Annals of Nuclear Energy 55 (2013) 341–350

Contents lists available at SciVerse ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Investigation of shielding properties of some boron compounds

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ARTICLE INFO

Article history:
Received 15 October 2012
Received in revised form 24 December 2012
Accepted 31 December 2012

Keywords:
Buildup factors
Effective atomic number
Boron compounds
Building-materials
Rayleigh/Compton ratios

ABSTRACT

Gamma and X-ray photon interaction parameters such as the equivalent atomic number (Z_{eq}), effective atomic number Z_{eff}, and exposure and energy absorption buildup factor have been computed for some boron compounds in the energy range of 15–100 keV. We have used WinXCom and ZXCom software to calculate the effective atomic number from Rayleigh/Compton (R/C) ratios. Finally, the selected boron compounds have been analyzed for application as radiation shielding materials. It is concluded that boric acid (M6) and concentrated colemanite (M1) have better shielding capability among the selected samples.

1. Introduction

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). Experiments are planned to get aiming at achieving gamma-ray buildup factors which are generally not easy to obtain. Therefore, studies of gamma-ray buildup factors have been carried out using some calculations. Buildup factor for gamma and X-ray is an important concept that must be considered in radiation shielding and dosimeter. Buildup factor is defined as the ratio of the total detector response to that of uncollided photons. Buildup factor data is the basic requirement for point kernel calculations commonly used in shield design. Buildup factor has been classified into two categories named as energy absorption buildup factor (EABF) and exposure buildup factor (EBF). The EABF is the buildup factor in which the quantity of interest is the absorbed or deposited energy in the interacting material or the detector response function is that of absorption in the interacting material. Whereas for the EBF the quantity of interest is the exposure and the detector response function is that of the absorption in air; that is, exposure is assumed to be equivalent to the absorbed dose in air as measured by the non-perturbing detector. In the past, many authors have reported data on photon buildup factors (Shultis and Faw, 2000; Asano and Sakamoto, 2007; Singh et al., 2008a,b; Küçük, 2010; Mann et al., 2012a,b). For instance, Asano and Sakamoto (2007) calculated the buildup factors for two types of heavy concretes (iron contained and barium-contained) using Monte Carlo simulation code, EGS4 up to penetration depth of 40 mfp and photon energy ranging from 0.015 to 15 MeV. Recently, Singh et al. (2008a) studied experimentally the gamma ray buildup factors in the medium of high volume fly ash concrete and water, using a point isotropic ^{137}Cs source.

Boron and its compounds such as concentrate colemanite, probertite, ulexite, TSW, tincal, boric acid, and Pellet waste has been used for fields related with radiation shielding. Concentrate colemanite, ulexite and tincal which can be used as shielding material for thermal and fast neutrons are raw borates. Probertite ($NaCaB_5O_9{\cdot}5H_2O$) and ulexite ($NaCaB_5O_9{\cdot}8H_2O$) possess identical chemical formula except for their water content. Probertite has the same B_2O_3, Na_2O and CaO content with ulexite. But the water content of probertite is less than ulexite. These boron ores are commonly used as control bars for of nuclear reactors and almost in all branches of industry in different ways. The trommel sieve waste (TSW) which forms during the boron ore production is considered to be a promising building material with its use as an admixture with Portland cement and considered to be an alternative radiation shielding material, also. Thus, to be having knowledge on the chemical composition and radiation interaction properties of TSW are important in terms of compared to other building

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http://dx.doi.org/10.1016/j.anucene.2012.12.024

materials (Kurudirek et al., 2010). We are willing to determine the importance of boron compounds with respect to radiation shielding.

Various researchers have indicated that there exists a direct relationship between (Z_{eff}) and EBF–EABF. For example, Mann et al. have observed that for the samples with lower effective atomic numbers (Z_{eff}) the values of EBF are larger, on the other hand for the samples with higher effective atomic numbers the values of EBF are comparatively small (Mann et al., 2012a). Kurudirek et al. have observed that EABF is higher than EBF due to the fact that the materials have higher (Z_{eff}) values than that of air. Thus, when the (Z_{eff}) increases the energy absorption in the medium will be more than absorption in air (Kurudirek and Topcuoglu 2011). From Singh et al. it can be concluded that **the** degree of violation of the Lambert–Beer law (value of energy absorption buildup factor) is less for the higher effective atomic number of the interacting material. Also, the energy absorption buildup factor depends strongly on the nature (Z_{eff}) of the material in the lower energy region, becomes almost independent in the intermediate energy region and shows a little dependence in the higher energy region (Singh et al., 2008b). The effective atomic number (Z_{eff}) is a useful parameter for the interpretation of the attenuation of X-ray or gamma radiation by a complex medium and medical radiation dosimeter. The (Z_{eff}) is related to the radiation interaction with matter and useful in some applications such as designing radiation shielding, computing absorbed dose and buildup factor (Manohara et al., 2008). İçelli et al. have calculated Rayleigh/Compton (R/C) ratio and (Z_{eff}) of boron compounds such as tincal, ulexite, probertite, boric acid, concentrate colemanite and TSW by using of ZXCOM code which is inspired from WinXCom, XCOM, respectively (Gerward et al., 2001, 2004; Berger and Hubbell, 1987, 1999). The (R/C) ratio is not novel, but its dependence on the operation of the (Z_{eff}) and ZXCom program is novel. The (Z_{eff}) calculations are not only energy dependent but also angle dependent. Also, this study has introduced a new perspective in respect of determination of the (Z_{eff}) using (R/C) ratio in order to compute buildup factors of samples (İçelli et al., 2012).

Some precautions must be taken by shielding the radiation sources. For this reason, it is important to determine the buildup factors to make corrections for effective exposure and energy deposition in different shielding materials. The EABF which is the quantity of interest is the absorbed or deposited energy in the interacting material. EABF and EBF values has been determine by using G–P fitting method for some boron compounds and TSW in the energy range 15–100 keV up to a penetration depth of 40 mfp. The values are of primary importance for radiation shielding design (Suteau and Chiron, 2005). The values are needed to product building materials which are made up from boron compounds and TSW for gamma radiation shielding (Mortazavi et al., 2010). Also, the knowledge of shielding effectiveness of the materials made up from boron compounds and TSW is a useful parameter. The buildup factors of these samples are not found in any compilation or tabulation. The first aim of this study is determination of composition of sample by fractional weight of the that makes up it. Secondly, from the elemental composition, buildup factors can be calculated in the selected energy region up to a penetration depth of 40 mfp.

The weight fraction of these samples is present in Table 1.

2. Theory

The American Nuclear Society Standard Committee working group has developed a set of gamma-ray point isotropic source buildup factors as a standard reference database for 23 elements in the range $Z = 4–92$ and three compounds or mixtures namely, air, water and concrete at 25 standard energies in the energy range of 0.015–15.0 MeV with suitable interval up to the penetration depth of 40 mean free path for use in shielding calculations. For now, there are no new reference data for buildup factors. Meanwhile, it should be all right to use the 1991 standard, since the possible discrepancies are expected to be small for the low-Z materials.

2.1. Calculation of effective atomic number and equivalent atomic number

The calculation method proposed here is developed from the concept that a given the (Z_{eff}) can completely define a mixture for the Rayleigh to Compton scattering ratio measurement, such a measurement like a single atom characterized by its atomic number. We have demonstrated that this formula is applicable for any material for a given scattering angle or X-ray photon energy (Duvauchelle et al., 1999; İçelli et al., 2012). The (Z_{eff}) can be experimentally measured through the intensity ratio of Rayleigh to Compton (R/C) scattered peaks which are corrected for the photo-peak efficiency of the detector and the absorption of photons in the target and air. Then this ratio can be plotted as a function of atomic number and constitutes a fit curve. From this fit curve, the respective (Z_{eff}) of the composite materials are identified. The choices of the (E_0) and (θ) must be compromised (İçelli et al., 2012). We have comprised 180° scattering angle and in the energy range of 15–100 keV. Manohara et al., 2011 is reported that at low energies, the buildup factor is markedly decreased with increasing (Z_{eff}). So, we have selected energy range of 15–100 keV. This selection is important in terms of determination of EABF and EBF for radiation shielding effectiveness in X-ray energy region. Also, Singh et al., 2008a have attained that the value of buildup factor increases with increasing total scatter acceptance angle. The equivalent atomic number (Z_{eq}), is a parameter assigned to a compound or mixture by giving a heavy weight to Compton scattering, since the buildup factor is a consequence of multiple scattering for which the main contribution is due to Compton scattering. We have considered 180° scattering angle because of Compton scattering is maximum. As can be seen from the literature, the only study about (Z_{eff}) that dependents upon scattering angle is made by İçelli et al., 2012.

The equivalent atomic number (Z_{eq}) of a particular material has been calculated by matching the ratio $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$ of that material at a specific energy with the corresponding ratios of elements at the same energy. For the interpolation of Z_{eq} for which the ratio $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$ lies between two successive ratios of elements, the following formula (Mann et al., 2012a,b) has been employed:

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

where Z_1 and Z_2 are the atomic numbers of elements corresponding to the ratios R_1 and R_2 respectively, R is the ratio for the selected boron sample at a specific energy.

2.2. Buildup factor

In order to calculate the buildup factors, we have developed a new perspective. In this viewpoint, the (Z_{eff}) values are firstly determined by means of Eq. (7) of İçelli et al., 2012, the (Z_{eff}) values have been interpolated for elements having the G–P fitting parameters. After comprising for low energy range and 180° scattering angle, the buildup factors have been determined. The largest contribution to buildup factor comes from Compton scattering having a maximum at 180° scattering angle. The calculation methods for