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ORIGINAL PAPER

Studies on photon buildup for some thermoluminescent dosimetric compounds

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Abstract: Photon buildup for some $SrSO_4$, $BaSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$ and $ZnSO_4$ thermoluminescent dosimetric (TLD) compounds was investigated in the present work. Photon energy absorption buildup factors and photon exposure build factors were computed for the TLD compounds using the five-parameter geometric progression fitting method in energy range 0.015–15 MeV for penetration depths up to 40 mean free path. The buildup factors were studied as a function of photon energy, penetration depth and chemical compositions. Effective atomic numbers and air-kerma for the TLD compounds were calculated and ICRU standard tissue equivalence was discussed.

Keywords: Thermoluminescent; Dosimeter; Air-kerma; Effective atomic numbers; Buildup factors

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1. Introduction

There are several reports on mass attenuation coefficients, effective atomic numbers and effective electron densities for thermoluminescent dosimetric materials [1–4]. Extensive studies on thermoluminescent characteristics and luminescence of $MgSO_4$: Dy has been reported [5, 6]. A large difference in effective atomic numbers of $FeSO_4$, thermoluminescent and phantom materials has been noted at particular energies [7]. Recently, some novel thermoluminescent radiation dosimetric materials have been discovered [8].

The intensity of X-/γ-ray beam through a medium follows Lambert's Beer law;

$$I = I_0 e^{-\mu t} \tag{1}$$

where I and I_0 are transmitted and initial photon densities, μ is linear attenuation coefficient, and t is the thickness of medium. However, a buildup factor, B is required for broad beam, polychromatic and thick materials. Now the modified Eq. (1) is given as;

$$I = B \times I_0 e^{-\mu t} \tag{2}$$

which include the buildup factors, B. Various researchers have used the G-P fitting method to determine the photon buildup factor for thermoluminescent dosimetric [9, 10], heavy metal oxide glasses [11], human teeth [12], polymers [13], planet samples [14], dosimetric materials [15], gel dosimeters [16], nuclear track detectors [17], and superconductors [18] etc. These investigations on buildup factors for the low- and high-Z elements containing materials show that the G-P fitting method is useful technique for low as well as high-Z element materials.

The energy absorption buildup factors (EABF), exposure buildup factors (EBF) and air-kerma for some sulfate-based thermoluminescent dosimetric(TLD) compounds such as $SrSO_4$, $BaSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$ and $ZnSO_4$ are not available in the literatures. Therefore, in the present work, we have investigated the photon buildup for these compounds. The effective atomic numbers for few human organs, breast, cortical bone and soft tissue have been also calculated and compared with the selected TLD compounds. The buildup factors have been calculated using the G-P fitting method at photon energies 0.015–15 MeV for penetration depths up to 40 mean free path (mfp).

The dose rate from anisotropic point source is given by

$$D = \frac{S_0 B e^{-\mu x}}{K 4\pi r^2} \tag{3}$$

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where D is dose rate (unit of dose rate), S_0 is point source of gamma-ray (photon/s), B is buildup factor (dimensionless), μ is linear attenuation coefficient (length^{-1}), x is thickness of shield, K is conversion factor for gamma-ray to dose rate, and r is distance from source to receptor (unit of length). The attenuation of photon is accomplished by interaction processes. The photoelectric absorption completely removes the photon, pair production remove and regenerate the photons. However, in Compton scattering process the photon interacts with the electrons and loses some part of energy. Therefore, some photons reach to the receptor by penetrating the shield which is counted as lost in the calculation of attenuation coefficient. The concept of buildup factor in dose evaluation is introduced from here. After introduction of buildup of photon in the interacting medium, the buildup factor is becoming an essential parameter for exposure and energy absorption in the field of health physics, medical physics and radiation physics for shielding and dosimetry.

2. Computational method

2.1. Effective atomic numbers

The mass attenuation coefficients for the TLD compounds were estimated using mixture rule as

$$\mu_m = (\mu/\rho) = \sum_i^n w_i(\mu/\rho)_i \tag{4}$$

where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the ith element. The quantity w_i is given by

$$w_i = n_i A_i / \sum_j^n n_j A_j \tag{5}$$

with the condition $\sum_i^n w_i = 1$, where A_i is the atomic weight of the ith element and n_i is the number of formula units in the compounds. The μ/ρ value of individual element was taken from user-friendly Windows-based WinXcom program [19].

The effective atomic numbers for the TLD compounds were calculated using effective atomic cross section and electronic cross section. The details of the calculation procedures for σ_a and σ_e are given below. The total atomic cross sections (σ_t) for the compounds are obtained from the total mass attenuation coefficients, μ_m values using the following relation;

$$\sigma_t = \frac{\mu_m M}{N_A} \tag{6}$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of the compound and N_A is the Avogadro's number. The effective atomic cross section (σ_a) is calculated using the following equation:

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i \left(\frac{\mu}{\rho}\right)_i \tag{7}$$

The effective electronic cross section (σ_e) is calculated using the following equation;

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right) i = \frac{\sigma_a}{Z_{\text{eff}}} \tag{8}$$

where $f_i = \frac{n_i}{\sum_i n_i}$ denotes the mole fraction or fractional abundance of element i with respect to the number of atoms such that $\sum_i^n f_i = 1$, Z_i is the atomic number of ith element. The effective atomic number Z_{eff} of a compound is given as by the following relation;

$$Z_{\text{eff}} = \frac{\sigma_a}{\sigma_e} \tag{9}$$

2.2. Buildup factors

The ANSI/ANS-6.4.3, 1991 report [20] is published by the American Nuclear Society; a compilation of buildup factors at energies 0.015–15 MeV, and for penetration depths

Table 1 Equivalent atomic numbers for the thermoluminescent dosimeters

E (MeV)	$SrSO_4$	$BaSO_4$	$MgSO_4$	$MnSO_4$	$FeSO_4$	$ZnSO_4$
0.015	15.41	44.43	11.90	17.97	18.63	21.39
0.02	26.99	23.53	11.97	18.22	18.89	21.70
0.03	27.71	23.92	12.05	18.49	19.18	22.08
0.04	28.15	42.80	12.10	18.64	19.35	22.32
0.05	28.44	43.63	12.14	18.76	19.47	22.48
0.06	28.66	44.12	12.16	18.84	19.57	22.61
0.08	28.96	44.80	12.20	18.96	19.70	22.79
0.1	29.17	45.20	12.22	19.04	19.79	22.92
0.15	29.49	45.75	12.25	19.16	19.93	23.10
0.2	29.66	46.02	12.27	19.23	20.01	23.21
0.3	29.88	46.28	12.30	19.30	20.09	23.33
0.4	29.99	46.42	12.31	19.35	20.13	23.40
0.5	30.06	46.52	12.32	19.37	20.16	23.44
0.6	30.10	46.58	12.32	19.39	20.18	23.46
0.8	30.14	46.64	12.32	19.40	20.19	23.48
1	30.15	46.66	12.32	19.40	20.19	23.49
1.5	27.98	45.41	11.24	17.31	18.06	21.28
2	24.69	42.22	11.02	16.14	16.70	19.19
3	22.99	37.94	10.97	15.74	16.25	18.46
4	22.49	36.43	10.95	15.64	16.13	18.25
5	22.28	35.68	10.93	15.60	16.08	18.15
6	22.10	35.20	10.93	15.57	16.05	18.10
8	21.94	34.64	10.92	15.54	16.01	18.03
10	21.88	34.35	10.92	15.52	15.99	17.99
15	21.83	34.24	10.92	15.50	15.96	17.96

Table 2 G-P fitting parameters for EABF and EBF for $SrSO_4$

SrSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.017	0.355	0.249	11.740	−0.142	1.018	0.354	0.259	11.358	−0.179
2.00E−02	1.009	0.248	0.354	16.296	−0.369	1.011	0.121	0.669	11.181	−0.769
3.00E−02	1.021	0.348	0.249	14.424	−0.183	1.023	0.365	0.199	19.199	−0.161
4.00E−02	1.043	0.375	0.211	22.320	−0.246	1.046	0.332	0.241	13.689	−0.102
5.00E−02	1.077	0.351	0.243	13.158	−0.140	1.076	0.355	0.241	13.088	−0.140
6.00E−02	1.126	0.343	0.248	14.548	−0.149	1.113	0.368	0.234	13.609	−0.133
8.00E−02	1.247	0.396	0.217	14.399	−0.122	1.190	0.446	0.192	13.976	−0.109
1.00E−01	1.369	0.542	0.131	19.654	−0.086	1.282	0.504	0.166	13.878	−0.093
1.50E−01	2.074	0.455	0.217	13.284	−0.140	1.496	0.665	0.103	13.970	−0.057
2.00E−01	2.544	0.647	0.128	13.518	−0.097	1.665	0.819	0.056	13.701	−0.037
3.00E−01	2.891	0.890	0.047	12.890	−0.053	1.835	1.003	0.009	12.688	−0.020
4.00E−01	2.786	1.041	0.009	12.347	−0.037	1.882	1.119	−0.015	11.688	−0.014
5.00E−01	2.620	1.126	−0.012	11.786	−0.023	1.896	1.169	−0.025	10.076	−0.012
6.00E−01	2.496	1.161	−0.020	11.044	−0.019	1.880	1.197	−0.031	9.074	−0.010
8.00E−01	2.248	1.185	−0.027	9.296	−0.016	1.843	1.210	−0.034	7.756	−0.012
1.00E+00	2.154	1.189	−0.031	7.804	−0.011	1.813	1.192	−0.032	8.096	−0.011
1.50E+00	1.947	1.163	−0.030	10.537	−0.003	1.739	1.189	−0.038	17.551	0.011
2.00E+00	1.829	1.137	−0.027	23.770	0.007	1.717	1.128	−0.023	9.869	−0.003
3.00E+00	1.684	1.042	−0.001	12.216	−0.014	1.633	1.064	−0.008	12.576	−0.010
4.00E+00	1.578	0.986	0.016	12.968	−0.027	1.565	1.017	0.006	12.444	−0.018
5.00E+00	1.491	0.965	0.022	14.399	−0.034	1.498	0.994	0.014	13.173	−0.024
6.00E+00	1.418	0.957	0.027	13.500	−0.037	1.453	0.969	0.023	13.258	−0.032
8.00E+00	1.322	0.941	0.034	12.951	−0.039	1.368	0.954	0.030	13.566	−0.038
1.00E+01	1.267	0.922	0.044	14.033	−0.050	1.308	0.939	0.039	13.727	−0.047
1.50E+01	1.166	0.956	0.038	14.523	−0.043	1.186	0.930	0.050	14.064	−0.057

up to 40 mean free paths (mfp) for the elements $Z = 4$–92.[1] Harima et al. [24] have developed a five-parameter fitting formula, called geometric progression (G-P), which gives the buildup factors for compounds and mixtures, can be referred also the historical review by Harima [25]. The buildup factors $B(E, x)$ are calculated from the following equations [25]:

$$B(E,x) = 1 + \frac{b-1}{K-1}(K^X - 1), \quad \text{for } K \neq 1, \tag{10}$$

$$B(E,x) = 1 + (b-1)x, \text{ for } K = 1, \tag{11}$$

$$K(E,x) = cx^a + d\frac{\tanh(x/X_K - 2) - \tanh(-2)}{1 - \tanh(-2)}, \tag{12}$$

where E is the source energy, x is the penetration depth in units of mfp, and a, b, c, d and X_K are the G-P fitting parameters.

[1] The ANSI/ANS.6.4.3, 1991 standard has been administratively withdrawn. However, updating work is in progress for the standard [21–23].

The buildup factor of a given compound can be calculated by using the detailed procedure found else elsewhere [12–18]. The equivalent atomic numbers and G-P fitting parameters for the TLD compounds are given in Tables 1, 2, 3, 4, 5, 6 and 7, respectively.

The mfp parameter, or the relaxation length is reciprocal of linear attenuation coefficients ($x = 1/\mu$), where μ is linear attenuation coefficient (cm^{-1}). The mfp is the average distance of a single particle travels through a given material or compound before interacting with another material and mfp is the depth at which a fraction, *1/e* (~ 37 %), of a large homogeneous population of particles in a beam can penetrate.

2.3. Air-kerma

Air-kinetic energy released per unit mass (kerma) is defined as the initial kinetic energy of all secondary charged particles liberated per unit mass at a point of interest by uncharged radiation [26]. The computation of

Table 3 G-P fitting parameters for EABF and EBF for $BaSO_4$

BaSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.008	0.394	0.190	15.662	−0.083	1.008	0.387	0.203	16.966	−0.123
2.00E−02	1.013	0.301	0.292	15.572	−0.250	1.014	0.248	0.453	11.200	−0.414
3.00E−02	1.036	0.332	0.247	16.948	−0.177	1.037	0.373	0.201	23.677	−0.254
4.00E−02	1.507	0.422	0.105	22.149	−0.043	3.901	0.419	0.089	23.689	−0.042
5.00E−02	1.439	0.148	−0.059	10.127	0.043	3.191	0.137	−0.187	13.015	−0.008
6.00E−02	1.395	0.089	0.551	16.682	−0.122	2.560	0.069	0.783	13.976	−0.122
8.00E−02	1.334	0.064	0.632	14.114	−0.228	1.715	0.027	0.783	14.788	−0.218
1.00E−01	1.254	0.175	0.467	13.630	−0.249	1.258	0.197	0.458	13.767	−0.226
1.50E−01	1.443	0.252	0.356	13.982	−0.197	1.230	0.410	0.226	14.189	−0.122
2.00E−01	1.936	0.294	0.322	13.972	−0.195	1.362	0.507	0.172	14.463	−0.095
3.00E−01	1.681	0.502	0.185	13.927	−0.108	1.487	0.685	0.094	14.345	−0.047
4.00E−01	2.438	0.643	0.132	13.887	−0.099	1.608	0.832	0.053	14.157	−0.039
5.00E−01	2.501	0.757	0.090	13.758	−0.076	1.678	0.915	0.032	14.172	−0.031
6.00E−01	2.500	0.823	0.068	13.742	−0.064	1.706	0.971	0.016	13.987	−0.022
8.00E−01	2.410	0.905	0.042	13.642	−0.049	1.731	1.029	0.002	14.062	−0.016
1.00E+00	2.303	0.949	0.028	13.520	−0.040	1.724	1.054	−0.005	13.430	−0.014
1.50E+00	1.930	1.067	−0.004	13.555	−0.019	1.600	1.144	−0.026	10.343	−0.002
2.00E+00	1.850	1.046	0.003	13.071	−0.025	1.600	1.126	−0.021	12.634	−0.005
3.00E+00	1.707	0.979	0.025	12.952	−0.046	1.573	1.063	−0.001	12.667	−0.025
4.00E+00	1.578	0.948	0.037	13.735	−0.057	1.521	1.023	0.013	13.191	−0.036
5.00E+00	1.518	0.903	0.055	13.943	−0.074	1.501	0.971	0.032	13.445	−0.053
6.00E+00	1.451	0.894	0.061	14.143	−0.078	1.464	0.956	0.040	13.539	−0.059
8.00E+00	1.381	0.879	0.072	14.165	−0.085	1.438	0.921	0.058	13.812	−0.076
1.00E+01	1.312	0.921	0.062	14.339	−0.075	1.386	0.963	0.050	14.047	−0.067
1.50E+01	1.259	0.977	0.060	14.572	−0.073	1.362	1.036	0.044	14.337	−0.062

air-kerma is calculation of mass energy absorption coefficient, μ_{en}/ρ of a compound or mixture to the air. The values of μ_{en}/ρ of the elements are given in the compilation of Hubbell and Seltzer report [27].

3. Standardization of method

The present G-P fitting method has been compared by calculating the buildup factors for water (low-*Z*) and lead (high-*Z*) in the energy range of 0.015–15 MeV for selected penetration depth up to 40 mfp. The results obtained are compared with the ANSI/ANS-6.4.3, 1991 [20] standard the energy absorption buildup factors and the exposure buildup factors for randomly selected penetration depths up to energies 15 MeV. As shown in Figs. 1, 2 and 3, the energy absorption buildup factors and the exposure buildup factors computed using the present G-P fitting method are in good agreement with the ANSI/ANS-6.4.3, 1991 standard data except at *K*-edge for lead. The differences in buildup factors for lead are slightly higher than water but insignificant. This provides confidence in our results obtained for TLD compounds.

4. Results and discussion

The effective atomic numbers for the selected TLD compounds along with ICRU tissues is shown in Fig. 4. The energy absorption buildup factors (EABF) and the exposure buildup factors (EBF) for the TLD compounds are shown in Figs. 5(a)–5(f) and 6(a)–6(f), respectively. The EABF and EBF for the TLD compounds are plotted graphically for photon energy 0.015–15 MeV up to penetration depth 40 mfp. The air-kerma for the TLD compounds is shown in Fig. 7 for photon energies 1 keV–15 MeV. The EABF and EBF for the TLD compounds are discussed for photon energy, penetration depth and chemical composition dependency.

Table 4 G-P fitting parameters for EABF and EBF for $MgSO_4$

MgSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.038	0.402	0.210	13.145	−0.129	1.038	0.399	0.213	13.170	−0.131
2.00E−02	1.088	0.426	0.186	14.502	−0.919	1.086	0.438	0.179	14.315	−0.092
3.00E−02	1.291	0.443	0.192	14.250	−0.101	1.285	0.448	0.189	14.416	−0.102
4.00E−02	1.629	0.550	0.145	15.259	−0.077	1.602	0.551	0.145	15.129	−0.077
5.00E−02	2.214	0.615	0.133	13.749	−0.072	2.051	0.638	0.121	14.463	−0.063
6.00E−02	2.720	0.764	0.082	13.409	−0.057	2.420	0.778	0.077	14.572	−0.057
8.00E−02	3.701	1.031	0.006	14.301	−0.019	2.887	1.016	0.011	13.556	−0.023
1.00E−01	4.199	1.254	−0.042	12.826	0.004	3.044	1.202	−0.029	12.446	−0.007
1.50E−01	4.110	1.552	−0.096	13.531	0.032	2.992	1.429	−0.071	16.816	0.012
2.00E−01	3.661	1.656	−0.111	13.822	0.038	2.830	1.514	−0.084	16.280	0.018
3.00E−01	3.070	1.683	−0.117	14.198	0.040	2.583	1.547	−0.091	16.040	0.021
4.00E−01	2.764	1.631	−0.110	14.590	0.035	2.426	1.527	−0.090	15.769	0.022
5.00E−01	2.570	1.575	−0.102	14.774	0.033	2.306	1.495	−0.087	16.133	0.022
6.00E−01	2.420	1.536	−0.099	14.649	0.034	2.213	1.465	−0.084	15.853	0.024
8.00E−01	2.238	1.446	−0.085	14.774	0.029	2.093	1.395	−0.075	15.839	0.022
1.00E+00	2.116	1.375	−0.074	15.103	0.026	2.001	1.345	−0.068	15.743	0.023
1.50E+00	1.937	1.252	−0.054	14.338	0.020	1.876	1.234	−0.049	15.037	0.017
2.00E+00	1.845	1.154	−0.034	14.253	0.013	1.795	1.154	−0.034	14.457	0.012
3.00E+00	1.706	1.050	−0.009	10.665	−0.001	1.684	1.056	−0.011	10.493	0.001
4.00E+00	1.614	0.983	0.009	13.157	−0.012	1.606	0.992	0.006	12.980	−0.009
5.00E+00	1.542	0.946	0.019	12.682	−0.015	1.536	0.956	0.016	15.185	−0.020
6.00E+00	1.480	0.928	0.024	15.953	−0.027	1.494	0.914	0.031	11.462	−0.025
8.00E+00	1.388	0.903	0.033	12.281	−0.023	1.406	0.902	0.033	13.503	−0.026
1.00E+01	1.325	0.893	0.036	13.929	−0.029	1.347	0.876	0.043	13.208	−0.033
1.50E+01	1.226	0.891	0.038	14.721	−0.033	1.263	0.823	0.064	14.366	−0.056

4.1. Effective atomic numbers of TLD compounds

The variation of effective atomic number (Z_{eff}) for the TLD compounds in energy range 1 keV–15 MeV is shown in Fig. 4. In Fig. 4, Z_{eff} for some tissues like breast, cortical bone and soft tissue [28] are also shown. The Z_{eff} for $MgSO_4$ is found to be the lowest among the selected TLD compounds, which is comparable with the values of Z_{eff} for the cortical bone. It is observed that the Z_{eff} values for $BaSO_4$ are the highest in the selected region of interested energy. The Z_{eff} values for all the TLD compounds are <20 in the Compton scattering region. The Z_{eff} values for the TLD compounds in Compton scattering region at photon energy 1 MeV are found to be 14.47, 18.07, 10, 12.19, 12.36 and 13.05 for $SrSO_4$, $BaSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$ and $ZnSO_4$, respectively. A very high peak of 53.29 is observed for $BaSO_4$ at near *K*-edge of Ba. Since the Z_{eff} values for $MgSO_4$ are nearer to cortical bone which resembles that the photon interaction characteristics of each other; therefore, it can be considered suitable for dose monitoring.

4.2. Energy absorption buildup factor and exposure buildup factor of TLD compounds

The variation trend of the buildup factors is observed similar up to photon energy of 3 MeV. In low energy, the buildup factors are small because the photons are completely removed through absorption by photoelectric absorption, gradually increase with the energy due to multiple scattering as dominance of Compton scattering in the intermediate-energy and finally again reduces in high-energy region as dominance of pair production as shown in Fig. 5(a)–5(f). In high-energy photon region (>3 MeV) another absorption process, pair/triplet production dominates in bringing down EABF and EBF. The EABF and EBF for $BaSO_4$ (having highest Z_{eff}) are found to be the lowest among the selected the TLD compounds. The EABF

Table 5 G-P fitting parameters for EABF and EBF for $MnSO_4$

MnSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.009	0.492	0.144	29.096	−0.283	1.009	0.492	0.144	29.082	−0.285
2.00E−02	1.022	0.416	0.199	26.471	−0.291	1.026	0.311	0.260	17.409	−0.181
3.00E−02	1.075	0.347	0.248	13.022	−0.145	1.074	0.364	0.120	12.947	−0.133
4.00E−02	1.165	0.374	0.229	14.516	−0.134	1.161	0.386	0.220	14.137	−0.123
5.00E−02	1.300	0.405	0.216	14.724	−0.127	1.279	0.414	0.213	14.207	−0.124
6.00E−02	1.462	0.473	0.181	14.897	−0.103	1.402	0.487	0.176	14.358	−0.098
8.00E−02	1.991	0.490	0.196	11.918	−0.095	1.647	0.611	0.128	14.322	−0.074
1.00E−01	2.517	0.628	0.138	12.159	−0.084	1.849	0.755	0.078	14.329	−0.051
1.50E−01	3.384	0.925	0.036	13.428	−0.042	2.132	0.996	0.012	13.698	−0.023
2.00E−01	3.515	1.123	−0.010	12.798	−0.024	2.221	1.155	−0.020	12.066	−0.015
3.00E−01	3.183	1.298	−0.046	9.546	−0.010	2.238	1.274	−0.042	10.184	−0.011
4.00E−01	2.843	1.377	−0.065	22.548	0.016	2.197	1.309	−0.048	9.176	−0.010
5.00E−01	2.622	1.391	−0.069	17.354	0.014	2.124	1.340	−0.057	16.346	0.004
6.00E−01	2.464	1.384	−0.069	18.207	0.017	2.065	1.345	−0.061	20.365	0.013
8.00E−01	2.262	1.350	−0.066	16.544	0.017	1.973	1.326	−0.061	17.736	0.015
1.00E+00	2.128	1.309	−0.060	15.837	0.017	1.910	1.292	−0.057	16.354	0.015
1.50E+00	1.941	1.226	−0.047	14.984	0.015	1.820	1.212	−0.043	16.217	0.013
2.00E+00	1.839	1.147	−0.030	15.768	0.007	1.760	1.149	−0.031	15.179	0.008
3.00E+00	1.692	1.058	−0.010	11.734	−0.003	1.661	1.059	−0.009	11.013	−0.005
4.00E+00	1.593	0.997	0.007	12.929	−0.013	1.588	0.998	0.008	11.902	−0.017
5.00E+00	1.517	0.956	0.020	14.609	−0.026	1.517	0.975	0.014	12.160	−0.017
6.00E+00	1.447	0.950	0.021	15.342	−0.029	1.469	0.957	0.019	13.816	−0.021
8.00E+00	1.356	0.922	0.032	12.461	−0.028	1.388	0.927	0.030	13.539	−0.030
1.00E+01	1.294	0.906	0.039	13.557	−0.036	1.327	0.913	0.036	13.541	−0.034
1.50E+01	1.191	0.926	0.036	14.363	−0.036	1.231	0.889	0.050	13.152	−0.049

Table 6 G-P fitting parameters for EABF and EBF for $FeSO_4$

FeSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.010	0.322	0.320	18.910	−0.381	1.011	0.262	0.447	7.640	−0.497
2.00E−02	1.023	0.271	0.342	14.357	−0.259	1.024	0.292	0.285	11.153	−0.150
3.00E−02	1.067	0.272	0.243	12.629	−0.140	1.065	0.382	0.060	12.267	−0.115
4.00E−02	1.146	0.368	0.232	14.328	−0.137	1.143	0.376	0.226	13.974	−0.127
5.00E−02	1.266	0.395	0.221	14.539	−0.130	1.248	0.407	0.215	14.171	−0.123
6.00E−02	1.411	0.457	0.188	14.783	−0.106	1.359	0.468	0.186	14.297	−0.106
8.00E−02	1.813	0.548	0.154	14.682	−0.080	1.587	0.584	0.138	14.341	−0.078
1.00E−01	2.270	0.673	0.107	15.155	−0.073	1.779	0.718	0.090	14.306	−0.056
1.50E−01	3.257	0.876	0.050	13.421	−0.050	2.068	0.953	0.023	13.691	−0.028
2.00E−01	3.470	1.072	0.002	12.890	−0.032	2.175	1.118	−0.012	12.581	−0.019
3.00E−01	3.170	1.269	−0.041	10.288	−0.011	2.200	1.254	−0.038	10.287	−0.011
4.00E−01	2.847	1.351	−0.060	26.844	0.017	2.167	1.296	−0.046	9.784	−0.009
5.00E−01	2.615	1.375	−0.066	16.825	0.012	2.123	1.302	−0.048	8.699	−0.011
6.00E−01	2.477	1.360	−0.064	20.788	0.016	2.054	1.330	−0.058	23.113	0.014

Table 6 continued

FeSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
8.00E−01	2.259	1.342	−0.064	15.924	0.015	1.961	1.319	−0.059	18.589	0.016
1.00E+00	2.129	1.302	−0.059	16.406	0.016	1.902	1.288	−0.056	17.207	0.016
1.50E+00	1.943	1.222	−0.046	15.062	0.015	1.813	1.211	−0.043	16.213	0.013
2.00E+00	1.837	1.149	−0.031	15.722	0.008	1.757	1.148	−0.031	15.173	0.008
3.00E+00	1.691	1.058	−0.010	12.015	−0.003	1.660	1.058	−0.009	10.395	−0.006
4.00E+00	1.591	0.997	0.007	13.053	−0.014	1.586	0.996	0.010	10.254	−0.017
5.00E+00	1.512	0.962	0.018	14.701	−0.025	1.515	0.979	0.013	11.811	−0.016
6.00E+00	1.444	0.953	0.021	15.104	−0.029	1.468	0.957	0.020	13.466	−0.022
8.00E+00	1.351	0.931	0.029	13.086	−0.026	1.388	0.927	0.031	13.430	−0.032
1.00E+01	1.291	0.908	0.039	13.433	−0.037	1.321	0.919	0.039	13.423	−0.041
1.50E+01	1.190	0.922	0.038	14.248	−0.039	1.243	0.844	0.071	13.849	−0.070

Table 7 G−P fitting parameters for EABF and EBF for $ZnSO_4$

ZnSO4										
E (MeV)	EABF					EBF				
	b	*c*	*a*	X_k	*d*	*b*	*c*	*a*	X_k	*d*
1.50E−02	1.006	0.835	−0.117	8.663	0.173	1.006	0.844	−0.127	6.663	0.186
2.00E−02	1.015	0.335	0.269	13.424	−0.214	1.015	0.344	0.317	11.045	−0.250
3.00E−02	1.045	0.346	0.243	15.097	−0.163	1.046	0.373	0.212	18.253	−0.193
4.00E−02	1.098	0.360	0.233	13.878	−0.125	1.099	0.352	0.240	13.059	−0.129
5.00E−02	1.180	0.369	0.233	14.300	−0.134	1.169	0.388	0.221	14.082	−0.125
6.00E−02	1.282	0.414	0.208	14.737	−0.120	1.248	0.432	0.199	14.213	−0.112
8.00E−02	1.541	0.508	0.163	15.481	−0.091	1.416	0.522	0.161	14.415	−0.089
1.00E−01	1.890	0.581	0.140	15.467	−0.087	1.568	0.630	0.119	14.201	−0.069
1.50E−01	2.793	0.713	0.106	14.283	−0.088	1.841	0.836	0.054	13.926	−0.039
2.00E−01	3.140	0.911	0.046	13.021	−0.055	1.984	1.001	0.014	12.949	−0.027
3.00E−01	3.092	1.133	−0.011	11.553	−0.025	2.068	1.162	−0.021	11.199	−0.015
4.00E−01	2.833	1.241	−0.036	17.940	−0.005	2.064	1.232	−0.035	10.334	−0.012
5.00E−01	2.622	1.286	−0.047	12.974	−0.003	2.031	1.265	−0.043	8.486	−0.009
6.00E−01	2.482	1.289	−0.049	14.533	0.000	1.991	1.281	−0.047	14.253	0.000
8.00E−01	2.270	1.282	−0.049	11.376	−0.001	1.928	1.268	−0.047	12.222	0.000
1.00E+00	2.130	1.275	−0.053	17.598	0.014	1.865	1.265	−0.051	18.571	0.015
1.50E+00	1.936	1.215	−0.044	15.541	0.014	1.785	1.207	−0.042	15.801	0.012
2.00E+00	1.835	1.146	−0.030	16.601	0.007	1.743	1.145	−0.029	16.713	0.006
3.00E+00	1.689	1.054	−0.007	12.651	−0.006	1.657	1.050	−0.005	11.458	−0.010
4.00E+00	1.591	0.984	0.014	12.386	−0.021	1.579	1.004	0.008	11.119	−0.015
5.00E+00	1.501	0.968	0.018	15.216	−0.030	1.512	0.979	0.015	13.385	−0.021
6.00E+00	1.437	0.944	0.027	13.014	−0.033	1.461	0.965	0.019	13.672	−0.024
8.00E+00	1.342	0.924	0.035	12.275	−0.034	1.380	0.938	0.030	13.392	−0.033
1.00E+01	1.280	0.911	0.041	13.908	−0.043	1.316	0.927	0.038	13.530	−0.043
1.50E+01	1.176	0.947	0.033	14.524	−0.036	1.219	0.918	0.047	13.488	−0.052

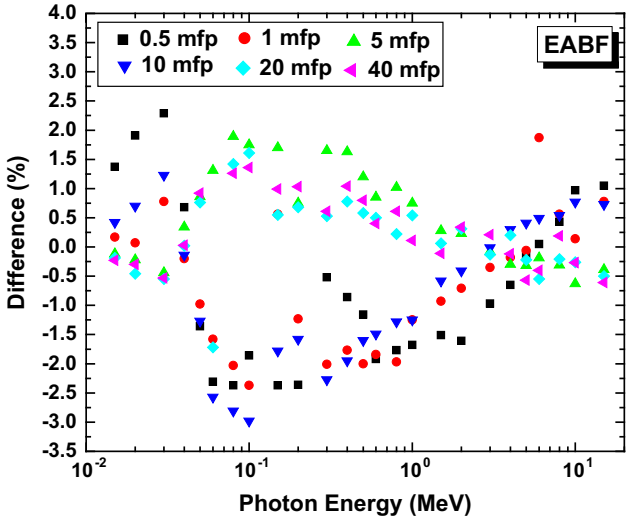

Fig. 1 Difference (%) between ANSI database and present G-P fitting work with respect to the calculated values of EABF for water at some penetration depths up to 15 MeV as a function of photon energy

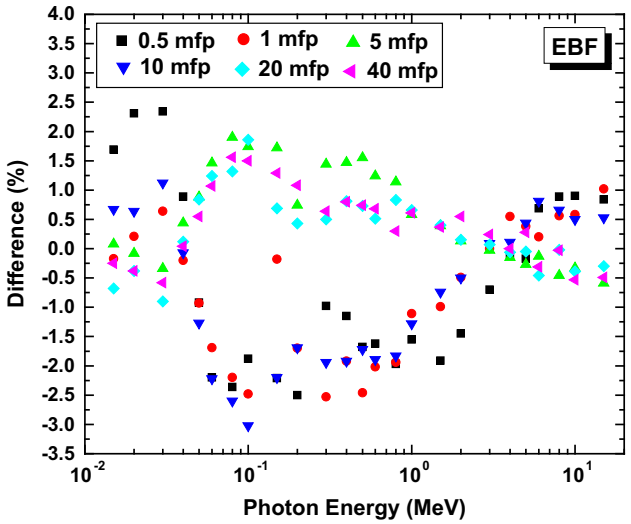

Fig. 2 Difference (%) between ANSI database and present G-P fitting work with respect to the calculated values of EBF for water at some penetration depths up to 15 MeV as a function of photon energy

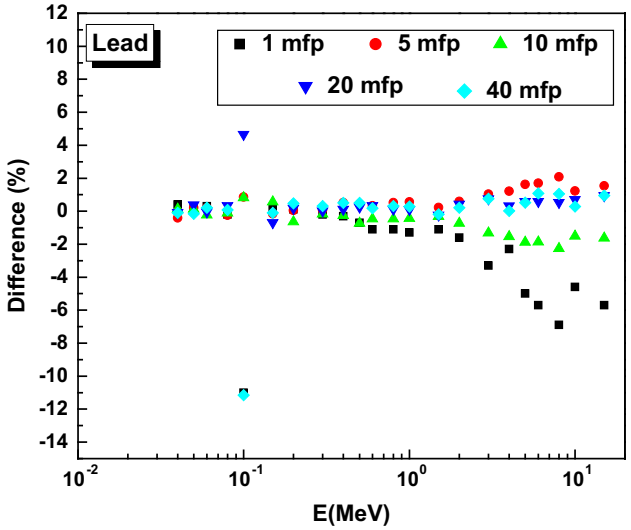

Fig. 3 Difference (%) between ANSI/ANS-6.4.3, 1991 standard data and present G-P fitting work with respect to the calculated values of EBF for lead at some penetration depths up to 15 MeV as a function of photon energy

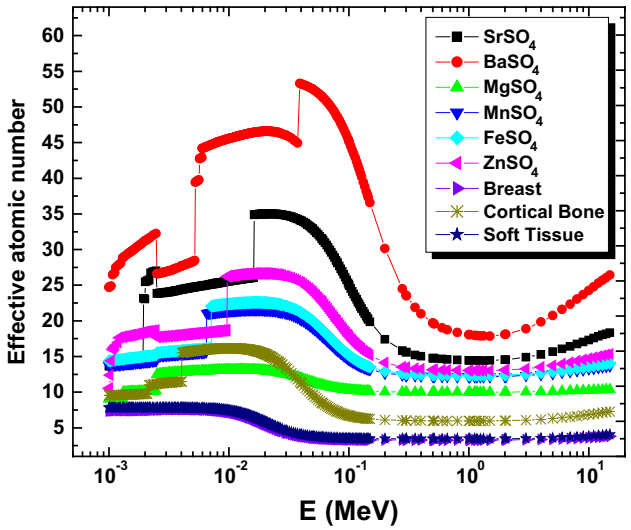

Fig. 4 Effective atomic numbers for the thermoluminescent dosimetric compounds

for the TLD compounds are found to be 31.44, 587.34, 9.96, 14.13, 14.72 and 18.11 for $SrSO_4$, $BaSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$ and $ZnSO_4$, respectively, for penetration depth 40 mfp at energy 15 MeV. The EBF for the TLD compounds are found to be 37.18, 1094.10, 10.64, 17.33, 22.80 and 26.68 for $SrSO_4$, $BaSO_4$, $MgSO_4$, $MnSO_4$, $FeSO_4$ and $ZnSO_4$, respectively, for penetration depth 40 mfp at energy 15 MeV.

The variation of EABF and EBF for the TLD compounds with penetration depths are of very importance in the field of dosimetry. It is found that the EABF and EBF for the TLD compounds increase with the penetration depths. It is to be noted that difference in buildup factors of TLD compounds increases with decrease in energy. The buildup factors for $BaSO_4$ are observed to be the lowest in low and intermediate energies among all the selected TLD compounds, whereas it shows increasing trend in high energies different from the other compounds.

In general the EABF and EBF for all the TLD compounds decrease with increase in penetration depth and photon energy, whereas $BaSO_4$ shows reverse behavior. This can be explained using the partial photon interaction processes namely the photoelectric effect, the Compton

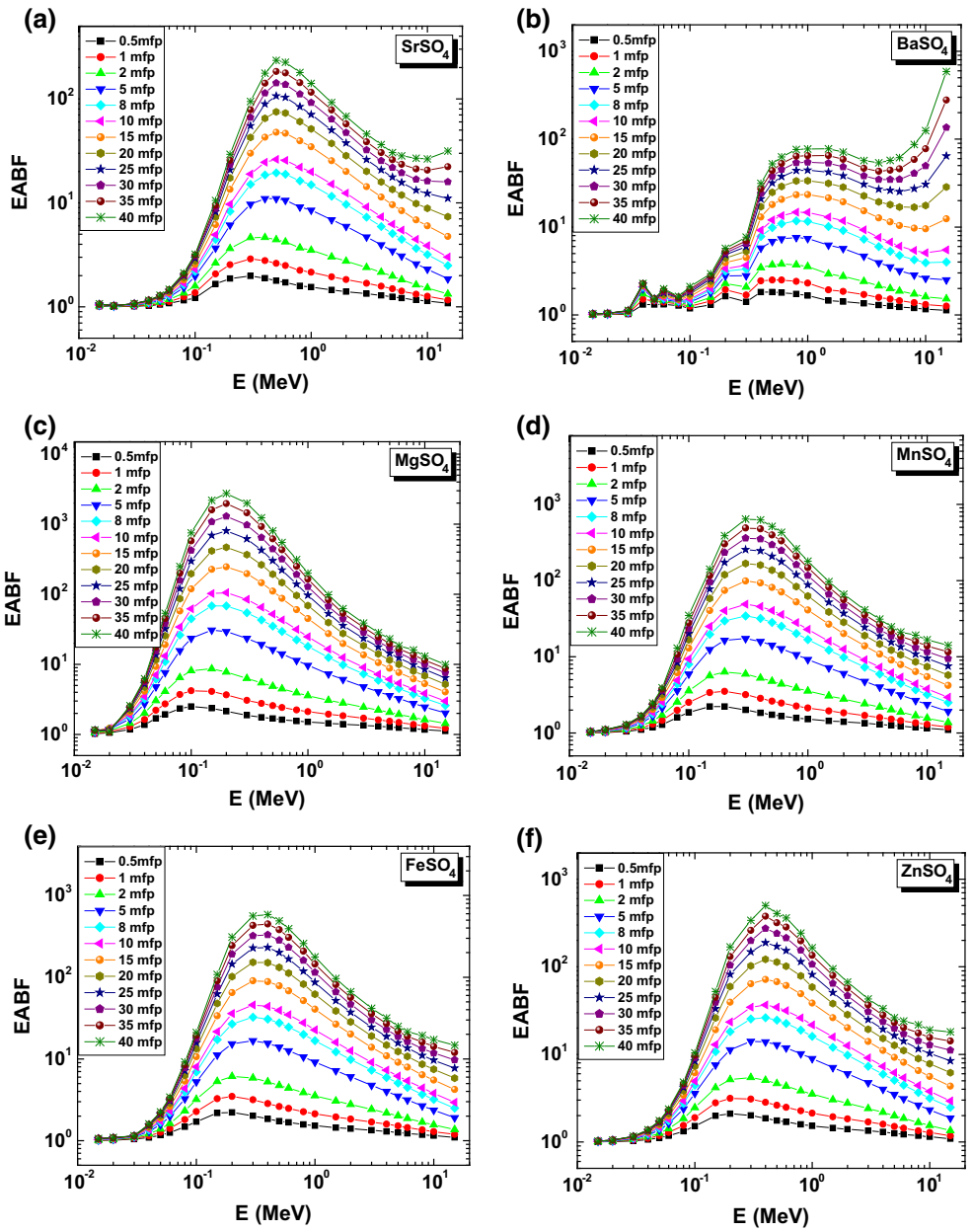

Fig. 5 Energy absorption buildup factors for (**a**) $SrSO_4$ (**b**) $BaSO_4$ (**c**) $MgSO_4$ (**d**) $MnSO_4$ (**e**) $FeSO_4$ (**f**) $ZnSO_4$ dosimetric compounds

scattering and the pair production. In low energy, the small values of buildup factors are due to dominance of photoelectric effect which results in the fast removal photons thereby not allowing these photons to buildup in the medium. The EABF and EBF at 0.015 MeV energy are roughly constant (unity) and for all the penetration depths.

The Z_{eq} for TLD compounds plays the similar roll of a composite material as Z of an element. Therefore, it can be explained that the EABF and EBF of the TLD compounds are minimum in low energy due to dominance of photoelectric effect as the interaction cross section is directly proportional to Z_{eq}^{4-5}. With increase in photon energy, buildup factors increase due to multiple scattering as Compton scattering dominates with Z_{eq}. In high-energy region (>3 MeV), pair production takes over the Compton scattering process as dependent upon Z_{eq}^2. The reason for large EABF and EBF for $BaSO_4$ above 3 MeV is the dominance of pair production due to the highest Z_{eq}. In the pair production, the electron–positron pairs generate and buildup in large penetration as well as originate the

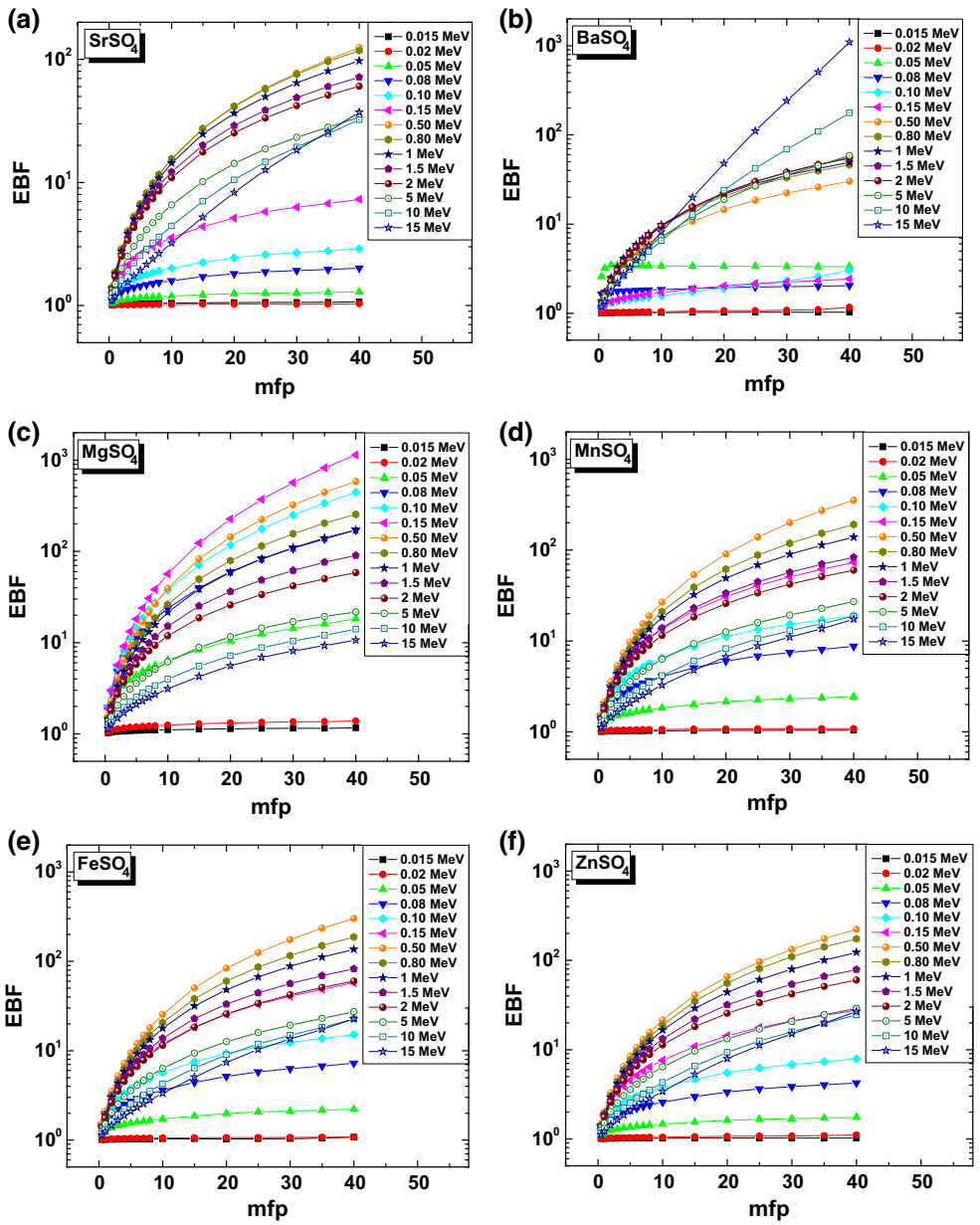

Fig. 6 Exposure buildup factors for (**a**) $SrSO_4$, (**b**) $BaSO_4$, (**c**) $MgSO_4$, (**d**) $MnSO_4$, (**e**) $FeSO_4$, (**f**) $ZnSO_4$ dosimetric compounds

secondary photons (0.511 MeV) by annihilation of positron with electron at rest. These secondary photons may escape from the TLD compounds of low penetration depth, whereas buildup for large penetration depths.

4.3. Air-kerma of TLD compounds

The variation of air-kerma of the TLD compounds for photon energy 1 keV to 15 MeV is shown in Fig. 7. It is to be noted that the air-kerma values for $MgSO_4$ are the lowest among all the TLD compounds. We have found that the air-kerma values for all the TLD compounds reach to unity for photon energy region 1–3 MeV. The air-kerma values for $MgSO_4$ are in range of 0.91–4.62 in the photon energy range from 1 to 150 keV and above 150 keV, it is in range of unity. The air-kerma values for all the TLD compounds vary due to dominance of photoelectric effect in photon energy region 1–150 keV. It is observed that the air-kerma values for TLD compounds are independent upon chemical compositions in the photon energy range of 800 keV to 4 MeV.

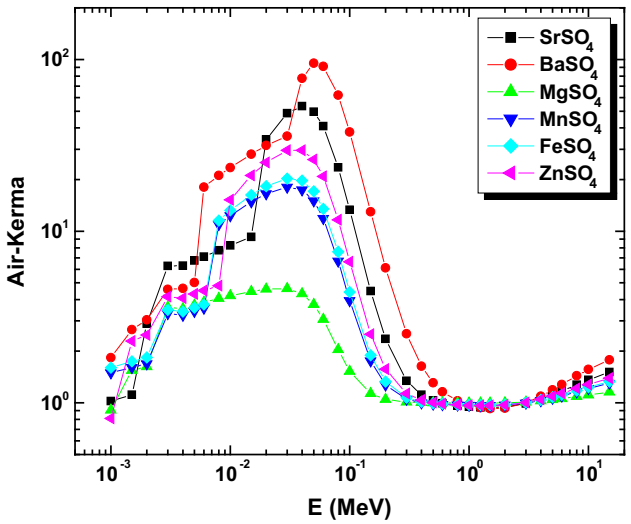

Fig. 7 Kerma relative to air for the thermoluminescent dosimetric compounds

5. Conclusions

The photon interaction for some thermoluminescent dosimetric compounds has been studied for effective atomic numbers, energy absorption buildup factors, exposure buildup factors and air-kerma. The G-P fitting method has been used for calculation of the buildup factors in the energy range 0.015–15 MeV, penetration depth up to 40 mfp. The effective atomic numbers for the TLD compounds are found to be higher than the tissue substitutes.

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