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Calculation and Study on the Exposure Buildup Factor of Type 316 Stainless Steel

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Abstract

Buildup factor is an important parameter in the design of a radiation shielding system. As a manufacturing material commonly used for nuclear equipment, type 316 stainless steel is selected as the research object of this article. Exposure geometric progression fitting parameters and the corresponding exposure buildup factor (EBF) are calculated for type 316 stainless steel in the photon energy range of 0.015 MeV - 15 MeV, as well as penetration depth up to 40 mean-free-paths (mfp), and studied as a function of the photon energy and penetration depth. It can be observed that EBF changes significantly with the photon energy and penetration depth. These changes are attributed to the dominant interaction process in different photon energy regions. Besides, EBFs of 1.17 MeV and 1.33 MeV are interpolated using the obtained data and compared with those from the MCNP5 simulation by introducing a co-concentric multi-layer model, respectively. The results obtained from the Geometric Progression method are consistent with those calculated by the MCNP5 code. Buildup factors for type 316 stainless steel obtained in this article can be used as a reference for shielding performance assessment of the equipment made of type 316 stainless steel.

Subject Areas

Genetic Engineering, Nuclear Engineering

Keywords

Type 316 Stainless Steel, Exposure Buildup Factor, Point-Kernel Method, Geometric Progression Method, Monte Carlo Method

1. Introduction

In order to reduce personnel exposure to ionizing radiation and protect the environment, it is essential to evaluate the radiation shielding performance of different materials used to manufacture the nuclear component. There are three commonly used methods to evaluate the radiation shielding performance of a material, *i.e.*, the Monte Carlo method, the analytical method and the point-kernel method. Because of its simplicity and convenience, the point-kernel method is often used to deal with the complex shielding problems [1]. Buildup factor, a key element determining the accuracy of the point-kernel method, must be calculated in advance [2].

Buildup factor, defined as the ratio of the total detector response to that of un-collided photons, may refer to different quantities of interest, e.g., exposure to the interacting material [3]. Buildup factor was initially introduced and measured by White in 1950 [4]. There have been many calculations of the buildup factor for different materials so far. In 1954, theoretical sets of buildup factors for six elements and water were provided by Goldstein Wilkins [5]. In 1970, Institute of Engineering Mechanics in the Chinese Academy of Sciences published a manual of gamma-ray shielding parameters and gave the exposure and absorbed dose buildup factors of concrete, iron and lead [6]. In 1991, the American Nuclear Society and American National Standard Institute issued a standard called *Gamma-ray attenuation coefficient and buildup factors for engineering materials* (ANSI/ANS-6.4.3) and presented buildup factors for 23 elements of the atomic number from 4 to 92, 1 compound and 2 mixtures in the photon energy range of 0.015 MeV - 15 MeV and penetration depth up to 40 mean-free-paths (mfp) [7]. Because of its high strength, good plasticity and corrosion resistance, type 316 stainless steel is an ideal material for the manufacture of nuclear equipment, e.g., the reactor vessel and radioactive material transport container [8] [9]. However, there has been no research about the exposure buildup factor (EBF) of type 316 stainless steel until now.

In this article, the exposure geometric progression (G-P) fitting parameter and the corresponding EBF are calculated for type 316 stainless steel in the photon energy range of 0.015 MeV - 15 MeV and penetration depth up to 40 mfp. Besides, EBFs of 1.17 and 1.33 MeV are calculated based on the data obtained in this article and validated with the MCNP5 simulation, respectively. The results obtained in this article are useful for the shielding performance assessment of the component made of type 316 stainless steel.

2. Materials and Methods

2.1. Type 316 Stainless Steel

Type 316 stainless steel is an austenitic chromium-nickel stainless steel containing 2% - 3% molybdenum. Due to the addition of molybdenum, type 316 stainless steel not only improves the chloride corrosion-resistance compared with the type 304 stainless steel, but also increases its strength at high temperatures. In China, type 316 stainless steel has been used in the manufacture of different components of the pressurized water reactor and fast neutron reactor [8] [10].

The elemental composition by weight percentage of type 316 stainless steel used here is taken from a China national standard [11] and given in Table 1.

2.2. Calculation of EBF Using the G-P Method

Generally, the calculation of EBFs using the G-P method can be done in three steps as followed.

2.2.1. Calculation of the Equivalent Atomic Number

The interaction of photon and matter depends on the equivalent number of the matter (Z_{eq}) which is energy-dependent and can be estimated by the ratio (R) of the Compton partial interaction coefficient (μ_c) and mass attenuation coefficients (μ_t) at specific energy. To evaluate Z_{eq} of type 316 stainless steel at specific energy, μ_c and μ_t are obtained using WinXCom code and the interpolation of Z_{eq} is done using the following formula [12]:

$$Z_{eq}=\frac{Z_1\left(\log\left(R_2\right)-\log\left(R_{316}\right)\right)+Z_2\left(\log\left(R_{316}\right)-\log\left(R_1\right)\right)}{\log\left(R_2\right)-\log\left(R_1\right)} \tag{1}$$

where R_1 and R_2 are the (μ_c/μ_t) ratios of the two successive elements of atomic numbers corresponding to Z_1 and Z_2, respectively. R_{316}, lying between R_1 and R_2, is the (μ_c/μ_t) ratio of type 316 stainless steel at specific energy.

To calculate Z_{eq} of type 316 stainless steel, the values of μ_c and μ_t in the photon energy range of 0.015 MeV - 15 MeV are obtained for type 316 stainless steel and elements from $Z = 1$ to $Z = 60$ using WinXCOM program at first [13]. And then, the values of Z_{eq} of type 316 stainless steel are calculated by match the ratio R (μ_c/μ_t) of type 316 stainless steel and two successive elements according to Formula (1). The Z_{eq} obtained here is shown in Table 2.

2.2.2. Calculation of the G-P Fitting Parameters

The calculation of EBF using the G-P method requires five fitting parameters, *i.e.*, b, c, a, X_k and d. ANSI/ANS-6.4.3 has given these parameters for 23 elements, 1 compound, 2 mixtures and 25 photon energies. However, Z_{eq} of type 316 stainless steel does not match that of any matter given in ANSI/ANS-6.4.3. G-P fitting parameters of type 316 stainless steel at specific energy can be calculated in a similar procedure as Z_{eq}, *i.e.*, interpolated from Z_{eq} using the following formula [14]:

$$p_{316}=\frac{p_1\left(\log Z_2-\log Z_{eq}\right)+p_2\left(\log Z_{eq}-\log Z_1\right)}{\log Z_2-\log Z_1} \tag{2}$$

where p_1 and p_2 are the G-P fitting parameters taken from ANSI/ANS-6.4.3, corresponding to the elements with atomic numbers Z_1 and Z_2, respectively.

Table 1. The standard chemical composition of type 316 stainless steel [11].

Element	C	Si	Mn	P	S	Ni	Cr	Mo	Fe
wt (%)	0.08	1.0	2.0	0.045	0.03	12.0	17.0	2.5	65.345

Table 2. The calculated Z_{eq}s of type 316 stainless steel.

Energy (MeV)	Z_{eq}	Energy (MeV)	Z_{eq}
0.015	25.751	0.600	26.514
0.020	26.312	0.800	26.489
0.030	26.379	1.000	26.538
0.040	26.415	1.500	26.376
0.050	26.439	2.000	26.251
0.060	26.448	3.000	26.166
0.080	26.473	4.000	26.115
0.100	26.476	5.000	26.116
0.150	26.500	6.000	26.129
0.200	26.515	8.000	26.087
0.300	26.498	10.00	26.087
0.400	26.492	15.00	26.119
0.500	26.508		

p_{316} is the G-P fitting parameter (*i.e.* b, c, a, X_k and d) of type 316 stainless steel corresponding to Z_{eq}. The calculated exposure G-P fitting parameters for type 316 stainless steel are given in Table 3.

2.2.3. Estimation of the EBF

EBFs of type 316 stainless steel ($B(E, x)$) in the photon energy range of 0.015 MeV - 15 MeV and penetration depth up to 40 mfp are estimated with the calculated G-P fitting parameters using the G-P method [15]:

$$B(E,x) = 1 + (b-1) \times (K^x - 1) \big/ (K-1) \quad \text{when} \quad K \neq 1 \tag{3}$$

$$B(E,x) = 1 + (b-1) \times x \quad \text{when} \quad K = 1 \tag{4}$$

$$K(E,x) = cx^a + d \times \left[\tanh\left(\frac{x}{X_k} - 2\right) - \tanh(-2)\right] \Big/ \left[1 - \tanh(-2)\right] \tag{5}$$

where E is a specific photon energy in MeV; x is the source-detector distance in the material in mfp; $K(E, x)$ is a parameter, the variation of which represents the photon dose multiplication and changes in the shape of the energy spectrum.

2.2.4. Interpolation of Buildup Factors for Specific Energy Not Given in ANSI/ANS-6.4.3

For specific photon energy (E) in the photon energy range of 0.015 MeV - 15 MeV not given in ANSI/ANS-6.4.3, EBF corresponding to E (B) can be interpolated from E using the following formula:

$$B = \frac{B_1(\log E_2 - \log E) + B_2(\log E - \log E_1)}{\log E_2 - \log E_1} \tag{6}$$

Table 3. The calculated exposure G-P fitting parameters for type 316 stainless steel.

Energy (MeV)	*b*	*c*	*a*	X_k	*d*
0.015	1.004	1.526	−0.533	5.652	0.344
0.020	1.012	0.127	0.636	11.323	−0.665
0.030	1.027	0.372	0.192	27.042	−0.282
0.040	1.056	0.335	0.247	12.056	−0.116
0.050	1.095	0.364	0.234	13.838	−0.136
0.060	1.142	0.399	0.213	14.071	−0.117
0.080	1.254	0.466	0.182	14.396	−0.099
0.100	1.372	0.549	0.147	14.073	−0.081
0.150	1.635	0.731	0.083	14.097	−0.049
0.200	1.813	0.897	0.037	13.300	−0.034
0.300	1.954	1.082	−0.007	11.973	−0.019
0.400	1.978	1.178	−0.025	10.847	−0.014
0.500	1.957	1.231	−0.037	8.620	−0.008
0.600	1.937	1.241	−0.039	8.259	−0.010
0.800	1.896	1.232	−0.038	7.777	−0.011
1.000	1.836	1.241	−0.045	17.236	0.009
1.500	1.748	1.195	−0.040	16.224	0.011
2.000	1.711	1.123	−0.021	8.052	−0.006
3.000	1.626	1.059	−0.005	12.003	−0.013
4.000	1.553	1.026	0.005	12.930	−0.019
5.000	1.483	1.009	0.012	13.126	−0.026
6.000	1.441	0.981	0.023	13.364	−0.036
8.000	1.354	0.974	0.029	13.645	−0.043
10.000	1.297	0.949	0.042	13.968	−0.056
15.000	1.199	0.958	0.049	14.375	−0.060

where B_1 and B_2 are EBFs corresponding to the photon energy E_1 and E_2 given in ANSI/ANS-6.4.3, respectively. E just lies between E_1 and E_2.

2.3. Calculation of EBF with MCNP5 Code

2.3.1. Calculation of Exposure Rate Considering Both the Collided and Un-Collided Photons

In order to calculate EBF for type 316 stainless steel, an MCNP5 model is setup. As illustrated in Figure 1, a point mono-energetic source is placed at the center of a sphere filled with type 316 stainless steel and the outside space is dry air. For the model of thick penetration depth, an onion-layered structure is set up and

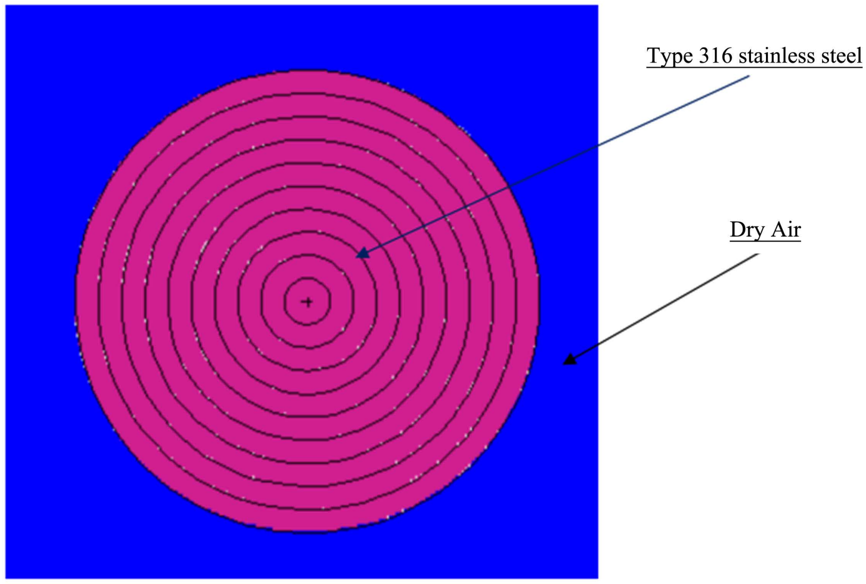


Figure 1. The simulation geometry drawn by MCNP visual editor.

the thickness of each layer is 1 mfp. To reduce statistical error, the importance of each layer doubles from inside to outside. The photon and electron (MODE P E) is considered to transport primary photons and all secondary electrons and photons. Surface-crossing flux estimator (F2 card) is set to the surface of the sphere to record the total average flux on the surface of the spherical shield and works with the dose energy card (DEn) and dose function card (DFn) to obtain the total exposure ($\dot{X}_{\text{total}}$). The mass energy absorption coefficient (μ_{en}/ρ) of dry air used to calculate the dose function value is given in **Table 4**.

2.3.2. Calculation of Exposure Considering Only Un-Collided Photon

For a gamma-ray point isotropic source of specific energy, exposure rate caused by the un-collided flux on the surface of a spherical shield ($\dot{X}_{\text{un-collided}}$) can be calculated analytically using the following expression:

$$\dot{X}_{\text{un-collided}} = E \times \frac{A}{4\pi r^2} \times \left(\mu_{en}/\rho\right)_{\text{air}} \times \left(e/W_{\text{air}}\right) \times \mathrm{e}^{-\mu_l \times r} \tag{7}$$

where E is the photon energy in MeV; μ_l is the linear attenuation coefficient for the photon energy of intereste in the shield material, μ_l of 1.17 MeV and 1.33 MeV are 2.701 × 10^{-2} cm^{-1} and 2.623 × 10^{-2} cm^{-1}, respectively [16]; $(\mu_{en}/\rho)_{air}$ is the mass energy absorption coefficient of type 316 stainless steel, $(\mu_{en}/\rho)_{air}$ of 1.17 MeV and 1.33 MeV are 2.701 × 10^{-3} m^2/kg and 2.623 × 10^{-3} m^2/kg, respectively [15]. A is the activity of the point isotropic source in Bq; r is the radius of the spherical shield in cm; e is the charge of an electron, *i.e.*, 1.602 × 10^{-19} C; W_{air} is the average energy required to produce an ion pair in dry air, *i.e.*, 33.85 eV. EBF of type 316 stainless steel (B) can be calculated using the following expression:

$$B = \frac{\dot{X}_{\text{total}}}{\dot{X}_{\text{un-collided}}} \tag{8}$$

Table 4. The mass energy absorption coefficient (μ_{en}/ρ) of dry air [7].

Energy (MeV)	μ_{en}/ρ (cm^2/g)	Energy (MeV)	μ_{en}/ρ (cm^2/g)
0.010	4.640E+0	0.600	2.953E−2
0.015	1.300E+0	0.800	2.882E−2
0.020	5.255E−1	1.000	1.000E−2
0.030	1.501E−1	1.500	2.545E−2
0.040	6.694E−2	2.000	2.342E−2
0.050	4.031E−2	3.000	2.054E−2
0.060	3.004E−2	4.000	1.866E−2
0.080	2.393E−2	5.000	1.737E−2
0.100	2.318E−2	6.000	1.644E−2
0.150	2.494E−2	8.000	1.521E−2
0.200	2.672E−2	10.00	1.446E−2
0.300	2.872E−2	15.00	1.349E−2
0.400	2.949E−2	20.00	1.308E−2
0.500	2.966E−2		

3. Results and Discussion

3.1. Photon Energy and Penetration Depth Dependency of EBF

Based on the data listed in **Table 3** and Formulas (3)-(5), the values of EBF in the photon energy range of 0.015 MeV - 15 MeV as well as penetration depth up to 40 mfp are calculated here. The variation of EBF with the photon energy and penetration depth is illustrated in **Figure 2**. In order to show the variation trend of EBF more clearly, the variation of EBF with the photon energy at certain penetration depths (1, 5, 10, 20, 30 and 40 mfp) and the variation of EBF with the penetration depth at certain photon energies (0.015, 0.1, 1, 5, 10 and 15 MeV) are shown in **Figure 3** and **Figure 4**, respectively.

It is noted that the EBF values of type 316 stainless steel are lower in the low-energy and high-energy range while higher in the intermediate-energy range. In the low energy range, photo-electric effect is the dominant process, resulting in a complete removal of the incident photons and a little buildup of photons, e.g., EBFs for 0.015 MeV photon are slightly greater than 1.0 for all penetration depths. In the intermediate energy range, due to the dominance of Compton scattering that only degrades the photon energy and fails to remove photons completely, the scattered photons exist for a longer time, resulting in a large value of EBF. In the high energy range, pair production starts dominating which results in a strong absorption of photons. However, secondary photons generated by electron-positron annihilation pile up and result in a small increase in EBF.

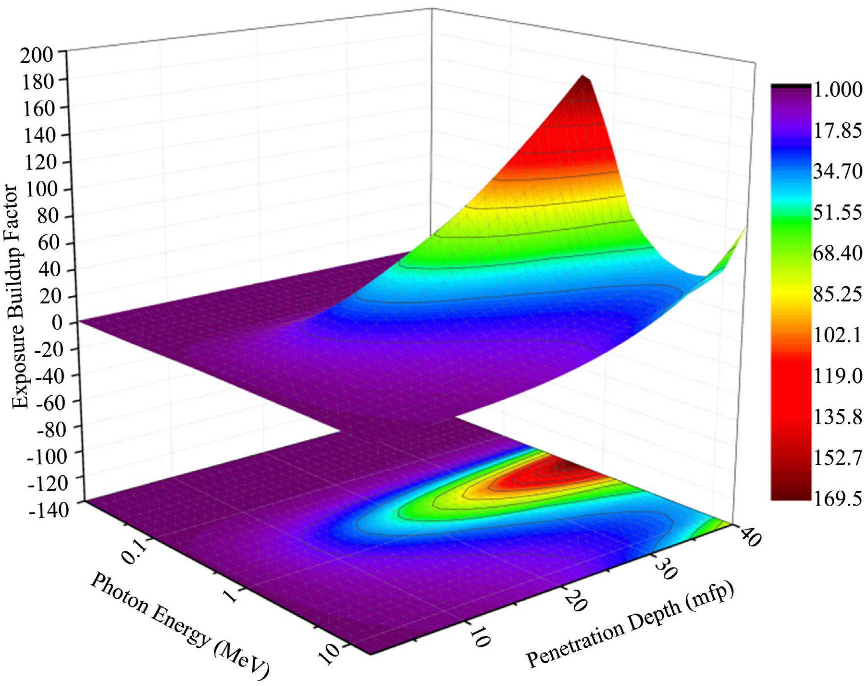


Figure 2. Variation of EBF with the photon energy and penetration depth.

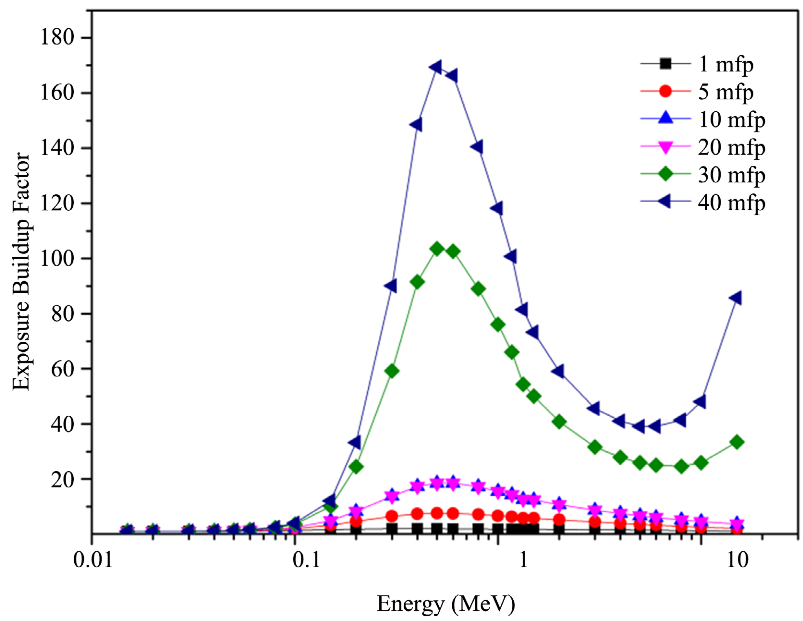


Figure 3. EBF for type 316 stainless steel in the photon energy range of 0.015 MeV - 15 MeV at 1, 5, 10, 20, 30, 40 mfp.

As for the variation of EBF with the penetration depth, it can be clearly observed that EBFs increase with the penetration depth and the increasing rate of EBF in the intermediate energy range (e.g., 1 MeV) is higher than those of other energy ranges. This is attributed to the increase of penetration depth prevents photons from escaping but producing more scattering, especially for the 1 MeV photon, and leads to the increase of EBF.

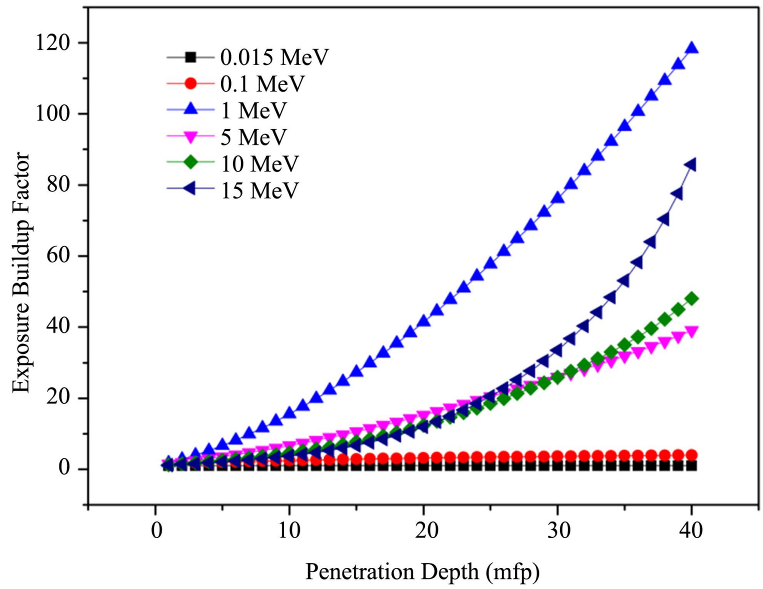


Figure 4. EBF for type 316 stainless steel in the penetration depth up to 40 mfp at 0.015, 0.1, 1, 5, 10 and 15 MeV.

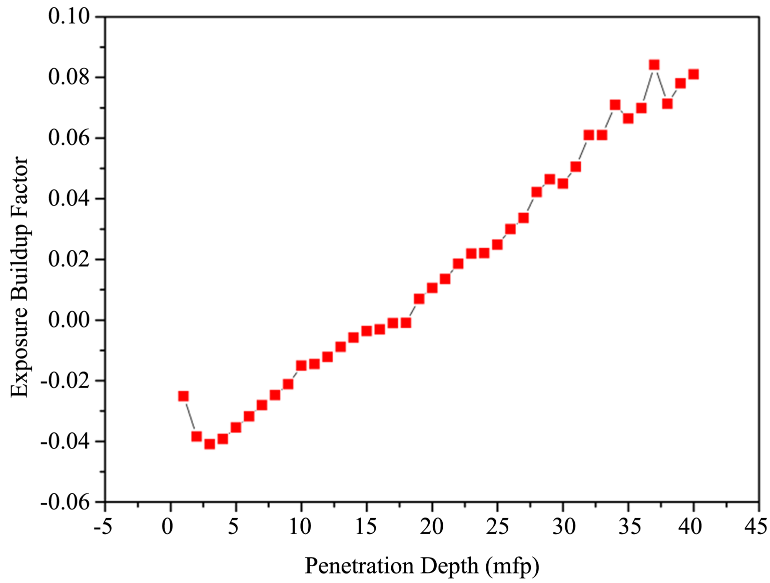
3.2. Comparison between Results Obtained from the G-P Method and Monte-Carlo Method

Since the energy of gamma rays emitted by ^{60}Co is often used as a benchmark to evaluate the shielding performance of a material, EBFs at 1.17 MeV and 1.33 MeV are calculated based on the data obtained above. EBFs calculated here (B_G) are validated with those obtained using the MCNP5 (B_M). Variations of $(B_M - B_G)/B_M$ for 1.17 MeV and 1.33 MeV are given in **Figure 5(a)** and **Figure 5(b)**, respectively.

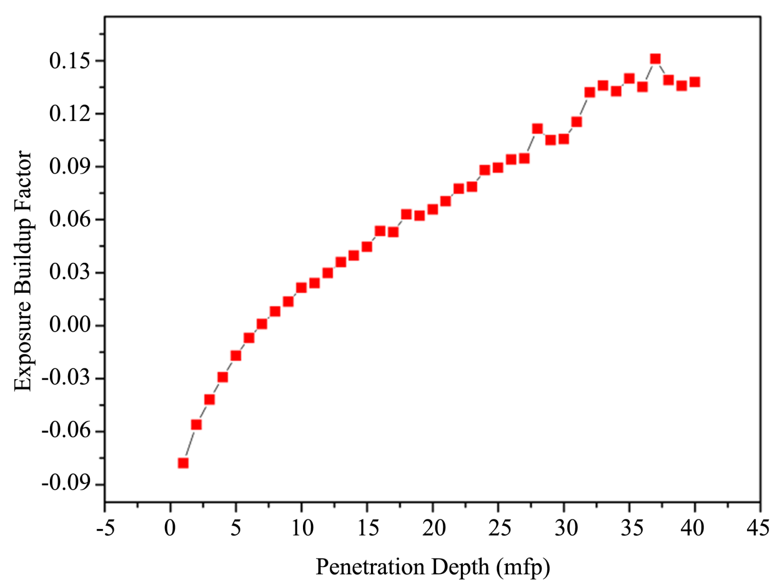
It can be seen from 5(a) and 5(b), for the penetration depth up to 40 mfp, B_Ms are consistent with B_Gs for 1.17 MeV and 1.33 MeV, respectively. The maximum values of $(B_M - B_G)/B_M$ are 8.10% and 15.10% for 1.17 MeV and 1.33 MeV, respectively. Therefore, the bi-linear interpolation is applicable to calculate EBF at specific energy for type 316 stainless steel using the results obtained in this article. Besides, $(B_M - B_G)/B_M$ for 1.17 MeV and 1.33 MeV can be found to increase with the penetration depth for both 1.17 MeV and 1.33 MeV. The reason for the deviation between B_M and B_G lies in the following aspects:

1) The Monte Carlo model used here is a concentric multilayer model. Being different from the infinite slab model used by ANSI/ANS-6.4.3, the tally surface in the concentric multilayer model can record not only the photons originating from the source point but also the secondary scattered photons in the opposite direction of the emergence of photon. With the increase of the radius, more scattered photons move towards the opposite direction of the emergent photon and are recorded by the tally.

2) Compared with ANSI/ANS-6.4.3, the reaction cross-sections used by MCNP5 are new and the results based on these cross-sections may be more accurate if the simulation model is correct. Besides, it cannot be denied that there



(a)



(b)

Figure 5. Variation of $(B_M - B_G)/B_M$ with the penetration depth up to 40 mfp: (a) 1.17 MeV; (b) 1.33 MeV.

are certain errors in the results obtained using the G-P method, bi-interpolation and MCNP5 simulation.

4. Conclusions

In this article, the G-P method is used to calculate EBF of type 316 stainless steel produced in China in the photon energy range of 0.015 MeV - 15 MeV and penetration depth up to 40 mfp. It can be observed that EBFs change significantly with the photon energy and penetration depth. Values of EBF are minimum in the low and high photon energy range whereas they are higher in the intermediate photon energy range. Besides, EBFs at 1.17 MeV and 1.33 MeV are calculated based on the obtained data using the bi-linear interpolation and compared with those using MCNP5 by introducing a concentric model. The interpolated results are consistent with the MCNP5 simulation results. The maxima of $(B_M - B_G)/B_M$ are 8.10% and 15.10% for 1.17 MeV and 1.33 MeV, respectively. The results of the present work are helpful for practical calculations in the manufacture of nuclear equipment.

Conflicts of Interest

The authors declare no conflicts of interest.

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