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Gamma-ray buildup factors study for deep penetration in some silicates

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ABSTRACT

The gamma ray buildup factors for six silicate samples have been calculated, in the energy range of 0.015–15 MeV for penetration depths up to 100 mfp (mean free path), using five parameters based geometric progression (G-P) fitting formula with modified expression for dose multiplication factor [$K(E, x)$]. The computations were done using ANSI/ANS 6.4.3-1991 (American National Standard). The extrapolation to the buildup factors of the selected samples beyond 40 mfp and up to 100 mfp in this energy range are new to the available literature. Calculated buildup factors of water have been shown good agreement with the available standard data. The obtained results for all samples have been compared and verified by using WinXCom software and GEANT4 Monte Carlo simulations.

1. Introduction

The energetic gamma rays are hazardous for living cells and tissues. Therefore a detailed study is required for the safe and acceptable use of gamma radiations, radioactive materials and nuclear energy. Additional area of interest is gamma radiation shielding development has been grown considerably due to leakage of radioactive materials, dumping of nuclear waste, increasing demand of radiotherapy and nuclear weapons. The basic objective of the radiation shielding is to protect the living beings from the hazardous effects of the gamma radiations. In order to develop effective shields for radioactive waste management the understanding of deep penetration of gamma rays is required. The present work will be helpful for reducing radioactive radiation pollution to the environment.

The buildup factors are used to obtain the corrected response to the uncollided photons by including the contribution of the scattered photons. It can be defined as the ratio of the total detector response to that of uncollided photons. The buildup factor measures the degree of violation of the Lambert–Beer law ($I = I_o * e^{-\mu x}$) due to multiple scattering of photons. The modified equation becomes $I = B * I_o * e^{-\mu x}$ (Singh et al., 2008), where B is the buildup factor for one energy at the shield thickness x, I_o is the initial dose rate, I is the shielded dose rate, μ is linear attenuation coefficient in cm^{-1} and 'x' is the shield thickness in cm. The average distance that photons of a given energy travel before an interaction in a given medium is equal to the reciprocal of the attenuation coefficient. The distance x in ordinary units can be converted into the dimensionless quantity μx, termed as mean-free-path (mfp). This parameter 'B' is always equal to or greater than unity ($B = 1$; in case narrow beam geometry, interacting material is thin and the photon is assumed to be mono-energetic, otherwise it is greater than unity). 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 and 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.

Different methods such as G-P fitting method (Harima et al., 1986), invariant embedding method (Shimizu, 2002; Shimizu et al., 2004), iterative method (Suteau and Chiron, 2005) and Monte Carlo method (Sardari et al., 2009) are available for computing buildup factors. It was shown by Shimizu et al. (2004) that by three different approaches (invariant embedding, G-P fitting and Monte Carlo methods) agree well for 18 low-Z materials within small discrepancies. When compared with other available approximations such as Berger, Taylor and three exponential, the geometric progression (G-P) fitting seems to reproduce the buildup factors with better accuracy. American National Standards ANSI/ANS 6.4.3 (American National Standard, 1991) has provided five G-P fitting parameters and buildup factor data for 23 elements (Be, B, C, N, O, Na, Mg, Al, Si, P, S, Ar, K, Ca, Fe, Cu, Mo, Sn, La, Gd, W, Pb and U), one compound (H_2O) and two mixtures (air and concrete) at

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Table 1
Elemental composition of the silicate-samples (Mann and Sidhu, 2012).

Sample	Symbols	Chemical formula and weight fraction in percentage
Kyanite	S1	Al_2SiO_5; O(49.37), Al(33.30), Si(17.33)
Sodium silicate	S2	Na_2SiO_4;O(39.32), Na(37.67), Si(23.01)
Datolite	S3	$CaBSiO_4(OH)$; H(0.63), B(6.76), O(50.00), Si(17.56), Ca(25.05)
Diopside	S4	$CaMgSi_2O_6$; O(44.33), Mg(11.22), Si(25.94), Ca(18.51)
Slag	S5	$Mg_3Si_4O_{12}H_2$; H(0.53), O(50.62), Mg(19.22), Si(29.62)
Anorthite	S6	$CaAl_2Si_2O_8$; O(46.01), Al(19.40), Si(20.19), Ca(14.41)
Water	Water	H_2O; H(11.20), O(88.80)

Table 3
Equivalent atomic numbers of silicate samples for incident photon energy range 0.015–15 MeV.

Energy (MeV)	Equivalent atomic number (Z_{eq})					
	S1	S2	S3	S4	S5	S6
0.015	11.31	10.98	13.71	13.59	11.15	13.17
0.02	11.34	11.04	13.89	13.70	11.19	13.27
0.03	11.39	11.04	14.08	13.83	11.24	13.38
0.04	11.40	11.10	14.16	13.88	11.28	13.46
0.05	11.43	11.16	14.26	13.98	11.34	13.52
0.06	11.43	11.13	14.34	14.08	11.34	13.57
0.08	11.39	11.17	14.42	14.05	11.35	13.52
0.10	11.58	11.15	14.38	14.12	11.55	13.69
0.15	11.98	10.94	14.41	14.43	10.90	13.44
0.20	11.50	12.95	14.94	14.48	10.50	14.49
0.30	11.50	12.50	14.50	14.50	10.50	14.50
0.40	11.50	12.50	14.50	14.50	10.50	14.50
0.50	11.50	12.50	14.50	14.50	10.50	14.50
0.60	11.50	12.50	14.50	14.50	10.50	14.50
0.80	11.50	12.50	14.50	14.50	10.50	14.50
1.00	11.50	12.50	14.50	14.50	10.50	14.50
1.50	11.50	12.50	14.50	14.50	10.50	14.50
2.00	9.79	8.80	12.81	12.83	9.70	9.76
3.00	10.37	10.40	12.48	12.51	10.28	12.58
4.00	10.69	10.40	11.32	12.23	10.57	11.94
5.00	10.62	10.35	11.87	12.44	10.14	11.99
6.00	10.92	10.69	11.83	12.06	10.40	11.92
8.00	10.42	10.48	11.85	12.39	10.49	12.16
10.00	10.63	10.56	11.81	12.13	10.50	11.91
15.00	10.61	10.59	11.77	12.27	10.51	12.01

25 standard energies in the energy range 0.015–15 MeV up to the penetration depth of 40 mean free path (mfp). The data are intended to be standard reference data for use in radiation analyses employing point-kernel methods. Harima et al. (1986) have showed that the absolute value of the maximum deviation of exposure buildup factors for water in the G-P fitting is within 0.5–3%, in the three-exponential approach is within 0.4–9.3%, in the Berger approach is within 0.9–42.7% and in the Taylor approximation is within 0.4–53.2%.

ANSI/ANS-6.4.3 (1991) standard has been administratively withdrawn in 2001, but the work is in progress for updating this much used standard by a working group chartered in 2007 by the American Nuclear Society (ANS). The reasons for the revision were (a) lack of self-consistency within the standard in which the mass attenuation coefficients tabulated in the standard were not necessarily used in the calculation of the buildup factors and the correction factors for coherent scattering and tissue dose, and (b) newer, presumably, more accurate attenuation coefficient data have become available (Chadwick et al., 2006) since the issuance of the 1991 standard (Ryman et al., 2008). Recently, a study has been made for the purpose of updating gamma-ray buildup factors for high-*Z* engineering materials that are presented in the current ANS standard (Ruggieri and Sanders, 2008). The working groups could proceed along a track of reaffirmation of the standards using PINS (Project Initiation Notification System) charter form. The G-P fitting method has been used by different researchers Singh et al. (2008, 2009), Kurudirek and Topcuoglu (2011) and Mann and Sidhu (2012) for calculating buildup factors up to 40 mfp. Brar et al. (1994), using G-P fitting formula has calculated the EABF for water, air and concrete up to 100 mfp.

In the present work the data for buildup factors up to 100 mfp for some low-*Z* silicates have been generated using G-P fitting formula with modified expression for the dose multiplication factor $K(E, x)$ (Sakamoto and Trubey, 1991). This work has been done with following objectives kept in mind. Firstly to check whether the G-P fitting formula is able to generate correctly the buildup factor data for deep penetration of 100 mfp? Secondly study the variations of buildup factors with penetration depths. An attempt has been made to compute EBF and EABF values by using the G-P fitting method for the selected samples in the energy range 0.015–15 MeV up to 100 mfp. The present study will be of prime importance for radiation shield designing (Suteau and Chiron, 2005) and production of a new materials made from the selected silicate samples for effective gamma radiation shielding. Mortazavi and Mosleh-Shirazi (2010) have been experimented to use datolite (S3) in heavy concrete for shielding nuclear reactors and megavoltage radiotherapy rooms. All the selected materials can be used in concrete and building materials (glass, tile, fibre–glass) for improving gamma-ray shielding properties.

2. Material and methods

The elemental compositions by weight percentage of the selected samples (kyanite, sodium silicate, datolite, diopside, slag and anorthite) have been taken from the literature (Mann and Sidhu, 2012) and listed in Table 1. The physical properties of the selected sample have been listed in Table 2. The selected silicates can be used in hardening/waterproofing of concrete, acid-proof cements, thermal insulation, plywood laminating, soil solidification, cement slurry thinners and roofing granules. In extruded brick and clay products, soluble silicate can reduce the force (power) required for extrusion, as well as decrease shrinkage on firing. The

Table 2
Physical properties of the samples (Mann and Sidhu, 2012).

Properties	S1	S2	S3	S4	S5	S6
Chemical formula	Al_2SiO_5	Na_2SiO_4	$CaBSiO_4(OH)$	$CaMgSi_2O_6$	$Mg_3Si_4O_{12}H_2$	$CaAl_2Si_2O_8$
Density (in g/cm^3)	3.56–3.67	2.30–2.50	2.96–3.00	3.25–3.55	3.20–3.60	2.74–2.76
Molecular-weight (in g)	162.05	138.06	159.98	216.55	379.27	278.21
Hardness (in mohs)	4.0–7.0	6.0–6.5	5.0–5.5	6.0–6.5	6.0–7.0	6.0–6.5
Si content (% by wt.)	17.33	23.01	17.56	25.94	29.62	20.19
Colour	Blue, White, Gray, Green, Black.	Colourless, white	Colourless, white	Blue, Brown, Colourless, Green, Gray	Gray, Brown	Colourless, reddish grey, white