Indian Journal of Pure & Applied Physics
Vol. 52, September 2014, pp. 579-587

Gamma-ray and neutron shielding properties of some soil samples

Vishwanath P Singh[a]*, N M Badiger[a] & Nil Kucuk[b]

[a]Department of Physics, Karnatak University, Dharwad 580003, India

[b]Department of Physics, Faculty of Arts and Sciences, Uludag University, 16059 Bursa, Turkey

*E-mail: kudphyvps@rediffmail.com

Received 26 July 2013; revised 24 June 2014; accepted 24 July 2014

Gamma-ray and neutron shielding properties of five different types of soil samples, namely clay loam, clay, loam, sandy clay loam and sandy loam have been studied in the present paper. Gamma-ray shielding effectiveness of the soil samples was studied by mass attenuation coefficient, half-value layer thickness and exposure build-up factors (EBFs). The EBFs of the soil samples were calculated by GP (Geometrical Progression) fitting formula for the wide photon energy range (0.015-15 MeV) up to the penetration depths of 40 mean free paths. Fast neutron (2-12 MeV) removal cross-section of the soil samples was calculated by partial density method. The photon energy, chemical composition and penetration depth dependency of EBFs of all the soil samples have also been studied. The clay loam among the selected soil samples was found to be the good soil radiation shielding material. This study should be useful for various applications of soil for gamma-ray and neutron shielding.

Keywords: Soil, Exposure buildup, GP fitting, Shielding, Gamma, Neutron shielding

1 Introduction

Radiation shielding materials have been an interesting research area in nuclear, radiation physics and radiation protection. The photon attenuation coefficient is a fundamental vital parameter for characterizing the penetration and diffusion of gamma-rays in any medium. The effects of different parameters of medium on the attenuation coefficients of soils have been studied and documented[1]. The photon attenuation coefficient characterizes the penetration and diffusion of gamma-rays in composite materials such as soil[2]. Gamma-ray build-up factors are geometry dependent parameters which correct the attenuation calculations for poly-chromatic rays, thick absorbing material and wide beam geometries. The build-up factors include the contribution of the radiation field produced by the collided part of the beam. As far as application of build-up factors in practical shielding problems is concerned, the build-up factors have been incorporated into point-kernel methods of dose calculations in the variety of radiation sources. The concept of build-up factor was introduced by White[3] and Fano[4].

The intensity of a gamma-ray beam through a medium follows Lambert Beer ($I=I_0e^{-\mu t}$) law under the conditions such as (i) mono-chromatic rays (ii) thin absorbing material, and (iii) narrow beam geometry. In case, any of the conditions is not being met, this law is no longer applicable. The law is made applicable by introducing a correction factor called as "build-up factor". The build-up is defined as the ratio of total value of specified radiation quantity at any point to the contribution to that value from radiation reaching to the point without having undergone a collision. The build-up factors are computed by various codes such as PALLAS[5], ADJMON-I[6,7] and EGS4[8]. These codes use an accurate algorithmic of Klein-Nishina cross-sections which eliminated other sources of errors.

The compilation for build-up factors by various codes is reported in ANSI/ANS-6.4.3-1991 by American Nuclear Society[9]. The data in the report covers the energy range 0.015-15 MeV up to the penetration depth of 40 mean free paths (mfp). The build-up factors in the ANS-6.4.3 are for 23 elements of atomic number, Z=4 to 92. Harima[10] developed a fitting formula, called Geometrical Progression (GP) which gives build-up factors of the good agreement with the ANS-6.4.3. The GP fitting formula is known to be accurate within the estimated uncertainty (<5%) and Harima reviewed extensively and reported the current gamma-ray build-up factors [11]. Various researchers investigated gamma-ray build-up factors in different materials such as concretes[12], soils and ceramic[13,14], building materials[15], silicate[16], gaseous mixture[17], fly-ash bricks[18], alloys[19] and neutron shielding[20] which show that the GP fitting is very useful method for estimation of the exposure build-up factors.

The objective of the present study is calculation of shielding effectiveness of five different soil samples such as clay loam, clay, loam, sandy clay loam and sandy loam by mass attenuation coefficients, half-value layer (HVL) thickness and exposure build-up factors (EBFs) at energies varying from 0.015 to 15 MeV. Soils are found to be potential radiation shielding materials[1]. Shielding materials are required to shield neutron and γ (or X-ray) radiations. The neutron shielding effectiveness of the soil samples was estimated by calculation of neutron removal cross-section for average energy neutron of 2-12 MeV. This study should be useful for potential applications of soil samples for radiation shielding.

2 Experimental Details

In the present study, we have taken five soil samples containing silica as major composition. The chemical compositions of the soil samples are given in Table 1. These chemical compositions of the soils were taken from literature[21]. The soil samples whose elemental composition depends on the mix proportions, whose densities ranging from 1.34 to 1.45 g cm^{-3}.

2.1 Mass attenuation coefficient (μ/ρ)

The transmission of gamma-ray is dependent upon the thickness of the medium and linear attenuation coefficient (μ). The μ is a parameter which is dependent upon the atomic number of the elements of the medium and energy of incident gamma-ray. Mass attenuation coefficient (μ/ρ) is another parameter defined for the photon interaction considering the interaction probability dependency. The μ/ρ values of the soil samples are calculated by mixture rule and given by:

$$(\mu/\rho)_{\text{soil}} = \sum_{i}^{n} w_i \left(\frac{\mu}{\rho}\right)_i \qquad \ldots(1)$$

where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the i$^{\text{th}}$ element. The (μ/ρ) of the elements have been taken from the WinXcom program[22], the advance version of XCOM program[23]. The atomic numbers and atomic masses of the elements[24] were taken from atomic weight of elements 2009, IUPAC.

2.2 Half-value layer (HVL)

HVL is the thickness of the interacting medium to reduce the intensity of gamma-ray to half of the incident upon it. The intensity of the gamma-ray is reduced by various physical processes like complete absorption, partial absorption, energy reduction and multiple scattering inside the medium. The HVL is inversely proportional to the μ_{soil} and is given as:

$$\text{HVL (cm)} = \frac{0.6932}{\mu_{\text{soil}}} \qquad \ldots(2)$$

where μ_{soil} is the linear attenuation coefficient of the soil samples, which is calculated by multiplication of $(\mu/\rho)_{\text{soil}}$ with the density. The mean free path (mfp) is the average distance travelled by gamma-ray in the medium between two successive collisions. The reciprocal of μ is called as mean free path of the medium.

2.3 Exposure build-up factors (EBF)

The EBFs and GP fitting parameters of soil samples are calculated by method of logarithmic interpolation from the equivalent atomic number, Z_{eq}. The computational work of these parameters is done in three steps as: (1) Calculation of equivalent atomic number, Z_{eq}, (2) Calculation of G-P fitting parameters, (3) Calculation of build-up factors

Since interaction processes of gamma-ray with a medium (namely, photo-electric absorption, Compton scattering and pair-production) are energy dependent, therefore Z_{eq} for each interaction varies according to

Table 1 — Chemical composition of the soil samples

Soil	Chemical components (%)												
	TC	Density (g.cm^{-3})	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	Cr_2O_3	MnO	Fe_2O_3	LOI
Soil-1	L	1.38	1.39	2.44	14.62	63.00	0.17	2.79	6.78	0.60	0.02	0.07	4.31	3.60
Soil-2	SL	1.45	2.02	1.30	12.75	78.40	0.32	2.51	1.76	0.50	0.01	0.07	2.79	<1
Soil-3	SCL	1.42	2.45	1.04	16.10	68.30	0.13	1.64	3.89	0.64	0.01	0.11	5.79	<1
Soil-4	C	1.24	0.23	1.94	13.14	55.90	0.11	1.91	11.00	0.60	0.03	0.10	4.53	10.00
Soil-5	CL	1.34	0.11	9.00	10.66	39.62	0.22	0.38	15.90	0.41	0.04	0.05	4.38	19.20

TC=Soil Texture Class, L=Loam, SL=Sandy Loam, SCL=Sandy Clay Loam, C=Clay and CL=Clay Loam and LOI: Loss of Ignition the photon energy. However, the build-up of gamma-ray in the medium is mainly due to multiple scattering events by Compton scattering, so that Z_{eq} is derived from the Compton scattering interaction process only.

The Z_{eq} for each soil sample is estimated by the ratio of $(\mu/\rho)_{\text{Compton}}/(\mu/\rho)_{\text{Total}}$, at a specific energy with the corresponding of an element at same energy. Thus, first the Compton partial mass attenuation coefficient $[(\mu/\rho)_{\text{Compton}}]$ and the total mass attenuation coefficients $[(\mu/\rho)_{\text{Total}}]$ are obtained for elements $Z= 4$ to 40 for the sample in the energy region 0.015-15 MeV using WinXCom[21]. The Z_{eq} of the soil samples is calculated by interpolation method formula employed by Harima and Maron[25,26].

$$Z_{eq}=\frac{Z_1(\log R_2-\log R)+Z_2(\log R-\log R_1)}{\log R_2-\log R_1} \qquad ...(3)$$

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 chosen soil sample at a specific energy. Variation of the obtained values of Z_{eq} with photon energy for the selected soil samples (i.e. Soils-1, 2, 3, 4 and 5) and world average soil (i.e. Soil-W) are shown in Fig. 1. The GP fitting parameters are calculated in a similar fashion of the Z_{eq}.

$$C=\frac{C_1(\log Z_2-\log Z_{eq})+C_2(\log Z_{eq}-\log Z_1)}{\log Z_2-\log Z_1} \qquad \ldots(4)$$

where C_1 and C_2 are the values of the GP fitting parameters corresponding to the atomic numbers of Z_1 and Z_2, respectively.

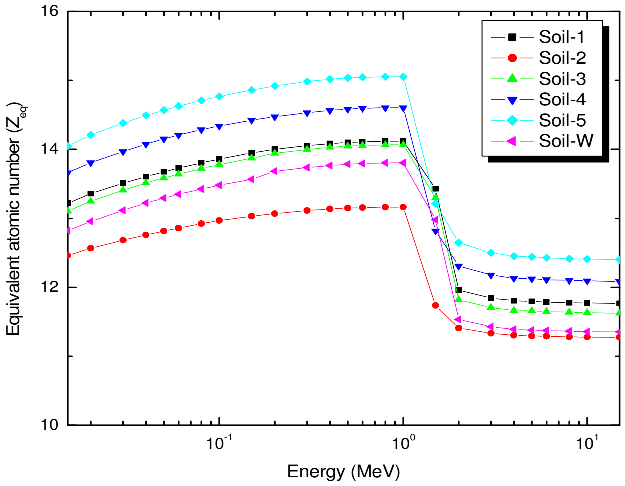

Fig. 1 — Equivalent atomic numbers of the soil samples as a function of photon energy

Third and final step is build-up factors estimation by GP fitting parameters (b, c, a, X_k and d) in the photon energy range 0.015-15 MeV up to a 40 mfp by equations Harima *et al.* and Harima[10,11] as:

$$B(E,x)=1+\frac{(b-1)(K^x-1)}{K-1} \quad \text{for} \quad K\neq 1 \qquad \ldots(5)$$

$$B(E,x)=1+(b-1)x \quad \text{for} \quad K=1 \qquad \ldots(6)$$

where

$$K(E,x)=cx^a+d\frac{\tanh(x/X_K-2)-\tanh(-2)}{1-\tanh(-2)} \qquad \ldots(7)$$

for penetration depth (X) ≤ 40 mfp

where x is the source-detector distance for the medium in terms of mfp and b, the value of the exposure build-up factor at 1 mfp, $K(E, X)$ is the dose multiplicative factor, and b, c, a, X_K and d are computed GP fitting parameters given in Table 2-4 which depend on the attenuating medium and source energy. The GP fitting parameters for the elements [9]were taken from the ANS-6.4.3 standard reference database.

2.4 Fast neutron removal cross-section

An approximate method for calculating the attenuation of fast neutrons by use of an effective removal cross-section has been developed to allow for scattering or build-up. The effective removal cross-section for compounds and homogenous mixtures may be calculated from the value of Σ_R (cm^{-1}) or Σ_R/ρ (cm^2/g) for various elements in the compounds or mixtures by mixture rule. Difference in application of mixture for neutron interaction as weight fraction is replaced by partial density and mass attenuation coefficient by neutron removal cross-section.

$$\Sigma_R/\rho = \Sigma_i w_i(\Sigma_R/\rho)_i \qquad \ldots(8)$$

and

$$\Sigma_R/\rho = \Sigma_i \rho_i(\Sigma_R/\rho)_i \qquad \ldots(9)$$

The Σ_R/ρ values of elements of the soils have been taken from Kaplan and Chilton[27,28]. The values obtained for effective neutron removal cross-section are accurate within 10% of the experimental values investigated for aluminium, beryllium, graphite, hydrogen, iron, lead, oxygen, boron carbide etc[29].

3 Results and Discussion

Gamma-ray and neutron shielding properties of the soil samples was discussed by calculation of μ/ρ, HVL, EBF and Σ_R. The uncertainties in our calculation results are negligible.

3.1 Mass attenuation coefficient

Variation of μ/ρ with photon energy for the soil samples is shown in Fig. 2. It is shown that the μ/ρ values of the soil samples are high (order of 10) in photo-absorption region, reduces gradually and become lowest (0.02 MeV) in Compton scattering region. These variations can be explained by photon energy and atomic number dependency of interaction cross-section of the elements such as photo-electric effect, Compton scattering and pair-production and explained in detail by Kucuk *et al*[21].

3.2 Half-value layer

The variation of HVL thickness with gamma energy for the soil samples, world soil and ordinary concrete is shown in Fig. 3. We found that HVL values are low in photo-absorption region and gradually increase in Compton scattering region. It is to be noted that the soil samples require almost same thickness to find equal shielding effectiveness of gamma-ray radiation except clay. It is to be noted that the HVL of soil-W is comparable with the soil samples. The ordinary concrete was found to be lowest HVL as compared with the selected soil samples.

3.3 Exposure build-up factors

Variation of EBF values with photon energy of the soil samples is shown in Fig. 4(a-f) at different penetration depths. The EBF values of all the soil samples were found to be small in low as well as high photon energies with a peak at 0.2 MeV in intermediate energy at different penetration depths (i.e.1, 5, 10, 20, 30 and 40 mfp). It was found that the EBF values of clay loam (Soil-5) were the lowest whereas sandy loam (Soil-2) were the highest in low-, intermediate-and high-energies for low-penetration depth (<5 mfp). The pattern of EBF values of the soil samples become reverse in high-penetration depths (>5 mfp).The variation of EBF values can be explained by dependency of gamma-ray interaction cross-sections on photon energy and atomic number of constituent elements.

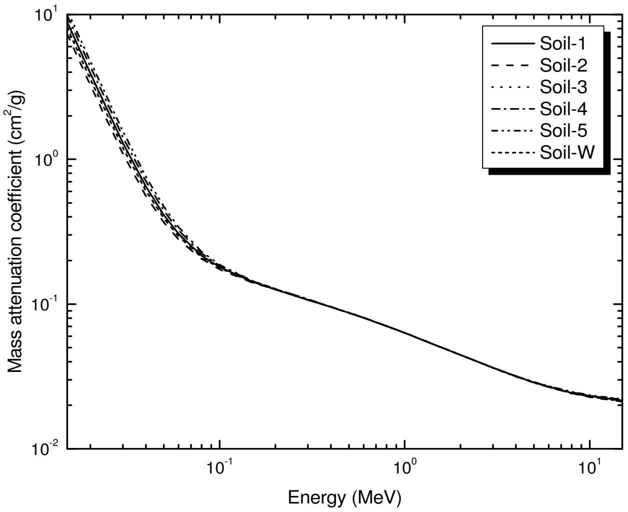

Fig. 2 — Variation of mass attenuation coefficients with photon energy for the soil samples

The Z_{eq} plays the same role of a medium as Z of an element. The EBF values of the soil samples are minimum in low energy due to photo-electric dominates as the interaction cross-section is directly proportional to Z^{4-5}/E^{3-4}. With increase in photon energy, EBF values increase due to multiple scattering as Compton scattering dominates with Z. In high-energy region (>3 MeV) pair-production takes over the Compton scattering process as it is dependent upon Z^2 and log (E). The EBF values were found to be in the range 1.01-874.55, 1.02-1171, 1.01-883.67, 1.01-800.55, 1.01-737.67, 1.01-980.82 for loam (Soil-1), sandy loam (Soil-2), sandy clay loam (Soil-3), clay (Soil-4) and clay loam(Soil-5), respectively. We found that EBF values start increasing in high-energy (>8 MeV) for 20 and 40 mfp penetration-depth for all the soil samples. The reason for such variation is the chemical composition dependency[12] of the soil samples.

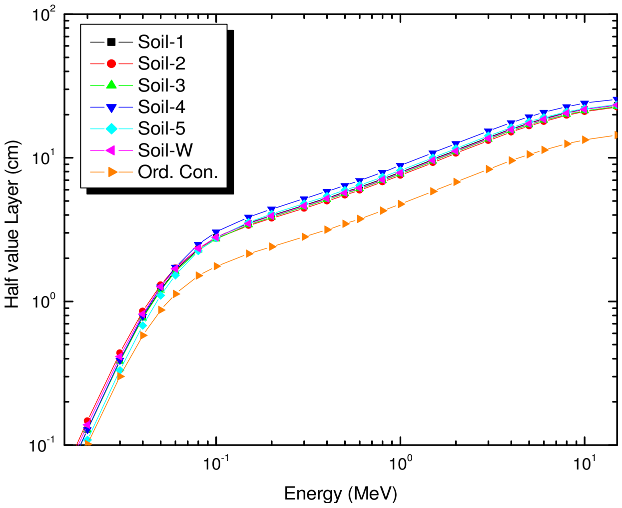

Fig. 3 — Variation of half-value layer thickness with photon energy for the soil samples, world average soil and ordinary concrete

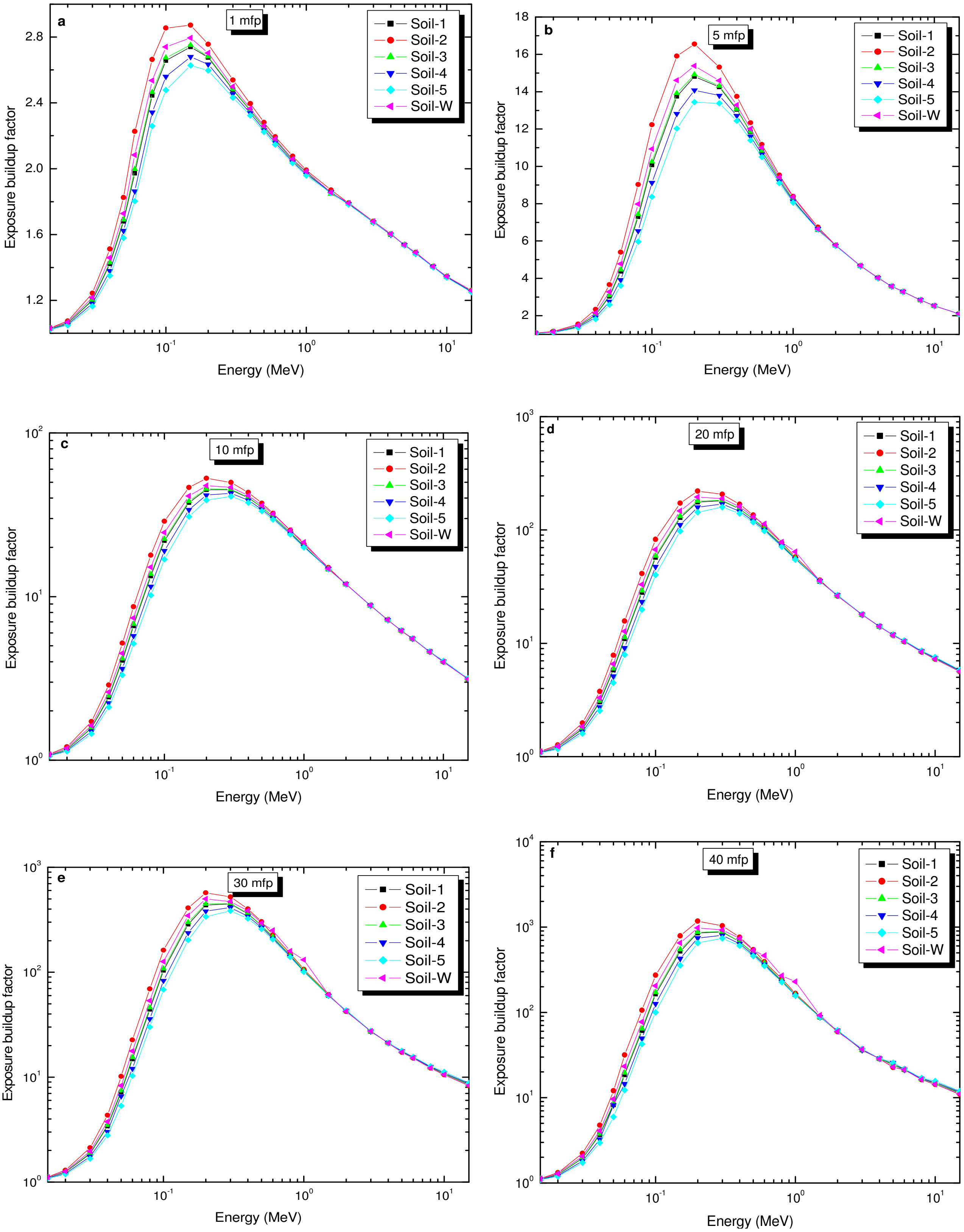

Fig. 4 — (a-f) Variation of exposure build-up factors with photon energy for the soil samples and world average soil

Table 2 — GP fitting parameters of EBF for Soil-1 and Soil-2 in photon energy range 0.015-15 MeV

E (MeV)	Soil-1					Soil-2				
	b	c	a	Xk	d	b	c	a	Xk	D
0.015	1.0276	0.3838	0.2186	14.7132	–0.1479	1.0332	0.3977	0.2086	14.3573	–0.1358
0.02	1.0611	0.3994	0.2050	15.2139	–0.1158	1.0747	0.4074	0.2021	14.0356	–0.1079
0.03	1.2002	0.4080	0.2073	14.5245	–0.1105	1.2431	0.4303	0.1952	14.8776	–0.1035
0.04	1.4216	0.4766	0.1795	14.5033	–0.0999	1.5121	0.5157	0.1606	14.8714	–0.0861
0.05	1.6796	0.6066	0.1236	15.5067	–0.0645	1.8250	0.6601	0.1037	15.9463	–0.0522
0.06	1.9720	0.7007	0.0952	14.6584	–0.0533	2.2271	0.7103	0.0995	13.1755	–0.0578
0.08	2.4455	0.8543	0.0536	14.3432	–0.0476	2.6633	0.9327	0.0327	13.0435	–0.0340
0.1	2.6570	1.0305	0.0091	13.5587	–0.0283	2.8550	1.1137	–0.0098	12.9584	–0.0182
0.15	2.7403	1.2773	–0.0428	10.9645	–0.0055	2.8723	1.3540	–0.0575	21.9337	0.0069
0.2	2.6758	1.3748	–0.0580	7.7236	–0.0052	2.7559	1.4494	–0.0729	16.3649	0.0102
0.3	2.4801	1.4670	–0.0777	17.0158	0.0135	2.5387	1.5053	–0.0842	16.2976	0.0168
0.4	2.3524	1.4702	–0.0805	15.9353	0.0159	2.3963	1.4945	–0.0844	16.3619	0.0185
0.5	2.2491	1.4527	–0.0796	16.3010	0.0179	2.2817	1.4711	–0.0825	16.3932	0.0192
0.6	2.1736	1.4231	–0.0759	18.4190	0.0211	2.1938	1.4441	–0.0802	17.2935	0.0225
0.8	2.0508	1.3838	–0.0728	15.3236	0.0210	2.0755	1.3842	–0.0722	16.0805	0.0203
1	1.9774	1.3230	–0.0630	15.9571	0.0186	1.9917	1.3338	–0.0655	15.8433	0.0210
1.5	1.8493	1.2300	–0.0480	15.6207	0.0167	1.8700	1.2333	–0.0490	14.6953	0.0168
2	1.7873	1.1550	–0.0330	16.0443	0.0109	1.7916	1.1544	–0.0336	15.1352	0.0116
3	1.6755	1.0628	–0.0127	15.5948	–0.0017	1.6806	1.0588	–0.0117	12.5432	–0.0002
4	1.5995	0.9961	0.0052	12.9897	–0.0091	1.6035	0.9936	0.0057	12.9099	–0.0090
5	1.5376	0.9439	0.0224	11.1570	–0.0214	1.5366	0.9514	0.0184	13.6666	–0.0208
6	1.4861	0.9299	0.0254	11.8802	–0.0203	1.4910	0.9200	0.0289	11.5694	–0.0230
8	1.4052	0.9020	0.0338	13.7811	–0.0280	1.4057	0.9020	0.0333	13.6230	–0.0267
10	1.3431	0.8838	0.0414	13.1121	–0.0333	1.3456	0.8789	0.0424	13.1613	–0.0334
15	1.2553	0.8416	0.0586	14.2650	–0.0523	1.2602	0.8298	0.0620	14.3188	–0.0548

Table 3 — GP fitting parameters of EBF for Soil-3 and Soil-4 in photon energy range 0.015-15 MeV

E (MeV)	Soil-3					Soil-4				
	b	c	a	Xk	d	b	c	a	Xk	D
0.015	1.0284	0.3893	0.2119	15.1389	–0.1430	1.0250	0.3639	0.2435	13.1471	–0.1658
0.02	1.0629	0.3947	0.2096	14.7831	–0.1172	1.0540	0.4182	0.1842	16.9278	–0.1101
0.03	1.2046	0.4107	0.2055	14.6362	–0.1093	1.1804	0.3959	0.2154	14.0257	–0.1159
0.04	1.4305	0.4806	0.1775	14.5456	–0.0983	1.3795	0.4584	0.1885	14.3378	–0.1066
0.05	1.6908	0.6144	0.1204	15.6159	–0.0625	1.6233	0.5698	0.1392	15.0530	–0.0463
0.06	1.9974	0.7002	0.0962	14.4520	–0.0538	1.8633	0.6872	0.0974	15.1805	–0.0542
0.08	2.4652	0.8614	0.0518	14.2065	–0.0463	2.3425	0.8142	0.0656	14.1555	–0.0508
0.1	2.6743	1.0378	0.0075	13.5059	–0.0274	2.5600	0.9909	0.0186	13.7957	–0.0334
0.15	2.7509	1.2834	–0.0440	11.7985	–0.0045	2.6805	1.2407	–0.0355	10.9455	–0.0094
0.2	2.6808	1.3794	–0.0589	8.2337	–0.0043	2.6345	1.3480	–0.0532	8.3517	–0.0069
0.3	2.4831	1.4691	–0.0780	16.8885	0.0136	2.4549	1.4496	–0.0748	18.1215	0.0130
0.4	2.3541	1.4720	–0.0808	15.8612	0.0160	2.3378	1.4541	–0.0776	16.5940	0.0148
0.5	2.2506	1.4539	–0.0798	16.3005	0.0181	2.2354	1.4420	–0.0776	16.3059	0.0167
0.6	2.1752	1.4235	–0.0759	18.5354	0.0213	2.1589	1.4192	–0.0754	17.3225	0.0194
0.8	2.0517	1.3843	–0.0729	15.3051	0.0211	2.0420	1.3789	–0.0718	15.7098	0.0207
1	1.9785	1.3230	–0.0630	15.8950	0.0185	1.9671	1.3230	–0.0630	16.7415	0.0196
1.5	1.8480	1.2330	–0.0487	14.9407	0.0165	1.8571	1.2305	–0.0482	15.7483	0.0170
2	1.7884	1.1548	–0.0332	15.8170	0.0110	1.7851	1.1544	–0.0327	15.8585	0.0103
3	1.6768	1.0617	–0.0124	14.7756	–0.0013	1.6738	1.0627	–0.0124	15.4430	–0.0023
4	1.6006	0.9954	0.0053	12.9679	–0.0090	1.5992	0.9939	0.0061	12.9114	–0.0101
5	1.5373	0.9460	0.0213	11.8489	–0.0212	1.5368	0.9431	0.0232	10.2636	–0.0208
6	1.4874	0.9271	0.0264	11.7942	–0.0211	1.4837	0.9339	0.0242	12.0466	–0.0197
8	1.4054	0.9020	0.0336	13.7371	–0.0276	1.4041	0.9036	0.0336	13.8531	–0.0283
10	1.3438	0.8824	0.0417	13.1258	–0.0333	1.3412	0.8875	0.0407	13.0842	–0.0332
15	1.2566	0.8383	0.0595	14.2800	–0.0530	1.2522	0.8489	0.0564	14.2988	–0.0508

Table 4 — GP fitting parameters of EBF for Soil-5 and Soil-W in photon energy range 0.015-15 MeV

E (MeV)	Soil-5					Soil-W				
	b	c	a	Xk	d	b	c	a	Xk	D
0.015	1.0228	0.3513	0.2596	11.9814	–0.1767	1.0304	0.3952	0.2069	15.1364	–0.1378
0.02	1.0488	0.4273	0.1781	16.8151	–0.1012	1.0678	0.3864	0.2182	13.8329	–0.1191
0.03	1.1642	0.3946	0.2148	14.1541	–0.1158	1.2177	0.4187	0.2002	14.9659	–0.1057
0.04	1.3495	0.4495	0.1915	14.3800	–0.1075	1.4583	0.4932	0.1710	14.6774	–0.0932
0.05	1.5784	0.5451	0.1505	14.8726	–0.0822	1.7272	0.6397	0.1099	15.9711	–0.0560
0.06	1.8032	0.6582	0.1079	14.9662	–0.0592	2.0834	0.6988	0.0997	13.7559	–0.0557
0.08	2.2596	0.7800	0.0766	13.4276	–0.0513	2.5356	0.8866	0.0450	13.7162	–0.0418
0.1	2.4776	0.9576	0.0267	13.9750	–0.0378	2.7395	1.0651	0.0013	13.3073	–0.0241
0.15	2.6275	1.2082	–0.0290	11.5052	–0.0127	2.7944	1.3088	–0.0488	15.2258	–0.0005
0.2	2.5969	1.3235	–0.0488	8.9254	–0.0085	2.7025	1.3996	–0.0629	10.5832	–0.0001
0.3	2.4319	1.4336	–0.0721	19.1325	0.0125	2.4991	1.4795	–0.0798	16.7183	0.0145
0.4	2.3243	1.4396	–0.0749	17.2271	0.0139	2.3659	1.4787	–0.0815	15.9628	0.0167
0.5	2.2232	1.4323	–0.0759	16.3089	0.0157	2.2594	1.4590	–0.0802	16.3231	0.0185
0.6	2.1464	1.4149	–0.0748	16.5173	0.0179	2.1810	1.4288	–0.0752	18.3413	0.0217
0.8	2.0347	1.3738	–0.0707	15.6918	0.0203	2.0582	1.3848	–0.0717	15.4636	0.0209
1	1.9586	1.3224	–0.0629	16.9548	0.0202	1.9827	1.3255	–0.0601	15.8176	0.0190
1.5	1.8521	1.2300	–0.0480	15.8137	0.0169	1.8552	1.2301	–0.0480	15.9815	0.0200
2	1.7831	1.1537	–0.0323	15.5904	0.0097	1.7907	1.1545	–0.0335	15.3432	0.0114
3	1.6735	1.0604	–0.0115	13.5897	–0.0023	1.6796	1.0595	–0.0119	13.1161	–0.0005
4	1.6021	0.9864	0.0087	12.6516	–0.0125	1.6028	0.9940	0.0056	12.9240	–0.0090
5	1.5339	0.9482	0.0213	10.5001	–0.0189	1.5368	0.9501	0.0191	13.2375	–0.0209
6	1.4827	0.9336	0.0249	12.1500	–0.0213	1.4902	0.9217	0.0283	11.6217	–0.0226
8	1.4012	0.9084	0.0323	13.8628	–0.0275	1.4056	0.9020	0.0334	13.6491	–0.0269
10	1.3386	0.8927	0.0397	13.0649	–0.0332	1.3452	0.8797	0.0423	13.1533	–0.0334
15	1.2493	0.8560	0.0541	14.5151	–0.0497	1.2594	0.8317	0.0615	14.3102	–0.0544

Table 5(a) — Neutron removal cross-section of Soil-1, 2 and 3 samples

Ele.	Soil-1 ρ= 1.38 g cm^{-3}		Soil-2 ρ= 1.45 g cm^{-3}		Soil-3 ρ=1.42 g cm^{-3}	
	Partial density	Σ_R (cm^{-1})	Partial density	Σ_R (cm^{-1})	Partial density	Σ_R (cm^{-1})
C	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
Na	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
O	6.57E-01	2.66E-02	7.21E-01	2.92E-02	6.88E-01	2.79E-02
Na	1.48E-02	5.04E-04	2.12E-02	7.23E-04	2.58E-02	8.79E-04
Mg	2.11E-02	7.04E-04	1.11E-02	3.70E-04	8.90E-03	2.96E-04
Al	1.11E-01	3.25E-03	9.55E-02	2.80E-03	1.21E-01	3.54E-03
Si	4.22E-01	1.25E-02	5.19E-01	1.53E-02	4.53E-01	1.34E-02
P	1.07E-03	3.02E-05	1.98E-03	5.61E-05	7.80E-04	2.21E-05
S	0.00000	0.00000	0.00000	0.00000	0.00000	0.00000
K	3.32E-02	8.21E-04	2.95E-02	7.29E-04	1.94E-02	4.78E-04
Ca	6.95E-02	1.69E-03	1.78E-02	4.33E-04	3.94E-02	9.58E-04
Ti	5.12E-03	1.05E-04	4.27E-03	8.75E-05	5.43E-03	1.11E-04
Cr	1.75E-04	3.65E-06	1.06E-04	2.20E-06	7.10E-05	1.48E-06
Mn	8.14E-04	1.65E-05	8.06E-04	1.64E-05	1.20E-03	2.44E-05
Fe	4.33E-02	9.26E-04	2.76E-02	5.91E-04	5.75E-02	1.23E-03
Total	1.3800	0.0471	1.4500	0.0503	1.4200	0.0488

Table 5(b) — Neutron removal cross-section of Soil-4, 5 and world soil

Ele.	Soil-4 ρ= 1.24 g cm^{-3}		Soil-5 ρ= 1.34 g cm^{-3}		Soil-W ρ=1.40 g cm^{-3}	
	Partial density	Σ_R (cm^{-1})	Partial density	Σ_R (cm^{-1})	Partial density	Σ_R (cm^{-1})
C	0.00000	0.00000	0.00000	0.00000	2.80E-02	1.41E-03
Na	0.00000	0.00000	0.00000	0.00000	1.40E-03	6.27E-05
O	5.81E-01	2.35E-02	5.96E-01	2.42E-02	6.86E-01	2.78E-02
Na	2.37E-03	8.08E-05	1.35E-03	4.62E-05	8.82E-03	3.01E-04
Mg	1.62E-02	5.40E-04	9.00E-02	3.00E-03	8.82E-03	2.94E-04
Al	9.64E-02	2.82E-03	9.36E-02	2.74E-03	9.94E-02	2.91E-03
Si	3.62E-01	1.07E-02	3.07E-01	9.06E-03	4.62E-01	1.36E-02
P	6.81E-04	1.93E-05	1.60E-03	4.54E-05	1.12E-03	3.17E-05
S	0.00000	0.00000	0.00000	0.00000	1.26E-03	3.49E-05
K	2.20E-02	5.43E-04	5.23E-03	1.29E-04	1.90E-02	4.70E-04
Ca	1.09E-01	2.65E-03	1.89E-01	4.58E-03	1.92E-02	4.66E-04
Ti	4.98E-03	1.02E-04	4.11E-03	8.42E-05	6.44E-03	1.32E-04
Cr	2.57E-04	5.34E-06	4.29E-04	8.92E-06	0.00E+00	0.00E+00
Mn	1.04E-03	2.10E-05	6.82E-04	1.38E-05	0.00E+00	0.00E+00
Fe	4.39E-02	9.40E-04	5.08E-02	1.09E-03	5.32E-02	1.14E-03
Total	1.2400	0.0419	1.3400	0.0450	1.3947	0.0487

From Fig. 1, it is found that Z_{eq} of sandy loam (Soil-2) is the lowest whereas clay loam (Soil-5) is the highest. It is due to sandy loam contains major composition of low-Z elements such as O (49.75%), Na (1.46%), Si (35.77%) and P (0.14%). The pair-production is proportional to Z^2, so low-Z_{eq} shows lowest EBF in high energy (>3 MeV).

It is to be noted that the EBF values increase with increase in photon energy and penetration-depth. As photon energy increases, the EBF values saturate in higher-penetration depths. At 15 MeV energy, soil samples showed largest EBF values and sandy loam lowest above 5 mfp penetration. It is due to pair/triplet production which generates electron/ positron pair. The positron at rest, annihilate with electron to produce two secondary photons of 0.511 MeV. In low-penetration depths, these photons may possibly escape from the medium however its multiple scatter in large-penetration depth.

3.4 Fast neutron removal cross-section

The effective fast neutron removal cross-section of the selected soil samples is given in Table 5(a,b). The effective removal cross-section is approximately constant for neutron[27] energy 2 to 12 MeV. In Table 5(a,b), the calculations are being given for the different soil samples. The effective fast neutron removal cross-section of a soil samples is calculated by partial density of the elements and their cross-sections. It was observed that the removal cross-section is the highest (0.0503) for sandy loam (Soil-2) whereas remaining all soil samples showed roughly constant (0.0419 to 0.0488) removals cross-section. Highest value of removal cross-section of sandy loam is observed due to highest elemental composition of low atomic number, O (49.74%) and highest density among the soil samples. The observed neutron removal cross-section values are roughly 2/3 of total cross-section for neutron [29] having energies in the range 6-8 MeV. Therefore, it is concluded that low atomic number elemental composition and density contribute a vital role in gamma-ray and neutron shielding properties.

4 Conclusions

In the present study, we have calculated shielding properties (μ/ρ, HVL and EBF) of the soil samples [i.e. Soil-1(loam), Soil-2 (sandy loam), Soil-3 (sandy clay loam), Soil-4 (clay) and Soil-5 (clay loam)] in photon energy range 0.015-15 MeV up to 40 mfp penetration depth. In general, all the selected soil samples are good gamma-ray shielding materials and comparable to world average soil. All the soil samples showed a peak value of EBF at 0.2 MeV and depend upon the incident photon energy, chemical composition and penetration depths. Sandy loam was found to be the best neutron shielding as compared with other soil samples.

Acknowledgement

The authors gratefully acknowledge to honorable Prof. L Gerward for providing the WinXCom program.

References

1 Mudahar G S & Sahota H S, *Appl Radiat Isot*, 39 (1988) 21.
2 Singh M & Mudahar S, *Appl Radiat Isot*, 43 (1992) 907.
3 White G R, *Phys Rev*, 80 (1950) 154.
4 Fano U, *Nucleonics*, 11 (1953) 55.
5 Takeuchi K & Tanaka S, *JAERI-M*, 84 (1984) 214.
6 Simmons G L, NBS Technical Note, *National Bureau of Standards*, 748 (1973).
7 Chilton A B, Eisenhauer C M & Simmons G L, *Nucl Sci Eng*, 73, (1980) 97.
8 Nelson W R, Hirayama H & Rogers D W O, *EGS4 code system*, Stanford Linear Accelerator Centre, Stanford, California, 265 (1985).
9 ANSI/ANS-6 4 3, 1991, *Gamma ray attenuation coefficient and buildup factors for engineering materials, American Nuclear Society*, La Grange Park, Illinois.
10 Harima Y, Sakamoto Y, Tanka S & Kawai M, *Nucl Sci Eng*, 94 (1986) 24.
11 Harima Y, *Radiat Phys Chem*, 41 (1993) 631-672.
12 Singh V P & Badiger N M, *Int J Nucl Ener Sci Tech*, 7 (2012) 75.
13 Sandeep G & Gurdeep S S, *J Appl Phys*, 2 (2012) 24.
14 Jasbir S D, Barjinderpal S & Gurdeep S S, *J Appl Phys*, 1 (2012) 14.
15 Mann K S, Singla J, Kumar V & Sidhu G S, *Ann Nucl Energy*, 43 (2012) 157.
16 Mann K S & Sidhu G S, *Ann Nucl Energy*, 40 (2012) 241.
17 Singh V P & Badiger N M, *J Radioprotection*, 48 (2013) 63.
18 Singh V P & Badiger N M, *J Ceramics*, (2013) 13.
19 Singh V P & Badiger N M, *Ann Nucl Energy*, (2013) (Accepted).
20 Kurudirek M, Sardari D, Khaledi N, Çakır C & Mann K S, *Ann Nuclear Energy*, 53 (2013) 485.
21 Kucuk N, Tumsavas Z & Cakır M, *J Radian Research*, 54 (2013) 578.
22 Gerward L, Guilbert N, Jensen K B & Levring H, *J Radiation Phys Chem*, 71 (2004) 653.
23 Berger M J, Hubbell J H, Seltzer S M, Chang J, Coursey J S, Sukumar R, Zucker D S & Olsen K, (2010). http://www.nist.gov/pml/data/xcom/index.cfm
24 Michael E W & Tyler B C, *Pure Appl Chem*, 83 (2011) 359.
25 Harima Y, *Nucl Sci & Eng*, 83 (1983) 299.
26 Maron M J, *Numerical analysis*: A Practical approach, Macmillan, New York, (2007).
27 Kaplan M F, *Radiation shielding*, Longman scientific & Technology, Lonman Group UK, Limited, Essex, England, (1989).
28 Chilten A B, Shultis J K & Faw R E, *Principle of Radiation Shielding*, Prentice-Hall, Englewood Cliffs, NJ, (1984).
29 Samuel G & Alexander S, 2004. *Nuclear Reactor Engineering*, Fourth Edition, Vol-1.