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A study of energy absorption and exposure buildup factors in natural uranium

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Abstract. Energy absorption and exposure buildup factor have been computed for natural uranium in the energy range of 0.05-15MeV up to penetration depth of 40 mfp. Five-parameter geometric progression (G-P) fitting method has been used to compute buildup factors of uranium. The variation of energy absorption and exposure buildup factors with, penetration depth and incident photon energies for the uranium has been studied. It has been concluded that the values of energy absorption and exposure buildup factors are very large at 0.15 MeV.

Keywords: energy absorption buildup factor; exposure buildup factor; uranium; GP fitting method

1. Introduction

Gamma radiations exposure to the human body can occur during nuclear research establishments, nuclear reactors, nuclear fuel cycle facilities and nuclear accidents. In the nuclear reactor, harmful radiations from the fuel and fission products, which consist of multi-energetic photons, were released and for protection from these highly penetrating radiations, thick walls of suitable shields were built around the nuclear reactor. The energetic gamma rays are hazardous for living cells and organisms, so a detailed study is required for the safe and acceptable use of gamma radiation, radioactive materials and nuclear energy. (Kurudirek *et al*. 2011, Mann and Sidhu 2012, Kaur *et al*. 2012)

In the most nuclear power plant the uranium (in various compounds) is widely used as the nuclear fuel, this element exposure to various gamma radiation energies. So study about photon interaction with this element is very important in nuclear power reactor shielding aspects. The gamma ray buildup factor is a multiplicative factor used to obtain the corrected response to the uncollided photons by including the contribution of scattered photons. Buildup factor is an important parameter in distribution of photon flux in every object (Chilton *et al*. 1984, Icelli *et al*. 2013). It can be defined as the ratio of the total detector response to that of uncollided photons (Mann *et al*. 2012). Although buildup factors have been widely calculated for shielding materials, it have also been applied to photon transport simulation in the material utilized in nuclear installation for shielding calculation .

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Values of B are dependent on atomic number of the attenuating medium, the energy of the gamma ray, the number of mean-free-path (mfp) lengths penetrated by the gamma ray, the cross-section data of each material, the geometrical form of the radiation source and the geometrical form of the attenuating medium (Kucuk *et al*., 2013). The buildup factor measures the degree of violation of the Lambert–Beer law ($I = I_0 e^{-\mu x}$) due to multiple scattering of photons. The modified equation becomes ($I = B I_0 e^{-\mu x}$) (Singh *et al*. 2008, Mann and Sidhu 2012).

The *B* shows the effect of photon scattering in broad beam geometry and always $B \geq 1$. For a completely absorbing medium with scattering cross section ($\sigma s=0$), buildup factor would be unity, $B=1$. The buildup factor *B* and the exponential attenuation factor $e^{-\mu x}$, are a function of μx (or number of mean free paths (mfp)) which can complicate calculations of the shield thickness *x* to reduce a photon intensity from I_0 to $I(x)$. The buildup factors are of two types viz. energy absorption buildup factor (EABF) and exposure buildup factor (EBF). The EBFs are for exposure in the air after penetration through the absorber or shielding material. Other types of buildup factors also exist, in particular energy absorption buildup factors (EABF) for energy deposition in an absorbing medium and dose buildup factors in absorbing media.

Since a primary assessment in radiation protection is the exposure field before and after use of a radiation shield, exposure buildup factors are of more general use with appropriate adjustments of the air exposure to obtain absorbed dose (James *et al*. 2006). Different methods such as G-P fitting method (Harima *et al*. 1986), invariant embedding method (Shimizu 2002; Shimizu *et al*. 2004), and Monte Carlo method (Sardari *et al*. 2009) are available for computing buildup factors.

Abdi Saray *et al*. (http://www.urmia.ac.ir/titles/fizik/.../p138) calculated EBF for the pointed and isotropic gamma sources in the uranium, aluminum and iron by using MCNP4C code, in the range of 0.1-10 MeV and 0.5-25 mean free path (mfp). In another work Kiyani *et al*. (2013) have studied the gamma buildup factors for pointed and isotropic gamma sources in depleted uranium, uranium dioxide, natural uranium, tin, water and concrete using MCNP4C code. In this present work an attempt has been made to compute EBF and EABF values by using G-P fitting method for natural uranium in the energy range 0.015–15 MeV up to a penetration depth of 40 mfp.

2. Study procedure

The geometric progression (G-P) fitting formula has been developed by Harima (Harima *et al*. 1986a; Sidhu *et al*. 2009). This is a theoretical method and is presented to determine the energy absorption and exposure buildup factors in most of the elements. The fitting parameters obtained by the GP formula and Taylor's formula are compiled in ANSI/ANS 6.4.3, (ANSI/ANS 6.4.3, 1991). To calculate the energy absorption and exposure buildup factors, the G-P fitting parameters were obtained by the method of interpolation from the equivalent atomic number (Z_{eq}) (Kurudirek *et al*. 2011, Salehi *et al*. 2014, Sardari and Kurudirek 2012). Computations are divided into the following steps:

2.1 Calculation of equivalent atomic number (Z_{eq})

In the first step, the equivalent atomic number Z_{eq}, of a particular material was calculated by matching the ratio, $(\mu/\rho)_{Compton} / (\mu/\rho)_{total}$, of that material at a specific energy with the corresponding ratio of an element at the same energy. Thus, firstly the Compton partial mass

attenuation coefficient $(\mu/\rho)_{Compton}$, and the total mass attenuation coefficients $(\mu/\rho)_{total}$, were obtained for uranium in the energy region 0.015–15.0 MeV using the WinXCom computer program (Gerward *et al*. 2001; Gerward *et al*. 2004) initially developed as XCOM (Berger and Hubbell 1999).For the interpolation of Z_{eq} for which the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{total}$ lies between two successive ratios of elements, the value of Z_{eq} was calculated by using the following formula:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \tag{1}$$

where Z_1 and Z_2 are the elemental atomic numbers corresponding to the ratios R_1 and R_2 respectively, and R is the ratio for the uranium at the specific energy.

2.2 Calculation of the geometric progression (GP) fitting parameters

In the second step, to calculate the G-P fitting parameters, a similar interpolation procedure was adopted as in the case of equivalent atomic number. The G-P fitting parameters for uranium were taken from the ANSI/ANS-6.4.3 (1991) standard reference database, which provides the G-P fitting parameters for elements from beryllium to iron in the energy region 0.015–15 MeV up to a depth of 40 mfp. G-P fitting buildup factor coefficients of the uranium were interpolated according to the given formula as follows:

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z2 - \log Z_1} \tag{2}$$

where P is the G-P fitting function coefficient corresponding to Z_{eq}, P_1 and P_2 are the values of G-P fitting function coefficients corresponding to the element atomic numbers Z_1 and Z_2, respectively, at a given energy, whereas Z_{eq} is the equivalent atomic number of the chosen material at the given energy.

2.3 Calculation of the exposure buildup factor

In the final step, the computed G-P fitting parameters (b, c, a, X_k and d) are used to compute the exposure build-up factors of uranium in the energies 0.015–15 MeV up to a depth of 40 mfp. With the help of the G-P fitting formula, as given by the equations (Harima *et al*. 1986):

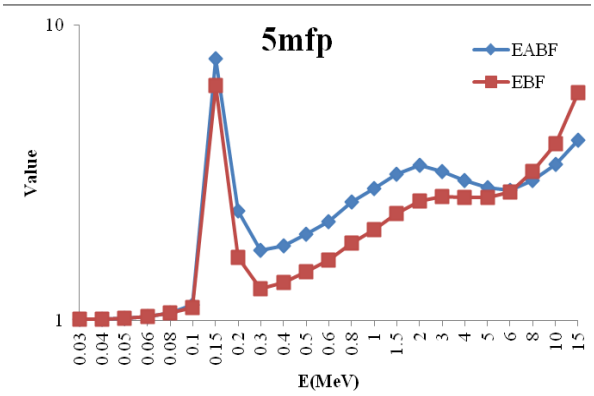
$$B(E,x) = 1 + \frac{(b-1)(k^x - 1) - \log Z_{eq})}{k-1} \quad \text{For } K \neq 1 \tag{3}$$

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

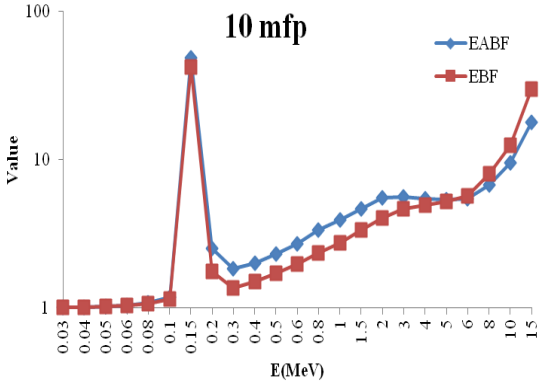
where

$$K(E,x) = px^a + d\frac{\tanh(x/Xk - 2)\tanh(-2)}{1 - \tanh(-2)} \quad \text{For } (x) \leq 40\text{mfp} \tag{5}$$

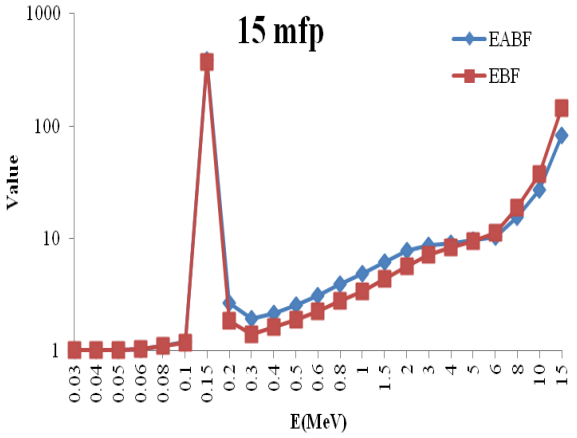
and E is the incident photon energy, x is the penetration depth in mfp, a, b, c, d and X_k are the G-P fitting parameters and b is the value of the buildup factor at 1 mfp. The parameter K represents photon dose multiplication and a change in the shape of the spectrum.



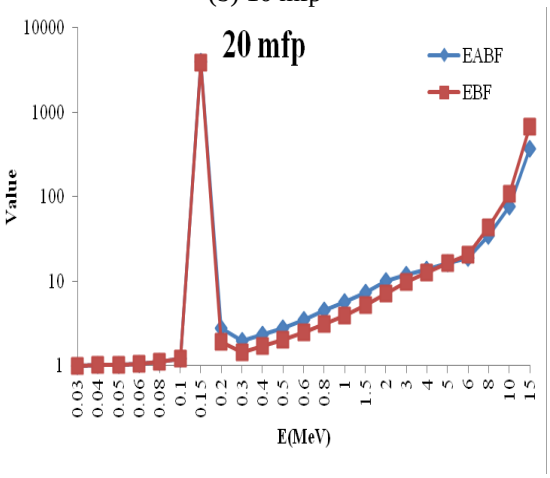
(a) 5mfp



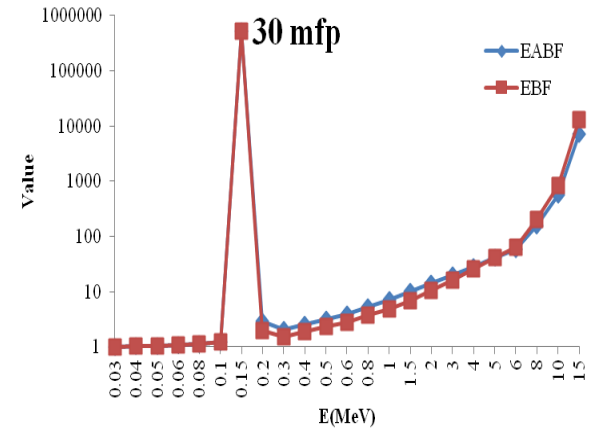
(b) 10 mfp



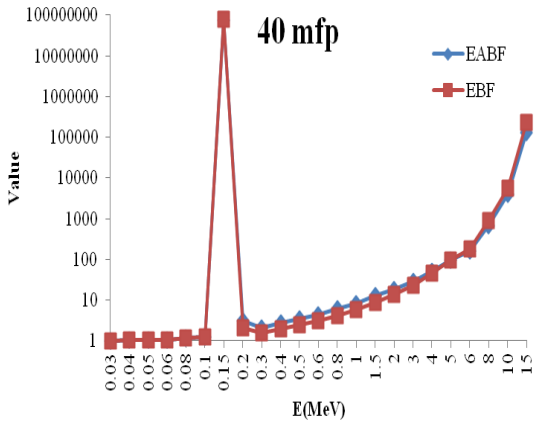
(c) 15mfp



(d) 20mfp

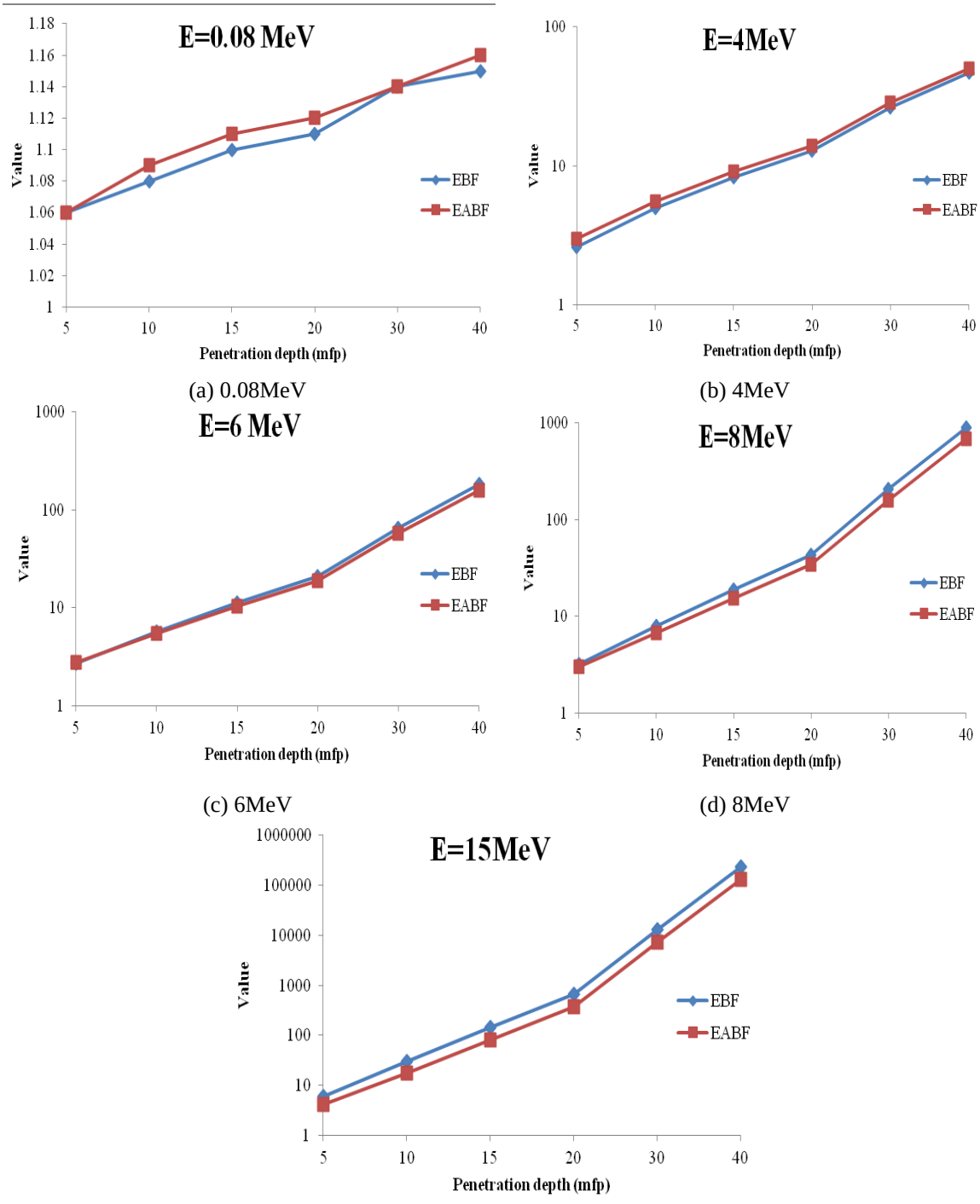


(e) 30mfp



(f) 40mfp

Fig. 1 Variation of EABF and EBF with incident photon energy (MeV) for uranium



(a) 0.08MeV (b) 4MeV

(c) 6MeV (d) 8MeV

(e) 15MeV

Fig. 2 Variation of EABF and EBF with penetration depth of uranium at energy ranges 0.08-15 MeV

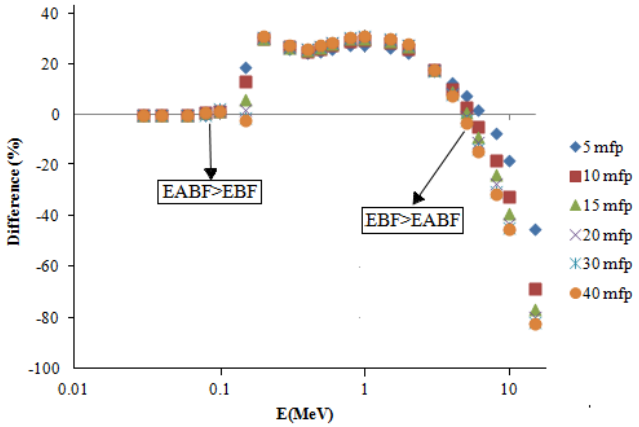


Fig. 3 Difference (%) between EABF and EBF for uranium in the energy region 0.015–15 MeV up to 40 mfp

3. Results and discussion

3.1 Variation of EABF and EBF with penetration depth

The variations of EABF and EBF with incident photon energy are shown in Figs. 1 and 2. It can be seen EABF and EBF has low values at lower and higher energies. This is due to the dominance of photoelectric absorption and pair production, which result in the complete removal of photons. The maximum values of EABF and EBF were observed at intermediate energies, where Compton scattering dominates. In this process, the photons are not completely removed but only their energies are degraded. Besides, their directions are changed. Hence, this process results in more multiple scattered photons, which leads to increase in the buildup of photons in the medium.

EABF and EBF increases with increasing penetration depth; these various complexities are shown in Fig. 3. It has been shown that with increasing penetration depths, EABF and EBF also increase due to increase in number of scattered photons. The maximum values of the EABF and EBF, which are in the order of 10^7, have been obtained at the largest penetration depth (40mfp) and in 0.15 MeV.

3.2 Comparison of exposure and energy absorption buildup factors

The maximum values of the EABF and EBF, which are in the order of 10^7, have been obtained at the largest penetration depths and in the intermediate energy region (energy of 0.15 MeV) where the uranium has maximum photon scattering cross section (Hubbell 1969) and the Compton scattering is the main interaction process.

Fig. 4 shows that the relative difference (%) between EABF and EBF in uranium. This figure shows that up 4 MeV the values of EABF are greater than EBF for all penetration depths. In the energy region 5-6 MeV the value of EBF began to increase at high penetration depth. Finally at 8 MeV the value of EBF is greater than EABF for all penetration depths. This observation can be justified in the following way:

For materials of high Z_{eq} such as uranium when compared to air, the absorption in the medium is much more than the absorption in the air. Since the EBF is based on the energy absorption response of air while EABF refers to that absorbed or deposited energy in the attenuating material, there are significant differences between EABF and EBF exist in the continuous energy region (Kurudirek and Ozdemirk 2011; Mann and Sidhu 2012). This significant difference occurs in the intermediate and high energy region due to the large values of EABF and EBF in uranium.

In intermediate energy region for $x \leq 20$ mfp observed that the EABF values are higher than EBF because photons build-up more. But for $x \geq 30$ mfp this frame becomes rivers, as in this penetration depth EBF values are higher than EABF for this energy region. In high energy region where the values of EBF are greater than EABF, for example the maximum differences up to 82% observed for the largest penetration depth (40 mfp) and the highest energy (15 MeV).

4. Conclusions

EABF and EBF in uranium were computed by using five-parameter geometric progression (G-P) fitting method. These computations for uranium, which widely used as fuel, are very useful in shielding calculation.

The maximum values of the EABF and EBF have been obtained at the largest penetration depths and in the intermediate energy (0.15 MeV) and high energy region (15MeV). Also obtained the maximum differences between EABF and EBF exist in two regions of energy.

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