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Exploitation of Taylor's Approximation in Program BUF for Gamma Buildup Calculations in Composite Shields: An Extended Study

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Abstract: The development of a radiation shield is utmost important to attenuate the intensity of radiation reaching out to the outer world. Such analyses involve calculations of buildup factors which are central to every shield design to be carried out. In particular, to justify the practical shielding necessities, one must investigate for multiple layered shield designs. For buildup factors, the Taylor's approximation has been broadly customized through numerous studies for single-layer shields and has been found sufficiently precise to provide buildup information in the compounds and the elements tested for. In this reference and connection to our previous study, here the author attempts a detailed investigation of Taylor's approximation through Program BUF toolkit for composite shields extending up to five-layered shields. Interestingly, the developed toolkit proves accurate enough to calculate buildup data for a composite shield design. Numerical calculations are carried out using BUF toolkit taking basis of Taylor's fitting formula. The validity of the developed source code is examined by comparing its results with the buildup data of composite shields available in literature. The results are able to reproduce the existing data, wherever possible, in both single- and composite shields extending to five-layer designs. In this paper, except for four-layered shields where no experimental data is available for comparison, the other results of the present work assuming composite shields up to five layers are directly made to compare with the corresponding simulation data available. Noticeably, the BUF results are seen to show good agreement with the experimental results. The source code BUF calculates buildup factor data in the energy range of 0.5 MeV-10 MeV for shields having effective atomic number lying between 10 and 92.

Keywords: Buildup factor, Composite shields, Program buf, Radiation dosimetry.

1 Introduction

Where there are advancements in the field of nuclear energy and technologies, there poses a parallel progress of the concern of handling the radiation exposure and its subsequent hazards. This fact makes the understanding of radiation interactions with matter significant to explore and investigate for the purpose of designing an appropriate radiation shield. Nonetheless it is quite justifiable to realize that a composite shield works superior as compared to a single-layer shield. Here, composite shield refers to the one in which the component materials are being stacked or mixed. However, mixing of materials, whether homogeneous or non-homogeneous, may prove a poor exercise owing to creation of gaps allowing the radiation to penetrate through [1-4] and therefore, stacking materials or a multi-layer design approach prevents all such abnormalities in the development of a composite shield and preferred to meet practical requirements. Moreover, in real-time applications, the radiation interacts via multiple attenuating media. Thus, the calculations of buildup data (B-data) taking a multi-layer approach of a composite shield are more crucial for investigation among scientists and radiation physicists. Here, the B-data refers to the buildup of produced secondary radiations in the shielding medium after interacting with the entered gamma photons into it. Thus, to have an apt radiation shield at the point of nuclear use, it becomes significant to carry out preliminary calculations of the secondary photons' buildup within the medium. To this concern, several simulation studies using invariant-embedding method [5] and Monte-Carlo method [6] have been developed over decades for B- data calculations for variety of elements and mixtures. The approach of exploiting empirical relations has also been exercised for a number of formulae [7] i.e., simplest linear approximation, Berger's approximation, Capo's and Broder's Formulae, G-P approximation [8] etc. dominantly taking a single-layer shield into consideration and measured

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by Trubey [9]. Later two- and three-layer shields were studied [10-15] using Monte-Carlo simulation techniques and G-P fitting approximation to determine B-data with different component elements. In 2019, Sajali et al [16] well reviewed the key findings for B-data in multi-layered shield designs discussing different material arrangements. All such techniques are developed and validated over years to provide precise information of buildup factors for a wide variety of commonly chosen elements, compounds, alloys and mixtures for radiation shielding. However, developing a computer program code usually provides faster resolutions and eludes relatively cumbersome analytical approaches. In this direction, the present study is an attempt to develop a computer program code toolkit for quick primary investigation of B-data particularly for manifold designs for better choice of shield in a nuclear facility and is an extended study of the simple linear approximation once employed to develop Program BMIX [7,17] by exploiting a better approximation here using Taylor's fitting formula [1] in the form of Program BUF. Remarkably, the program BUF is able to develop B-data for medium to high incident gamma energies ranging from 0.5 MeV to 10 MeV in single and multi-layered shields with effective atomic number lying in between 10 and 92. While our previous work [1] well demonstrated the application of code BUF in single-and double-layered shields, this paper extensively includes the buildup factors calculations in multifold shielding designs finding these more suitable for non-theoretical field applications. Here, the source code is investigated for composite shields up to five-layers and has been accordingly validated by the simulation studies available.

2 The Methodology

2.1 Taylor's Approximation

The methodology [1,17] takes up the concept of buildup factor which has been accepted globally for the grave understanding of transmission of gamma photons, their potential hazards, and the subsequent practical shielding calculations. Since a gamma photon interacts within a target medium via three possible processes namely photoelectric effect, Compton scattering and pair-production depending upon its incident energy. The evolution of B-data is instigated from those gamma photons that undergo scattering interactions in the shielding material and then after the low-intensity secondary radiation generated in the medium itself. To understand, consider Compton scattering mechanism that does not remove the complete incident photon unlike in photoelectric and pair-production processes producing secondary radiations, rather leaves behind a scattered photon of lesser energy although the latter mechanisms also lead to production of characteristic X-rays and annihilation gamma rays. Therefore, to account all such effects, a correction factor in the form of buildup factor B is introduced in the Lambert-Beer law $\phi = \phi_0 e^{-\mu x}$; μ and x being the attenuation coefficient and the penetration depth respectively, which explains the gamma ray interactions with the predefined beam geometry, target conditions and the nature of the incident beam making it $\phi = B\phi_0 e^{-\mu x}$. Hence, this correction part in the form of B accounts for the scattered radiation transmission within the shielding medium. In general, it may conveniently be described B as ratio of total dose flux to the uncollided flux. B-data depends on the incident photon energy, shield components, source geometry and target thickness [7,17]. With this dependence, it is appropriate to write B as $B(Z, E_\gamma, \mu x)$.

Now, Taylor's formula is one among the most useful fitting formulae that may be written as [1,17]

$$(\mu x) = A\,E(-\alpha 1\mu x) + (1 - A)\,Exp(-\alpha 2\mu x) \quad (1)$$

Here, the Taylor's coefficients A, $\alpha 1$, and $\alpha 2$ are energy functions. The specific value x = 0 implies that value of B approaches unity, since when there is no radiation shield present, there would be no buildup of secondary radiations in the shielding medium. The values of A, $\alpha 1$, and $\alpha 2$ in equation (1) are easily found at various places in literature [17-19]. Pertinent that the other available fitting formulae, although few more accurate usually involve complex mathematics than Taylor's approximation making latter more suitable for wider and extensive use. In the present work, equation (1) is exploited for primary calculations of B-data in single- and multi-layer shielding applications.

2.2 Effective Atomic Number Approach for Composite Shields

The calculations pertaining to atomic numbers of the component elements of a multi-layered shield get simplified considering the impression of effective atomic number. For this, we make use of Goldstein's approach [7] which offers homogeneous stacking of different layers of the components of the shield allotting a specified effective atomic number $\bar{Z}$ to the composite shield. Therefore, this approach facilitates the user to compensate for the errors that may get introduced from finite absorber media. In this situation, B-data depends on penetrated number of mean free paths (mfp's) by the gamma photons and on the effective atomic number $\bar{Z}$. Using this method, the effective atomic number of the composite shield $\bar{Z}$ may be calculated from the expression

$\bar{Z} = \frac{\sum_{i=1}^{3} Z_i \mu_i x_i}{\sum_{i=1}^{3} \mu_i x_i}$. Here, the denominator represents the actual shield thickness in units of mean free paths and B-data now, be determined by interpolating in the available B-data for a single shielding material of atomic number $\bar{Z}$ and attenuation thickness say $X = \sum_{i=1}^{3} \mu_i x_i$. It should be noted that the B-data determined here is for exposure buildup factor after passing through the shield despite other buildup factors like dose-equivalent buildup factors and energy deposition buildup factors for deposition of energy in the dium being of more common use for furthur estimations.

The source code BUF designed for numerical calculations of B-data is simple and of comprehensive nature [17]. It is very relevant to talk here about the application limits of the code BUF. Since the values of effective atomic number $\overline{Z}$ of the shield and incident gamma energies $E\gamma$ are to be used as base inputs into the program, these values must lie within the mesh data of Taylor's fit parameters A, $\alpha 1$, and $\alpha 2$ available in literature. For instance, the listed data of the parameters can be readily found for effective atomic number $\overline{Z}$ in the range $10(Water) < \overline{Z} < 92(Uranium)$ and the incident gamma energy within $0.5\ MeV < E\gamma < 10\ MeV$ in the reference manuals [17-19]. Despite this limiting range, the program, however, maintains its utility since the abovementioned range covers the most elements suitable for shield designing purposes.

3 Results and Discussion

In this section, the numerical computation for the exposure buildup factor for multi-layered shields are presented. The validity of the program for single element shield is already tested in the recent study [1], here the program results are demonstrated for multi-layered shields up to 5-layers. Further, for concrete mixtures, it is appropriate to choose values of Z in the range 11 to 27 for normal to heavy concretes [20]. Here, Z=12 is being chosen for program input. The values of attenuation coefficients μ for different materials have been taken from the data available at various places [9,17-19] for different incident energies E_{γ}. To draw a clear comparison, wherever possible, the values are chosen according to the available results. In other cases, arbitrary suitable inputs have been entered where such comparison could not be made possible lacking any available result. The program accepts maximum ten values at a time of incident gamma energies (E_{γ}) between 0.5 MeV and 10 MeV, a broad spectrum of gamma energies 1-10 MeV is chosen for calculation of buildup factors. Since the program BUF has already been demonstrated for single-layer shields, this work is dedicated to the calculation of B-data in multi-layered shields and the subsequent outputs are revealed in the following subsections.

3.1 Two-layered shield

The two-layer shield of lead (1 mfp) +water is chosen for buildup calculation which has been investigated earlier by Hirayama et al (1998) [15]. However, the program BUF buildup results for this two-layer shield in the energy range 1-10 MeV having attenuation thickness of lead (1 mfp) +water (9 mfp) are shown below, the comparison is made at gamma energy 10 MeV at various penetration depths up to 40 mfp with the EGS4 results given by Hirayama et al. It is observed from the program output that in the intermediate energy range near 1 MeV, the buildup factors have higher values that decrease with further rise in photon energy. The higher values correspond to the dominance of the Compton scattering at intermediate energies which merely degrades the incident energy and fails to remove the photon from the beam resulting into their buildup for a longer time in attenuating shield medium that subsequently leads to higher buildup data values.

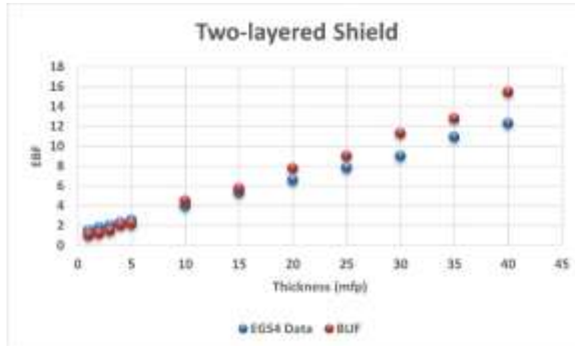

Fig. 1: Comparison of BUF B-data in a two-layer shield lead+water with EGS4 data [15] at 10 MeV.

scattering, which is a photon absorption interaction process and consequently, the buildup factor decreases. In addition, the attenuation thickness is seen to have dependence on incident energy. In figure 1, the variation of buildup factors with the penetration depth is depicted and a comparison with the EGS4 data given in Ref. [15] is made up to 40 mfp depths. An increasing rate is noticed with an increase in penetration depth which may be due to the rise of secondary annihilation gamma rays caused by the pair-production process inside the medium with increasing thickness. It is clear from the figure that the program BUF is in good agreement with the EGS4 data with slight differences towards high penetration depths.

3.2 Three-layered shield

For three-layered shield buildup data, shield composed of water (8 mfp)+iron(4 mfp)+lead is examined at 10 MeV point isotropic source. The choice of the shield and its thickness has their references with the study of Shin et al (1998) [15] using EGS4 codes. The trend of variation of buildup factors with incident energy is again the same as in two-layer shields. Since the pair-production process starts overriding the Compton scattering near photon energy 1.5 MeV, the buildup factors can be seen decreasing immediately after this for high incident energies. Since the attenuation thickness in the shield is different for different constituent materials and energies, the program is repeatedly run over and again to gain outputs at energy 10 MeV at desired penetration depths.

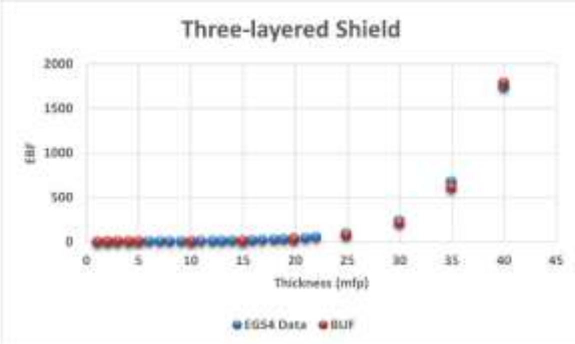

Fig. 2: Comparison of BUF B-data in a three-layer shield water+iron+lead with EGS4 data [15] at 10 MeV.

Figure 2 shows the dependence of buildup factors on penetration depth. The buildup data is observed to rise with penetration depths which might have relevance with the production of secondary annihilation gamma rays in the shielding medium. The comparison of BUF results with the EGS4 data given in Ref. [15] is performed which shows a strong agreement between the two. This excellent concordance of the two results clearly establishes the validity of developed program code BUF and highlights the efficacy of Taylor's approximation for multi-layer shields at high incident energies.

3.3 Four-layered shield

Since there is no reference data available in literature for exposure buildup factors for four-layered shields, the program BUF is arbitrarily input for calculations of buildup data in a four-layered shield composed of water (5 mfp)+iron(4 mfp)+lead(6 mfp) and concrete(8 mfp) at incident energy 5 MeV of which the program output is as given below in figure 3.

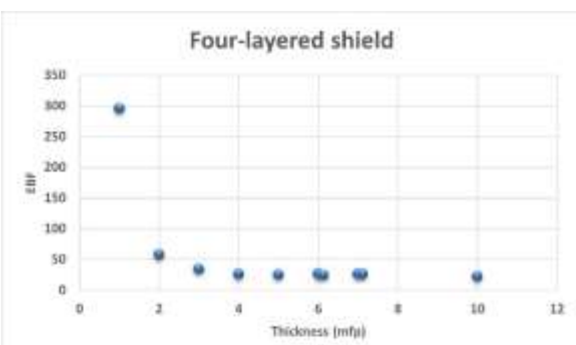

Fig.3: BUF B-data in a four-layer shield water+iron+lead+concrete at 5 MeV.

3.4 Five-layered shield

For a broad manifestation of program BUF in composite shields, a five-layer shield built from four materials, iron (3 mfp)+water(8 mfp)+lead(4 mfp)+aluminum(8mfp)+lead(1 mfp) is also selected and input to the program code BUF at indicated thickness of chosen materials.

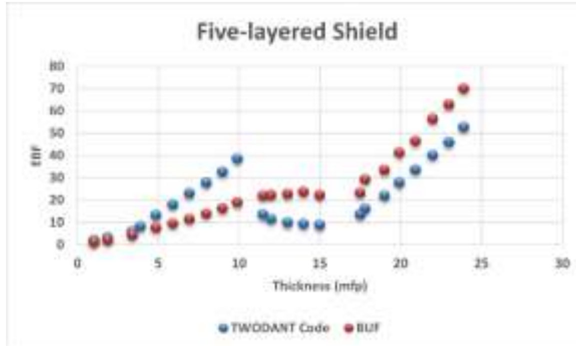

Fig. 4: Comparison of BUF B-data in a five-layer shield iron+water+lead+aluminum+lead with TWODANT data [21] at 1 MeV.

To enable a fair comparison of results, the choice of materials and thickness of various layers have been selected according to the experimental data [21] which assumes a spherical geometry keeping the source monokinetic at 1MeV. The program output displays B-data at incident gamma photon energies ranging from 1-10 MeV out of those results at incident photon energy 1 MeV are plotted in figure 4 and compared with the TWODANT code results by Suteau et al (2005) [21].

As has expected from the previous work, the source code BUF designed and developed for the exposure B-data required for further designing of a suitable radiation shield provides satisfactory results even for multilayered patterns seen and depicted in figures 1,2, 3 and 4 using two-, three-, four- amd five-layered protection shields. Though the program code BUF works within its application limits predefined in the early parts of this section, the domain adequately meets the required conditions of use. These extensive findings are reasonably significant in view of practical composite shielding requirements over single-layered covers at nuclear energy spots.

4 Conclusions

The numerical results of program code BUF for multi-layer shields have been found to agree well with the other available results of Monte-Carlo simulations in two-, three- and five-layered shields. The B-data is found to be dependent on atomic number of component elements Z, attenuation coefficient μ, shield thickness x and the photon energy. Noticeably, the attenuation thickness is dependent on the atomic number of the material used and the incident photon energy. The buildup factors have high values at medium energies mainly due to Compton scattering effect which diminishes with the pair-production process being predominant at higher energies. However, the production of secondary annihilation gamma rays due to pair-production interaction again may be the reason behind the high buildup factor values in large penetration depths. This is an expected trend generally observed in exposure buildup factors. Noticeably, the attenuation thickness is dependent on the atomic number of the material used and the incident photon energy.

The findings might be useful in preliminary investigation of buildup data of elements and therefore may find its future applications for getting primary estimations of buildup factors of various elements at different thicknesses and for single and multiple layers. Further, the approach may provide quick assessment of measured safety protocols at radiation facilities and medical applications.

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