Numerical Investigation on Photon Sensing Parameters for Some Thermoluminescence Dosimeters: A Comparative Study

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In the present work, twelve inorganic thermoluminescence dosimetric (TLD) materials doped with some rare earth elements (LiF: Sm, LiBaP2O7:Eu, CaCO3:Eu, CaSO4: Dy, SrSO4:Sm, CsSO4:Sm, BaSO4:Eu, Li3B2O6: Dy, MgB2O4:Gd, Al2O3:Gd, MgAl2O4:Ce and Li(CuAlF6:Eu) and three organic TLD materials (CsH16NO3, C6H12O2 and C4H6BaO4) were selected for comparative analysis on the basis of different photon sensing parameters. About nine photon sensing parameters viz. mass attenuation coefficient (MAC), linear attenuation coefficient (LAC), mean free path (mfp), half value layer (HVL), tenth value layer (TVL), effective atomic number (EAN), effective electron number (EEN), exposure buildup factor (EBF) and energy absorption buildup factor (EABF) were obtained for the selected fifteen TLDs. The simultaneous variation of these photon sensing parameters for the selected TLDs with photon energy and composition has been analyzed. The results of present comparative analysis help radiation physicists to easily select a particular dosimeter for their research laboratory from different existing compositions. All photon sensing parameters viz. MAC, LAC, mfp, HVL, TVL, EAN, EEN, EBF and EABF for selected TLDs for strongly depend upon incident energy and chemical composition in lower and higher energy regions. Among the selected TLDs; BaSO4: Eu3+ offers best results (maximum values for MAC, EAN, EEN; and minimum values for mfp, HVL, TVL, EBF, EABF); whereas MgB2O4:Gd3+ offers EAN value close to tissue and less variation in most of the sensing parameters with respect to photon energy.

Population growth leads to demand of goods and facilities which primes to the growth of different types of industries, scalability in urbanization as well as massive advancements in the technological sector. This huge expansion boosted the paradigm of devices advancements (smart devices, day-to-day life gadgets, homes, transportation vehicles as well as cities). Due to the usefulness of internet of things (IOE), demand for sensors is abruptly expanded in the last few years.1–3 Sensors have found their uses in different fields such as advanced automation, health technology sector, environmental sector, manufacturing field, and artificial intelligence etc. Sensors also play a crucial role in healthcare sector, smart wearable goods and gadgets, safety purposes, remediation of environment, detection of crops in agriculture from monitoring to control followed by detection. These applications make a huge demand for sensors which governs the global sensor market. In the year 2021, this market touched the value of $190 billion and it is poised cross $ 1 trillion by 2025. Figure 1 shows the global sensor market scenario. This upgrowing demand for sensors form the basis for research based on sensor performance in different fields. After fulfilling the requirements, different types of materials form the basis for different sensors.4–6

Thermoluminescent (TL) materials exhibits the thermally stimulated emission of visible photons subsequent to energy absorption from nuclear radiations. These materials have numerous applications in different scientific and applied fields viz. radiodiagnosis, radiotherapy, radiation protection, and research etc. TL material was first introduced by Daniels et al. in 1950s. TLDs were most important and widely used passive dosimeters for measuring absorbed dose because of its small size, reproducibility, re-usability, low hygroscopicity, low fading, lower cost, high sensitivity for low dose measurements and good response at high dose measurements.7–12 TLDs are used for monitoring radiation level over a fixed time span. Absorbed energy from intracting particle excite the material or phosphor. The excited electrons/holes struck in the metastable state in TL materials. These strucked eletrons/holes elcct to ground level with the release of trapped energy in the form of visible photons, only upon providing thermal energy (heating the material). The thermoluminescent dosimeters (TLDs) play a crucial role in global market as shown in Fig. 2. In the previous year i.e. 2021, global TLD services market reached to $588.30 million. By the end of year 2028, the expected size increase of TLD market is estimated to $1,776.23 million with an upward 17.1% compounded annual growth rate.13 Many researchers had made efforts to ameliorate dosimetric materials by developing new materials.14–19

Gerward et al.20 developed WinXCom software which provides the attenuation coefficients as well as cross sections for various types of photon interaction processes for all elements (for Z < 100) in tabular/graphical form. This software is very useful in theoretical computation of attenuation coefficients for different compounds and mixtures on the basis of mixture rule.

Furettea et al.21 reported the characteristics of newly developed complete tissue equivalent TLDs: Li3B2O6: Cu, In and Li2B2O6: Cu as sintered pellets. Authors had inspected the dosimetric properties for lithium borate TLD such as TL sensitivity, glow curves, photon dose response, minimum detectable dose, relative photon energy response, fading, precision of dose measurements, reproducibility and annealing procedure.

Gowda et al.22 had worked on basic radiation sensing properties (MAC, EAN and EEN) for some TLDs such as LiF, CaCO3, CaSO4, CaSO4.2H2O, SrSO4, CaSO4, BaSO4, C4H6BaO4 and 3CdSO4.8H2O at energy range between 2.5 keV and 1332.5 keV. Manohara et al.23 reported EABF for TLD materials such as LiF, BeO, Li3B2O6, Na2B2O6, CaSO4, MgF2 and CaSO4PO3; computed using G-P fitting method in the energy range of 0.015–15 MeV for penetration depths up to 40 mean free path (mfp). Authors determined the requirement of EABF in radiation dosimetry, diagnostics and therapy and also discussed tissue equivalent of TLD materials.

Onder et al.24 investigated MAC, EAN and EEN theoretically as well as for some dosimetric materials such as MgSO4, CaSO4, Al2O3, MgSi2O6, ZnSO4, CaSO4, CaF2, Na2SO4, Na2P2O7, CaF2PO4, SiO2, CaCO3 and BaSO4 in the energy range from 8 to 662 keV.

Recently, Yilmaz and Büyükyıldız25 explored calcium-based TLD materials (CaSO4, CaF2, CaF2PO4 and CaCO3) for radiation applications. Authors reported MAC, EAN, EABF, EBF, KERMA relative to air for energy regime between 80 keV to 2 MeV. One of the essential components that makes a TLD material more efficient is its density. TLD material with higher density exhibit more applications for sensing purpose. The density for selected TLDs lies

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between 1.29–4.69 g/cm³. The doping with rare earth metal elements enhances optical properties of material. Rare earth metals improve the luminescent properties of the phosphor. The common oxidation state is +3 as it is an energetically stable state and shields the host lattice. Due to higher storage capacity, rare earth metals offer number of applications in luminescent materials.26–28 Present work reports the comparative analysis of fifteen TLDs (twelve inorganic materials doped with rare earth elements and three organic materials) with respect to different photon sensing parameters. Mostly, researchers22–25 had neglected the composition of dopants while computing/measuring the photon sensing parameters; whereas dopants plays a significant role in the sensing property. Further, the variation of different photon sensing properties were also analysed with respect to photon energy and nature of the TLDs (chemical composition/density). The chemical composition and density of the selected TLDs were compiled and listed in Table I. All the selected TLDs are able to measure the doses from different nuclear radiations over wide ranges from μGy to KGy with few exceptions. Further, these TLDs can be re-used for 50/100 times after proper thermal annealing. Recently, Mann and Mann47 developed Py-MLBUF; an online-platform for computations of various gamma-rays shielding and sensing properties. It is a very user-friendly software package. The computations of various photon sensing and shielding properties were based on WinXCom database.20 Our present computational results for different radiation sensing properties of selected TLDs are in good agreement with the results generated with this online software.

**Theory**

Whenever nuclear radiation is incident on TLD crystal, it results in excitation of electron from valence band to conduction band. However, the presence of metastable levels in the imperfect crystal results in the trapping of these electrons creating electron or hole traps. In this way, the absorbed dose information is stored in TLD material for indefinite time period. When the TLD material is heated using external source, these electrons/holes become free and comes back to ground state by emitting photons specifically in visible region. There is only 1% chance of escaping electrons and holes from trapping centres over a period of few months. The intensity of released photon energy in visible region is proportional to the amount of energy absorbed from nuclear radiations. The intensity and energy of the emitted photons from TLD during thermal simulation is measured with a photomultiplier tube (PMT), which is converted and recorded in the form of electric pulse using appropriate electronic devices. The principle mechanism of the TLD is explained graphically in Fig. 3.

The comparative analysis of selected TLDs were investigated on the basis of following photon sensing parameters:

- Mass attenuation coefficient (MAC) measures the probability of photons interacted by means of absorbing or scattering with material. The ratio of linear attenuation coefficient and density is called MAC (cm² g⁻¹); which is a fundamental parameter to derive many other sensing parameters.48 WinXCom,20 a computer software provides partial attenuation coefficients owing to different photon interaction processes and their sum is MAC over wide range of energy from 1 keV to 100 GeV. This software computes MAC for TLDs using mixture rule; which is given by following formula: 

\[
(MAC)_{TLD} = \sum \frac{w_i}{MAC_i}
\]  

Where, \(w_i\) is weight fraction and \((MAC)_i\) is MAC of \(i\)th constituent element.

- Linear attenuation coefficient (LAC) is sum of partial attenuation coefficients for different partial photon interaction processes and measured in cm⁻¹. It depends on photon energy, density and composition of material.

\[
(LAC)_{TLD} = (MAC)_{TLD} (\rho)_{TLD}
\]
| Sr No. | TLD material | Dopant | Weight fraction | Density g/č.c. | Remarks | References |
|--------|--------------|--------|-----------------|---------------|---------|------------|
| 1      | LiF          | Sm<sup>3+</sup> | Li: 0.2667, F: 0.730, Sm: 0.003 | 2.64 | $Z_{\text{eff}}$ close to water/tissue | 29,30 |
| 2      | LiBaP<sub>2</sub>O<sub>7</sub> | Eu<sup>3+</sup> | Li: 0.217, O: 0.350, P: 0.19409, Ba: 0.430, Eu: 0.003 | 2.27 | Barium based | 31,32 |
| 3      | CaCO<sub>3</sub> | Eu<sup>3+</sup> | C: 0.119, O: 0.475, Ca: 0.397, Eu: 0.008 | 2.71 | Calcium based | 33,34 |
| 4      | CaSO<sub>4</sub> | Dy<sup>3+</sup> | O: 0.468, S: 0.234, Ca: 0.293, Dy: 0.003 | 2.32 | $Z_{\text{eff}}$ close to bone | 34,35 |
| 5      | SrSO<sub>4</sub> | Sm<sup>3+</sup> | O: 0.348, S: 0.174, Sr: 0.476, Sm: 0.0005 | 3.96 | Strontium based | 34,36 |
| 6      | BaSO<sub>4</sub> | Eu<sup>3+</sup> | O: 0.274, S: 0.137, Ba: 0.588, Eu: 0.0002 | 4.5 | Barium based | 38,39 |
| 7      | Li<sub>2</sub>B<sub>4</sub>O<sub>7</sub> | Dy<sup>3+</sup> | Li: 0.820, B: 0.255, O: 0.661, Dy: 0.001 | 1.29 | Lower density, $Z_{\text{eff}}$ close to tissue | 40,41 |
| 8      | MgB<sub>2</sub>O<sub>4</sub> | Gd<sup>3+</sup> | B: 0.240, O: 0.622, Mg: 0.135, Gd: 0.002 | 2.42 | Magnesium based, $Z_{\text{eff}}$ close to tissue | 42,43 |
| 9      | Al<sub>2</sub>O<sub>3</sub> | Gd | O: 0.470, Al: 0.529, Gd: 0.002 | 3.85 | Aluminium based | 44,45 |
| 10     | MgAl<sub>2</sub>O<sub>4</sub> | Ce<sup>3+</sup> | O: 0.449, Mg: 0.170, Al: 0.378, Ce: 0.001 | 3.65 | Aluminium based | 46 |
| 11     | LiCaAlF<sub>6</sub> | Eu<sup>3+</sup> | Li: 0.033, F: 0.641, Al: 0.100, Ca: 0.193, Eu: 0.001 | 2.98 | Gamma-neutron dosimetry and photonic applications | 7 |
| 12     | C<sub>2</sub>H<sub>4</sub>No<sub>2</sub> | — | H: 0.079, C: 0.404, N: 0.157, O: 0.359 | 1.42 | Organic | 34 |
| 13     | C<sub>3</sub>H<sub>2</sub>NO<sub>2</sub> | — | H: 0.064, C: 0.677, O: 0.257 | 1.36 | Organic | 34 |
| 14     | C<sub>4</sub>H<sub>2</sub>NO<sub>2</sub> | — | H: 0.03, C: 0.188, O: 0.250, Ba: 0.537 | 2.46 | Organic | 34 |
Mean free path (mfp) is the average distance traveled by incident photon beam between two successive collisions. Mean free path is the thickness of the material that attenuates 63% of photon intensity after travelling through an absorber. \[ \text{mfp} = \frac{1}{(LAC)_{TLD}} \]  

Half value layer (HVL) is the thickness of absorber that attenuates 50% of incident beam and expressed in cm. HVL can be expressed in terms of mfp after multiplying with the factor of log 2. \[ \text{HVL} = \frac{0.693}{(LAC)_{TLD}} \]  

Tenth value layer (TVL) is thickness of absorber that reduces the intensity of incoming gamma rays or photon beam to \( \frac{1}{10} \) (that is 90%). \[ \text{TVL} = \frac{2.303}{(LAC)_{TLD}} \]  

Effective atomic number (EAN) is a real number similar to atomic number of an element which helps in visualizing the photon interaction with compounds/mixtures. The ratio of an electron cross section to an atomic cross section is EAN and it is a dimensionless quantity. \[ \text{EAN} = \frac{\sigma_a}{\sigma_e} \]  

Where \[ \sigma_a = \frac{1}{N_A} \sum_i n_i (MAC)_{TLD} \sum_i n_i A_i \]  

and \[ \sigma_e = \frac{1}{N_A} \sum_i \frac{f_i A_i}{Z_i} (MAC)_i \]  

Effective Electron Number (EEN) represents the effective number \( Z \) of electrons present in the material of mass 1 g for interaction with incident photons and it is measured in number of electrons per gram. \[ \text{EEN} = \frac{(MAC)_{TLD}}{\sigma_e} \]  

Buildup factor is a correction term introduced in Lambert Beer’s law for extending the validity in conditions of multi-energetic source, beam divergence, and broad geometry. There are different formulations and codes for evaluation of it viz. Taylors method, invariant embedding method, GP fitting method, MCNP code etc. Both exposure buildup factor (EBF) and energy absorption buildup factor (EABF) were computed using GP fitting parameters \( (b, c, a, X_k \text{ and } d) \) provided by ANS/ANSI 6.4.3. The values of GP fitting parameters were provided as supplementary data. \[ B(E, x) = 1 + \frac{b - 1}{K - 1} (K^x - 1) \text{ for } K \neq 1 \]  

\[ B(E, x) = 1 + x (b - 1) \text{ for } K = 1 \]  

Where \[ K(E, x) = cx^2 + d \frac{\tan h(x/X_k - 2) - \tan h(-2)}{1 - \tan h(-2)} \]  

Results and Discussion  

Mass attenuation coefficient (MAC).—The MAC values for the selected TLD samples have been obtained from WinXCom computer software for wide photon energy range from 1 keV to 100 GeV. The variation of MAC for all selected TLD materials with energy has been shown in Fig. 4. MAC follows the trend of photon interaction mechanism; photoelectric effect (P.E.) dominates for low energies below 300 keV, Compton scattering (C.S.) effect dominates for intermediate energies between few hundred keV to few MeV, pair production (P.P.) effect initiates from...
different constituent elements have been listed in Table II. The initiating region lies in between 30 keV and 10 MeV for low-Z TLDs. The energies corresponding to absorption edges for elements such as Ba and Cd in low energy region as shown in Fig. 4a. Further, for such low-Z TLDs, Compton dominating region lies in between 30 keV to 10 MeV energy range. On the other hand, LiBa2O2:Eu3+ and SrSO4:Sm manifest highest value for MAC; whereas TLD materials having majority of lower Z constituent elements like Li2B4O7:Dy3+ and C3H7NO2, C7H8O2 exhibits lower values of MAC.

Linear attenuation coefficient (LAC).—Linear attenuation coefficient is directly related with MAC as expressed in Eq. 2. Hence, the variation of LAC with energy for the selected TLDs (as shown in Fig. 5) can be explained on similar basis as discussed above for MAC.

This parameter helps to further compute thickness normalizing parameters (TNPs) in terms of photon interaction mechanisms viz. mfp, HVL and TVL; which are of utmost importance in practical experimental work. These parameters helps in comparing different types of materials on the basis of their attenuation properties and independent of thickness values.

Mean free path (mfp).—Mean free path visualises an inverse relation with LAC as well as MAC. Figure 6 shows variation of mfp values with reference to incident photon energy for selected TLDs. The variation in mfp can be explained on the basis of three different energy regions (P.E., C.S. and P.P. dominant regions) in a similar way as discussed in previous section for MAC. In P.E. dominance region, values of mfp abruptly increases with increase in incident energy. In case of low-Z TLDs, the P.E. region dominate up to 30 keV energy value and do not show any abrupt variation due to the presence of absorption edges of constituent elements as shown in Fig. 6a. Whereas for high-Z TLDs, P.E. dominating region lies below 300 keV energy value and also depict sharp peaks due to absorption edges of constituent elements as shown in Fig. 6b. Further, the significant difference can be observed in mfp values of selected TLDs due to chemical composition in this P.E. dominant region. In P.E. dominant region, the mfp values for the selected TLDs lie in between 10−4 to 5 cm.

On conception of C.S. dominant region, the mfp parameter increases slowly with the increase in energy for all selected TLDs, but the dominance energy interval may vary according to difference in Z (high or low) of constituent elements for selected TLDs. The dominance energy range for C.S. region lies between 30 keV–10 MeV for low-Z TLDs and between 300 keV–5 MeV for high-Z TLDs. In C.S. dominant region, the mfp values for the selected TLDs shows less variation and lies in between 1 to 30 cm.

Above 10 MeV for low-Z TLDs and above 5 MeV for high-Z TLDs, P.P. region starts dominating. The mfp values for all TLDs decreases slightly and becomes constant above 400 MeV. Further, the significant difference can be observed in mfp values of selected TLDs due to chemical composition in this P.P. dominant region. Moreover, the variation of mean free path with energy for the present TLDs is in a good agreement with the findings of Issa et al.51

For a better sensing material, the TLDs must possesses minimum values for mfp. CdSO4:Dy, BaSO4:Eu and SrSO4:Sm (high-Z TLDs) shows lower mfp values and hence, offers better sensing properties as compared to other selected TLDs.
Half value layer (HVL) & tenth value layer (TVL).—These parameters, HVL and TVL are extremely favourable factors for exploring the gamma ray sensing parameters and for judgement of the gamma photons penetrating capability inside the material. These parameters along with mfp are collectively known as thickness normalizing parameters (TNPs). The conversion factors among different TNPs can be visualized from Eqs. 3–5. Figures 7–8 depict the variation of HVL and TVL parameters with energy for selected TLDs, respectively. The observation of these parameters has also been discussed on the similar basis of three photon interaction dominant processes.

In lower energy/P.E. dominant region, the variation of TNPs is most significant with energy alteration. The dominance energy range for P.E. region is up to 30 keV for low-Z TLDs (Figs. 7a–8a) and below 300 keV for high-Z TLDs (Figs. 7b–8b). As discussed above, the absorption edges do not show abrupt variation in low energy region for low-Z TLDs. For low-Z TLD, the HVL values lies between $10^{-4}$ to 1 cm ($10^{-4}$ to 10 cm for TVL). Whereas, for high-Z TLDs, the HVL values lies between $10^{-4}$ to 10 cm ($10^{-4}$ to 10 cm for TVL). In intermediate energy/CS dominant region, the variation of TNPs shows independent behaviour from chemical composition of constituent element (either heavy or low elements) and predicated similar values for all selected TLDs. The C.S. dominance energy region lies in between 30 keV to 10 MeV for Low-Z TLDs (300 keV–5 MeV for high-Z TLDs). HVL values lie between 1 to 10 cm (10 to 80 cm for TVL) for low—Z TLDs as well as high - Z TLDs.

Table II. Absorption edges of the constituent elements.

| Element (Z) | Energy corresponding to different absorption edges (keV) |
|------------|----------------------------------------------------------|
|            | K | L₁ | L₂ | L₃ | M₁ | M₂ | M₃ | M₄ | M₅ |
| Mg (12)    | 1.30 | — | — | — | — | — | — | — | — |
| Al (13)    | 1.56 | — | — | — | — | — | — | — | — |
| P (15)     | 2.14 | — | — | — | — | — | — | — | — |
| S (16)     | 2.47 | — | — | — | — | — | — | — | — |
| Ca (20)    | 4.04 | — | — | — | — | — | — | — | — |
| Sr (38)    | 16.10 | 2.22 | 2.01 | 1.94 | — | — | — | — | — |
| Cd (48)    | 26.71 | 4.02 | 3.73 | 3.54 | — | — | — | — | — |
| Ba (56)    | 37.40 | 5.99 | 5.62 | 5.25 | 1.29 | 1.14 | 1.06 | — | — |
| Sm (62)    | 46.80 | 7.74 | 7.31 | 6.72 | 1.72 | 1.54 | 1.42 | 1.11 | 1.08 |
| Eu (63)    | 48.50 | 8.05 | 7.62 | 6.98 | 1.8 | 1.61 | 1.48 | 1.16 | 1.13 |
| Gd (64)    | 50.20 | 8.38 | 7.93 | 7.24 | 1.88 | 1.69 | 1.54 | 1.22 | 1.19 |
| Tb (65)    | 52.00 | 8.71 | 8.25 | 7.51 | 1.97 | 1.77 | 1.61 | 1.28 | 1.24 |
| Dy (66)    | 53.79 | 9.05 | 8.58 | 7.79 | 2.05 | 1.84 | 1.68 | 1.33 | 1.29 |

Figure 5. Variation of LAC with energy for selected TLDs.

Figure 6. Variation of mfp with energy for (a) Low-Z TLDs, (b) High-Z TLDs and (c) All selected TLDs.
energy for the present TLDs is in good agreement with the findings of Tekin et al.\textsuperscript{52}

Lower TNPs signifies minimum thickness is effective for interaction and it will also lead to compactness of the material. Hence, for better sensing materials, the minimum values of TNP’s are required. Li$_2$B$_4$O$_7$: Dy, C$_7$H$_8$O$_2$ (low-Z TLDs) showed maximum and CdSO$_4$:Dy, BaSO$_4$:Eu and SrSO$_4$:Sm (high-Z TLDs) depict minimum TNP values. Therefore, it is clearly visualized that for sensing purpose, the High-Z TLDs possess good results than low-Z TLDs.

**Effective atomic number (EAN).**—Effective atomic number is a number that helps in visualizing the complexity of photon interaction with compounds or mixtures on Z scale at a particular photon energy. In pure element system, single number provides the whole information about atomic number but, in mixtures and compounds; the number of elements are present which make the system complicated. EAN can be calculated for mixtures and compounds using eqn (6).

The variation of EAN with energy for selected TLD materials has been shown in Fig. 9. EAN values for all the selected TLDs lie in between the lowest and highest atomic number of the constituent elements. Further, the variation of EAN with energy is minimum for those TLDs (C$_3$H$_7$NO$_2$, C$_7$H$_8$O$_2$) in which the variation in atomic number of constituent elements (1H, 6C, 7N, 8O) is less. Whereas, the variation of EAN with energy is maximum for those TLDs (BaSO$_4$: Eu, CdSO$_4$:Dy) in which the variation in atomic number of constituent elements (8O, 16S, 48Cd, 56Ba) is high. The variation in EAN has been observed whenever there is either a shift of dominance from one process to another or due to the absorption edges (as listed in Table II). The maximum values of EAN for different TLD materials has been observed in lower energy region/P.E. dominance region. The minimum value of EAN were observed for TLDs in intermediate energy/C.S. dominance region. The intermediate EAN values were observed for TLD materials in higher energy/P.P. dominant region. Moreover, the variation of EAN values with energy for the present TLDs is in good agreement with the findings of Gowda et al.\textsuperscript{22} and Manohara et al.\textsuperscript{23}

Among the selected TLDs, maximum EAN values were observed for BaSO$_4$:Eu$^{3+}$ and minimum EAN value were observed for C$_6$H$_4$BaO$_4$ TLD materials. Maximum EAN values signify better probability for photon absorption processes due to their strong dependence of cross-section on it. However, while choosing better TLD material; emphasis is given on other properties as well like its uniformity, equivalence with biological materials etc.

EAN values for some TLD materials viz. C$_3$H$_7$NO$_2$, C$_7$H$_8$O$_2$ and MgB$_4$O$_7$:Gd$^{3+}$ remain almost constant in the wide energy region from 1 keV to 100 GeV; which is one of the important requirement of an ideal dosimeter. Further, EAN values for MgB$_4$O$_7$:Gd$^{3+}$ remains nearly equal to 7.4 which matches well with most of the biological samples.
Effective electron number (EEN).—The effective electron number also known as electron density provides information about number of electrons present per unit mass in the material. Electron density parameter strongly depends on mass attenuation coefficient and effective atomic number (upon electronic cross-section $\sigma_e$) as described in Eq. 9. The variation of electron density with energy for selected TLDs observed to display attractive behaviour as shown in Fig. 10. Below 40 keV, random variation in EEN with energy has been observed for almost all TLDs due to absorption edges of different constituent elements present in them. In the limited energy region of 40 keV–300 keV, the value of EEN parameter decreases with increase in incident photon energy for the selected TLDs. In the extended energy limit of 300 keV–5 MeV, the value of EEN parameter becomes almost constant irrespective of change in incident photon energy as well as chemical composition for the selected TLDs. Beyond 5 MeV, EEN values increases with the increase in photon energy and gets saturated above 100 MeV for all TLDs. Moreover, the variation of EEN values with energy for the present TLDs is in good agreement with the findings of Un and Sahin53 and Manohara et al.23 This variation in EEN value with energy follows the similar trend as observed for MAC (Fig. 4) and for EAN (Fig. 8).

Buildup factor (B).—Buildup factor classified into two aspects; energy absorption buildup factor (EABF) and exposure buildup factor (EBF). Figure 11 showed the variation of EABF with incident photon energy (0.015–15 MeV) for low-Z and high-Z TLDs at 1, 5 and 10 mfp. It has observed that EABF values are small in lower and higher region, in contradiction of intermediate region. So, the explanation of EABF is based on three dominant photon interaction processes viz. P.E. (at lower energy region), C.S. (at intermediate energy region) and P.P. (at higher energy region). At 1 mfp, EABF values for low-Z TLDs lie in between 1–6; whereas for high-Z TLDs, its value lie in between 1–3. EABF for low-Z TLD attains a maximum value of 5.5; whereas for high-Z TLDs, it attains a maximum value of 2.9.

At 5 mfp, EABF values for low-Z TLDs lie in between 1–85; whereas for high-Z TLDs, EABF values lie in between 1–12. EABF for low-Z TLD attains a maximum value of 82; whereas for high-Z TLDs, it attains a maximum value of 11.

With the further increase in penetration depth (at 10 mfp), EABF values of low-Z TLD lie in between 1–600; whereas its value for high-Z TLDs, EABF lie in between 1–$10^6$. Further, for all selected low-Z TLDs, EABF values increase with energy, attains a maximum values in the region of 40 keV to 100 keV and thereafter decrease with the decrease in energy. However, for all selected high-Z TLDs, EABF increases and attains first maxima at 30 keV due to absorption edge of constituent elements and second maxima at 400 keV (except for SrSO4:Sm, which possess least $Z_{eff}$ among high Z TLDs). Moreover, EABF values observed for low –Z TLDs possess higher values as compared to high-Z TLDs at lower penetration depths from 1 to 10 mfp. Among the selected low Z TLDs, organic TLDs (C7H8O2 and C3H7NO2 having least $Z_{eff}$) possess maximum EABF values in the entire energy region. The mechanism behind the increased EABF values in intermediate energy region can be explained on the basis of dominance of C.S. photon interaction process; in which the energy of incident photon only degrades and do not get completely absorbed (as in lower and higher energies due to P.E. and P.P., respectively). As a result of it, the photons may aggregate and shows large EABF values.

At 20 mfp, EABF values for low-Z TLDs lie in between 1–4000; whereas for high-Z TLDs, EABF values lie in between 1–$2 \times 10^6$. EABF for low-Z TLD attains a maximum value of 4000; whereas for high-Z T

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**Figure 9.** Variation of EAN with energy for (a) Low-Z TLDs and (b) High-Z TLDs respectively.

**Figure 10.** Variation of EEN with energy for selected TLDs.
high-Z TLDs, it attains a maximum value of 90 due to C.S. (excluding the peak due to absorption edge of the constituent elements).

At 30 mfp, EABF values for low-Z TLDs lie in between $1 \times 10^4$; whereas for high-Z TLDs, EABF values lie in between $1 \times 10^{11}$. EABF for low-Z TLD attains a maximum value of $9 \times 10^4$; whereas for high-Z TLDs, it attains a maximum value of $10^3$.

With the further increase in penetration depth (at 40 mfp), EABF values for low-Z TLDs lie in between $1\times 10^5$; whereas its value for high-Z TLDs, EABF lie in between $1 \times 10^{15}$. EABF for low-Z TLD attains a maximum value of $9 \times 10^5$; whereas for high-Z TLDs, it attains a maximum value of $10^4$.

It has also been observed in Figs. 11 and 12 that at lower penetration depths (below 10 mfp) and lower energies (below 3 MeV), EABF values are inversely proportional to effective/equivalent atomic number of TLDs. Whereas at higher penetration depths (above 10 mfp) and also at higher energy above 3 MeV, the inverse behaviour had been predicted in EABF values in P.P.

**Figure 11.** Variation of EABF with energy for low-Z and high-Z TLDs at penetration depths of 1 mfp, 5 mfp and 10 mfp values.
dominant region (or higher energy region), EABF values are directly proportional to effective/equivalent atomic number of TLDs. It can be explained on the basis that at higher penetration depths (mfp) results in higher number of scattering centres and at higher energies above 3 MeV, P.P. results in creation of an electron-positron pair. In the sufficiently thick medium, the newly created charged particles can easily transfer their energy to the atoms of TLDs and after coming to rest can further undergo annihilation process. This results in elimination of charged particles with the creation of two photons.

Hence, the higher energy region of photon absorption dominance at large penetration depths get converted into photon buildup region; which results in increased EABF values.

Figure 13 showed the variation of EBF with incident photon energy (0.015–15 MeV) for low-Z and high-Z TLDs at 1, 5 and 10 mfp. At 1 mfp, EBF values for low-Z TLDs lie in between 1–7.5; whereas for high-Z TLDs, EBF values lie in between 1–4. EBF for low-Z TLD attains a maximum value of 7; whereas for high-Z TLDs, it attains a maximum value of 3.8 (with an exception at lower...
energies), otherwise the maximum value is 1.7 (in C.S. region or intermediate dominant energy region). At 5 mfp, EBF values for low-Z TLDs lie in between 1–140; whereas for high-Z TLDs, EBF values lie in between 1–40. EBF for low-Z TLD attains a maximum value of 130; whereas for high-Z TLDs, it attains a maximum value of 8. With the further increase in penetration depth (at 10 mfp), value of EBF for low-Z TLDs lie in between 1–10^3; whereas for high-Z TLDs, EBF values lie in between 1–10^3. EBF for low-Z TLD attains a maximum value of 950; whereas for high-Z TLDs, it attains a maximum value of 20. However, for all selected high-Z TLDs, EBF increases and attains first maxima at 30 keV due to absorption edge of constituent elements and second maxima at 80 keV (except for SrSO\textsubscript{4}:Sm, which possess least Z\textsubscript{eff} among high Z TLDs).

Figure 14 showed the variation of EBF with incident photon energy (0.015–15 MeV) for low-Z and high-Z TLDs at 20, 30 and 40 mfp. The explanation of EBF parameter is based on three
dominant photon interaction processes viz. P.E. (at lower energy region), C.S. (at intermediate energy region) and P.P. (at higher energy region). At 20 mfp, EBF values for low-Z TLDs lie in between $1 \times 10^4$; whereas for high-Z TLDs, EBF values lie in between $1 \times 10^5$. EBF for low-Z TLD attains a maximum value of $10^4$; whereas for high-Z TLDs, it attains a maximum value of $2 \times 10^5$ (with an exception at lower energies), otherwise the maximum value is 200. At 30 mfp, EBF values for low-Z TLDs lie in between $1 \times 4 \times 10^4$; whereas for high-Z TLDs, EBF values lie in between $1 \times 10^5$. EBF for low-Z TLD attains a maximum value of $4 \times 10^5$; whereas for high-Z TLDs, it attains a maximum value of $10^5$. With the further increase in penetration depth (at 40 mfp), EBF value for low-Z TLDs lie in between $1 \times 10^5$; whereas for high-Z TLDs, EBF values lie in between $1 \times 10^1$. EBF for low-Z TLD attains a maximum value of $2 \times 10^5$; whereas for high-Z TLDs, it attains a maximum value of $2 \times 10^3$. Moreover, the variation of buildup factors values with energy for
the present TLDs is in good agreement with the findings of Singh et al. and Singh et al.

Conclusions
From the present investigation on photon sensing parameters of selected TLDs, following conclusions can be drawn:

- For better sensing, higher density value is necessary for TLD material. Among the selected TLDs, CdSO₄: Sm³⁺ offers highest density whereas minimum density is offered by Li₂B₂O₅: Dy³⁺.
- All photon sensing parameters viz. MAC, LAC, mpf, HVL, TLV, EAN, EEN, EBF and EABF for selected TLDs strongly depends upon incident energy and chemical composition in lower and higher energy regions.
- The random variation of sensing parameters in lower energy due to absorption edges of constituent elements made the study more interesting.
- The buildup factors (EABF and EBF) possess maximum values in intermediate region where scattering process is dominant; minimum in lower and higher energy regions where photon absorption processes are dominant.
- The EABF and EBF increases with an increase in penetration depth of TLDs.
- TLDs must possess maximum values for MAC, EAN and EEN; whereas minimum values are required for mpf, HVL, TLV, EBF and EABF for better sensing results. Among the selected TLDs, BaSO₄: Eu³⁺ offers best results.
- Moreover, constancy of sensing parameters over wide energy region is also required. Among the selected TLDs, MgB₂O₇: Gd³⁺ offers EAN value close to tissue and almost constant behaviour for selected TLDs, following conclusions can be drawn:
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