquad (2)$$

where Z_1 and Z_2 represent the atomic numbers for the elements associated with the ratios R_1 and R_2, respectively. The ratio R is determined by dividing the Compton attenuation coefficient $(\mu/\rho)_{Compton}$ by the total attenuation coefficient $(\mu/\rho)_{Total}$ for the sample at the same energy level.

To determine the Geometric Progression (G-P) tuning parameters, an interpolation method was utilized for generating five G-P parameters (b, c, a, X_k, and d) of PA-6. This method is similar to the one used for calculating Z_{eq}. These parameters can be found in ANSI/ANS-6.4.3 [10]. Still, this database only includes information for twenty-three elements, including iron and two mixtures (air and concrete), with an energy range of 0.015 to 15.0 MeV and up to a penetration depth of 40 mean free paths. Such values were established in ANSI/ANS 6.4.3, whose calculations were carried out with the limits presented. Therefore, for the PA-6 element, G-P adjustment parameters were obtained from the adjustments proposed by Harima and colleagues [7]. They developed a fitting formula for the five geometric parameters (G-P), which provides factor values. This method allows interpolating the G-P parameters to the standard formulations provided by ANSI/ANS-6.4.3 using Equation 3.

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \quad (3)$$

where Z_1 and Z_2 are the atomic numbers of the elements adjacent to the component in question, as suggested by previous studies [10], and P1 and P_2 are the Geometric Progression (G-P) values at a specific energy corresponding to Z_1 and Z_2, respectively.

Therefore, the buildup factor is given by equations 4 and 5.

$$B(E,x) = 1 + (b-1)\frac{K_x - 1}{K-1}, \; K \neq 1 \quad (4)$$

$$B(E,x) = 1 + (b-1)x, \; K = 1 \quad (5)$$

where *b* is a parameter that represents the buildup factor corresponding to 1 mfp (mean free path), and the term K(E,x) denotes the photon dose multiplication factor, which can be obtained using Equation 6.

Equation 6 produces K(E,x), the photon dose multiplication factor, where b is the buildup factor corresponding to 1 mfp.

$$K(E,x) = cxa + d\,\frac{\tanh\left(\frac{x}{X_k} - 2\right) - \tanh(-2)}{1 - \tanh(-2)}, \; x \leq 40 \text{ mfp} \quad (6)$$

where *a*, *c*, *d*, and X_k represent the parameters of the G-P, E is the energy of the incident photon, and *x* is the penetration depth for values up to 40 mfp.

When dealing with multilayer arrangements in a heterogeneous medium, Broder's formulation is expected to be employed [9]. This approach takes into account all shielding layers. It assumes that the buildup factor at the boundary of each layer is the sum of the individual differences during the buildup process at each blade or layer. Simply put, Broder's formulation elucidates the contribution of each shielding layer to the total buildup factor. This correlation is represented by Equation 7 [9].

$$Bb(\mu x) = \left(\sum_{i=1}^{i=N} \mu_i x_i\right) = \sum_{i=1}^{N} B_n\left(\sum_{i=1}^{n} \mu_i x_i\right) - \sum_{i=2}^{N} B_n\left(\sum_{i=1}^{n-1} \mu_i x_i\right) \tag{7}$$

where $\mu_i x_i$ is the distance in terms of mpf of each sheet i, N is the G-P buildup factor for a given homogeneous material medium of the n-*th* layer of thickness $\left(\sum_{i=1}^{i=n} \mu_i x_i\right)$ [9].

The Transmission Factor (TF) quantifies the correlation between the strength of radiation that passes through a shielded area and the radiological measurements taken before and after shielding. To accurately compute this factor, it is essential to account for the direction of the radiation source and detector, which can be determined using Equation 8 [9].

$$TF = \frac{I}{I_0} = e^{-\mu x} * B(\mu x) \tag{8}$$

where TF represents the relationship between the initial radiation intensity (I_0) and the resulting radiation intensity (I).

Equation 8 defines the correlation between the initial radiation intensity (I_0) and the resulting radiation intensity (I) after crossing the shield. The former represents the intensity before interaction with the shield, while the latter corresponds to the intensity after passing through it. This equation can be interpreted as the multiplication of the exponential attenuation ($e^{-\mu x}$) with the buildup factor ($B(\mu x)$) [9].

To estimate the relative risk (RR) of solid cancer development, evaluating the occupants of a polymeric-shielded armored vehicle is necessary. The assumption here is that the radioactive environment consists mainly of gamma emissions with a maximum energy of 1 Mev and an integrated dose of energy distributed in the contaminated zone not exceeding 4 Sv. The relative risk (RR) associated with developing solid cancers is calculated based on the RERF model created by the Japanese Radiation Effects Research Foundation [11]. Equation 9 depicts this model, which predicts the likelihood of developing cancer due to radiation exposure up to a total body dose of 4 Sv. This dose is lethal for 50% of the exposed human population within 30 days of exposure. While the choice of solid cancer as a benchmark was arbitrary, it was selected to evaluate the impact of different polymers on tissue equivalence at varying thicknesses. To determine the influence of the polymers on tissue equivalence, as well as the resulting radiation dose and radiological risk (represented by the RR of developing solid cancer for both sexes at the age of 20 for testing purposes), the standard deviation (SD) value was estimated.

$$RR = r_0(a, s)[1 + \alpha_s D\exp(\beta(e - 25))] \quad (9)$$

where $r_0(a,s)$ is the basic incidence rate of morbidity in the potentially affected population in the absence of irradiation taken as the unit in this study, α_S is the age-specific linear excess relative risk per Gy considered as 0.45 (Gy^{-1}), and 0.77 (Gy^{-1}) for male and female, respectively. D is the radiation dose (Sv), e is the age (years), and β is the coefficient determining the modifying effect of age, both at the exposure and considered as -0.026 (y^{-1}) for both sexes.

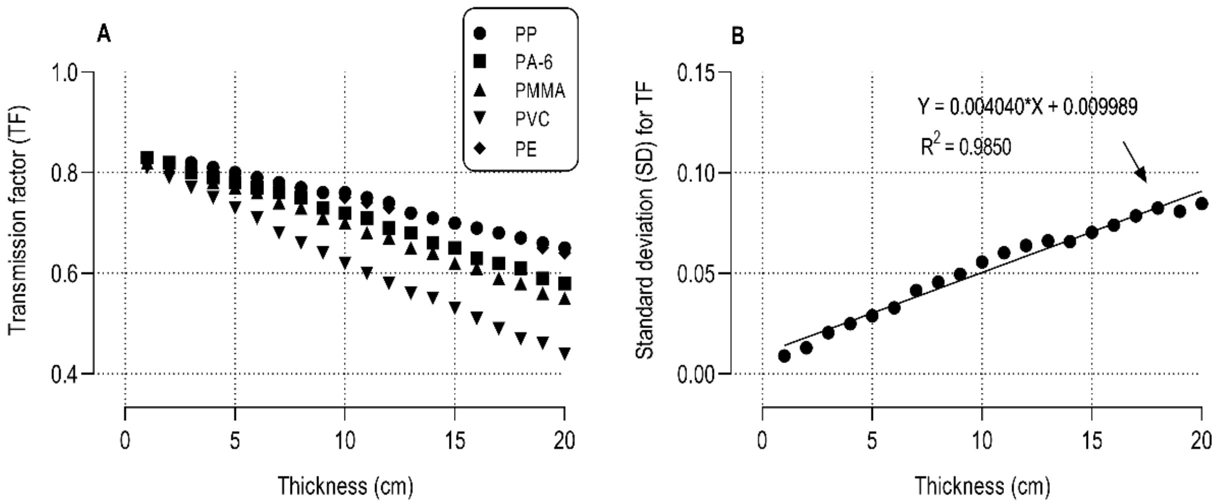
The 1 MeV energy range was selected to explore gamma radiation interactions within a higher energy range, resulting in a critical scenario. Understanding this energy range is significant as it can provide insight into the shielding effectiveness behavior expected at higher energies, which typically decreases as the energy of incident gamma radiation increases. The calculation methodology utilized in this study can be applied to any gamma radiation energy requiring evaluation. The subsequent stage of this research will examine the behavior of shields for different gamma energy ranges and other biological implications.

The study included a comprehensive list of equations (1 to 7) used for the calculations. These equations mainly represented intermediate steps or provided theoretical support for the methodology. However, the results from the calculations were not included in the text as they were deemed non-essential for understanding the achievements of the study.

3. RESULTS AND DISCUSSIONS

The polymers were evaluated in thickness variations from 1.00 to 20.00 cm in a bi-laminated shield of a 1.00 cm iron sheet. Figure 1 presents the results of the calculations for determining the transmission factors (TF) for each selected polymer. Each thickness in the range of 1 to 20 cm within the radiation field of photons with a maximum energy of 1 MeV is also considered.

Figure 1: The transmission factor (TF) for each polymer and each armor thickness (1A) and the estimate of each polymer's influence on each thickness (1B).

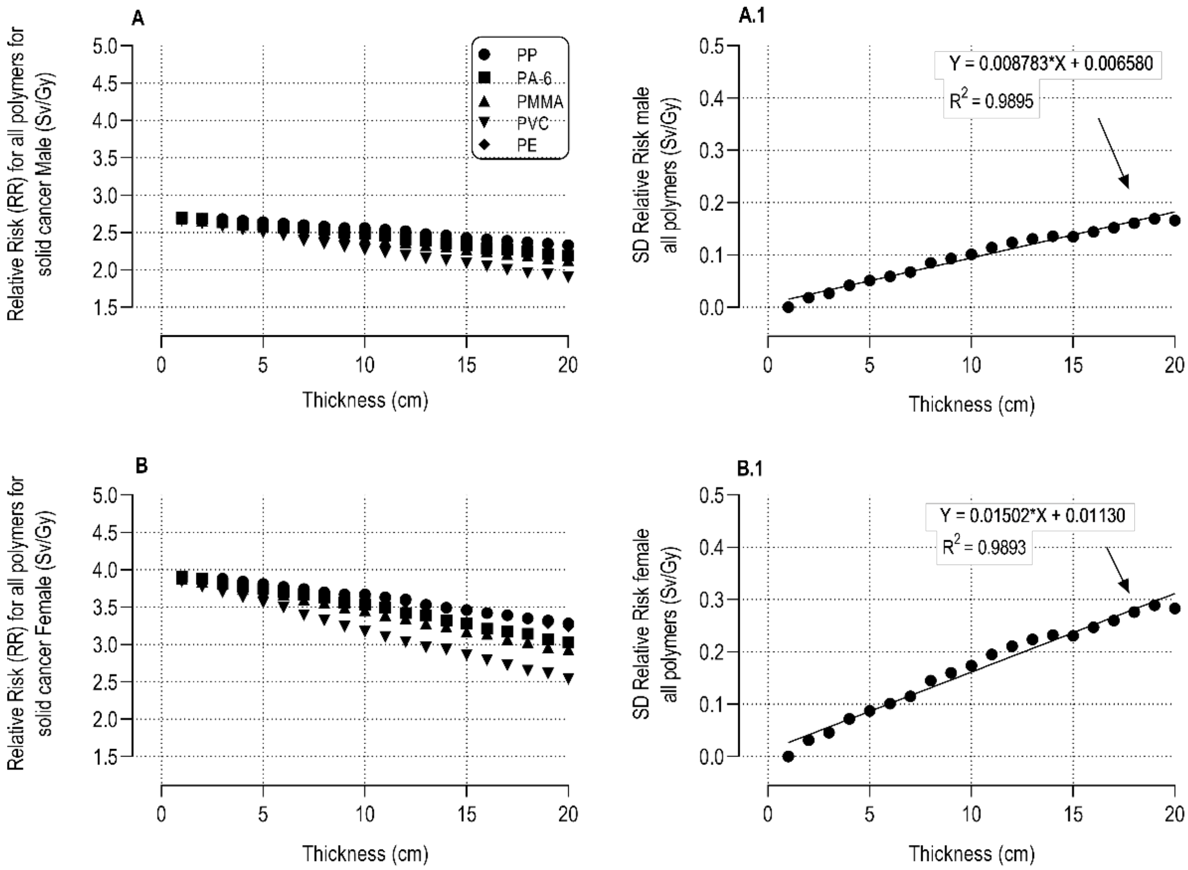


The results presented in Figure 1A show the direct beam attenuation (without shielding) for thicknesses ranging from 1 to 20 cm. The polymers exhibit regular behavior, but the PP polymer is consistently the least effective (highest TF), which is noteworthy. Also, a similar behavior can be observed when comparing the PP and PE curves. This similarity was expected due to these materials' close chemical composition, density, and attenuation coefficients. Figure 1B shows the standard deviation (SD) of TF dispersion values for the compounds in each thickness, representing their distribution of results. The results suggest that the studied polymers tend to be equivalent as the thicknesses get smaller. Therefore, when manufacturing polymeric shields, it is essential to consider the destination of the shield and the expected dose levels. Developing thin shields to minimize any negative financial impacts on the project is preferable, as different materials may have additional costs.

Polymers may be a viable option for enhancing protection against radiation exposure. These materials have the potential to significantly reduce the risk of radiation-related illnesses by lowering radiation doses. As shown in Figures 2A and 2B, this protection may decrease the relative risk of developing solid cancers. While the study focused on this particular morbidity, other development models for various illnesses are available [11]. To assess the effect of polymers on the risk of developing solid cancers in humans, the study analyzed individuals of both genders, aged 20 years for exemplification purposes, who were exposed to environmental radiation fields. The study considered photons in the radioactive field produced by nuclear releases with energy levels of 1 to 2 MeV or less [12]. Photons presenting less than 1 MeV energy levels have a higher potential for attenuation than those in higher energy ranges [12]. Assuming all photons in the radiation field have energy levels around 1 MeV, the proposed shielding can offer a reasonable protection factor.

Furthermore, the results indicate the effectiveness of the polymers in reducing the dose received by volunteers during the rescue operation. According to CNEN [13], the acute dose received must not exceed the maximum limit of 100 mSv. The polymers tested met research expectations when exposed to environmental doses of up to 153 mSv. The PP showed the poorest performance, reducing the dose to 98.8 mSv at its maximum thickness. In contrast, the PVC demonstrated the best performance among the analyzed polymers, reducing the dose to 70.4 mSv at its maximum thickness.

Figure 2: Both sexes' relative risk (RR) for radioinduced solid cancer development (A and B). Effect of each polymer for each thickness on the RR for both sexes (A.1 and B.1), 20 years old.



Risk equations indicate that the influence of polymeric materials decreases for thinner shields, regardless of sex. However, the risk varies up to 50% depending on the individual's sex. This can pose a challenge when designing equally effective shields for both male and female operators. Armor thickness can be modified to address this, or different polymers with varying thicknesses can be combined to achieve equivalent protection. Figures A.1 and B.1 provide additional information on the expected impact of the polymers on risk reduction at different thicknesses. Individual sex should still be considered when designing polymeric shields for hostile radioactive environments. Comparing figures A.1 and B.1, differences in their impact on risk reduction can be seen. The ratio between the slopes of the interpolated straight lines in the direction of B.1 to A.1 shows a difference of approximately 17% in favor of male operators. This highlights the need to factor in sex when designing polymeric shields for hostile radioactive fields.

The ongoing study on the shielding properties of polymers has yielded encouraging results during its preliminary phases. To establish the efficacy of polymer-based shielding in vehicular radiation protection, our team conducted empirical tests, followed by an analysis of radiological risks. Through experimental data, we were able to gauge the shielding capability of polymers, and our subsequent assessment of radiological risks has bolstered our confidence in the material's ability to provide adequate protection against radiation in a vehicular setting. While our study is still in its early stages, these promising results suggest that polymer-based shielding may be a viable alternative to traditional radiation shielding materials in vehicular applications.

Operations in a radiation field require measures to limit radiological exposure and ensure maximum protection. Adherence to the ALARA principle, which aims to keep radiation exposure As Low As Reasonably Achievable, is essential. However, following the ALARA principle can be challenging in hostile radiological conditions, such as accidents, intentional releases, or high-altitude environments. To address this, developing new materials for shielding vehicles operating in these environments and understanding the relationship between shielding and avoided radiation risk can be essential for establishing effective risk mitigation strategies. This study proposes exploring not only the most suitable polymer-based shielding but also information on the level of protection against radiological risks, and field intensities. The preliminary results introduce a unique combination of expected vehicle shielding protectiveness and the ability to predict radiological risk across various radiation environments and specific endpoints. These capabilities have the potential to enhance personnel safety and serve as an initial predictive tool for public epidemiological studies during evacuation procedures from contaminated areas.

4. CONCLUSIONS

According to the initial research, polymers may be effective as shielding components for human-crewed vehicles designed for use in highly radioactive environments. The findings indicate that the polymer selection, shielding material thickness, exposure level, radiobiological endpoint, and individual factors such as sex and age are all crucial considerations in developing a successful coping strategy. Nonetheless, identifying a polymeric material from the tested options that can offer optimal protection and reduce the risk of radiation exposure is a challenging goal for the next phase of this research endeavor.

ACKNOWLEDGMENT

The authors wish to thank the colleagues who contributed valuable comments and suggestions.

FUNDING

This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq Grant PQ n° 304636/2023-1, and n° 409490/2023-7).

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest concerning this article.

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