7.0 DOBIMETRIC AND RADIATION MEASURING MATERIALS

The radiation is measured by different types of detecting materials. The interaction of gamma-rays with detectors and dosimeters is essential for studying the characteristics of the detecting medium and its applications. The dosimetric materials are chosen which show the radiation interaction properties similar to the human body and tissues. In this chapter, gamma-ray interactions with dosimetric and radiation measuring materials have been discussed.

7.1 OPTICALLY STIMULATED LUMINESCENT DOSIMETERS

7.1.1 CALCULATION DETAILS

To determine the photon buildup factors for optically stimulated luminescent (OSL) dosimeters, we have considered $\text{Al}_2\text{O}_3$, BeO, MgO, NaMgF$_3$, Mg$_2$SiO$_4$, LiMgPO$_4$. The exposure buildup factors, EBF, energy absorption buildup factors, EABF are calculated using the above eqs (4.14)-(4.16). The effective atomic numbers and air-kerma are calculated using eqs (4.24) and (4.29), respectively.

Similar to the above, the effective atomic numbers for OSL dosimeters are calculated, and are shown in figure 7.1.1. The EABF and EBF for the OSL dosimeters are computed using G-P fitting method for photon energy in the range 0.015-15 MeV. The variation of EABF for the OSL dosimeters with photon energy at penetration depths 5, 10, 20, 40 mfp is shown in figures 7.1.2(a)-(b). The variation of EBF for the OSL dosimeters with penetration depths at photon energies 0.015, 0.15, 1.5 and 15 MeV is shown in figures 7.1.3 (a)-(b). The differences between EBF and EABF for Al$_2$O$_3$ and BeO are shown in figures 7.1.4(a)-(b) and the air-kermas for the dosimeters are shown in figure 7.1.5. The EABF and EBF of the OSL dosimeters have been reported by Singh and Badiger$^{190}$.

![Figure 7.1.1: Effective atomic numbers for optically stimulated luminescent dosimeters, adipose tissue, breast, water and PMMA](image-url)
Variation of effective atomic numbers for OSL dosimeters for photon energy in the range 1 keV-15 MeV is shown in the figure 7.1.1. In the figure 7.1.1, effective atomic numbers for water, poly-methyl methacrylate (PMMA) phantom, adipose tissue and breast (standard body tissues given in ICRU-44\(^{78}\)) are also plotted. The effective atomic numbers for water and PMMA phantom are found in the range from 3.34 to 7.99. The effective atomic numbers for BeO are found to be the lowest among the selected OSL dosimeters, which are comparable with water and PMMA in photoelectric absorption region.

It is observed that the effective atomic numbers for LiMgPO\(_4\) and Li\(_2\)Al\(_2\)O\(_4\) are the highest in photoelectric absorption region whereas lower than remaining other OSL dosimeters in the Compton scattering region. The effective atomic numbers for LiMgPO\(_4\) and Li\(_2\)Al\(_2\)O\(_4\) gradually become equal to Al\(_2\)O\(_3\), MgO, NaMgF\(_3\) and Mg\(_2\)SiO\(_4\) in pair production region. The effective atomic numbers for the OSL dosimeters in Compton scattering region (>100 keV) are found in the range 10.16–10.29, 6.04–6.25, 10.10–10.20, 10.04–10.08, 10.16–10.28, 9.14–9.49 and 9.26–9.73 for Al\(_2\)O\(_3\), BeO, MgO, NaMgF\(_3\), Mg\(_2\)SiO\(_4\), LiMgPO\(_4\) and Li\(_2\)Al\(_2\)O\(_4\), respectively. The BeO is found to be the most promising OSL dosimeter as effective atomic numbers are comparable with human body tissues, water and PMMA phantom.
Figure 7.1.2b: Energy absorption buildup factors for optically stimulated luminescent dosimeters versus photon energy at penetration depths 20 and 40 mfp

The EABF and EBF for the OSL dosimeters are found to be maximum in the intermediate energy region whereas minimum in low- and high-energies. The variation trend of the buildup factors is observed similar up to photon energy of 3 MeV. The variation of EABF and EBF can be explained by partial photon interaction processes as the above. The EABF and EBF values of the BeO are found the highest among the selected OSL dosimeters. The EABF of the OSL dosimeters are found to be in the range 1.09-65.16, 1.13-349.16, 1.16-2458.79 and 1.19-27830.70 at penetration depths 5, 10, 20 and 40 mfp, respectively. The EBF of the OSL dosimeters are found in the range of 1.10-73.60, 1.13-405.37, 1.16-2896.70 and 1.19-33339.65 at penetration depths 5, 10, 20 and 40 mfp, respectively.
The variation of EABF and EBF for the OSL dosimeters with penetration depths are very important in dosimetry where maximum dose is delivered inside the material. It is found to be that the EABF and EBF for the OSL dosimeters increase with the penetration depth initially and afterwards saturate in high-energy region. It is observed that the EABF and EBF for the BeO in energy region 0.015-15 MeV are the highest. It is to be noted that difference in buildup factors of OSL dosimeters increases with decrease in energy. The buildup factors for Li$_2$Al$_2$O$_4$ are observed the lowest in low and intermediate energy among all the OSL dosimeters. Other OSL dosimeters such as MgO, NaMgF$_3$, Mg$_2$SiO$_4$ and LiMgPO$_4$ show the buildup factors equivalent to Li$_2$Al$_2$O$_4$. Therefore, in low- energy region Li$_2$Al$_2$O$_4$ and BeO with the highest and the lowest $Z_{eq}$ are having the lowest and highest buildup factors, respectively.

The differences (%) between EABF and EBF for Al$_2$O$_3$ and BeO for photon energy in the range 0.015-15 MeV are shown in the figures 7.1.4 (a)-(b). The differences vary from 42.97 to 47.42. In case of Al$_2$O$_3$, the differences become negative in high energy region (>5 meV) whereas for the BeO it is intermediate- and high-energies.
Figure 7.1.3b: Exposure buildup factors for optically stimulated luminescent dosimeters versus penetration depths at photon energy 1.5 and 15 MeV.

Figure 7.1.4a: Difference (%) between EABF and EBF for Al₂O₃ versus photon energy at penetration depths 1, 5, 10, 20 and 40 mfp.
Figure 7.1.4b: Difference (%) between EABF and EBF for BeO versus photon energy at penetration depths 1, 5, 10, 20 and 40 mfp

Figure 7.1.5: Air-kerma of optically stimulated luminescent dosimeters versus photon energy

Variation of air-kerma for the OSL dosimeters for photon energy in the range 1 keV-15 MeV is shown in the figure 7.1.5. It is to be noted that the air-kermas for the BeO are the lowest in the entire energy region. The air-kermas for all the OSL dosimeters are in the range 0.62 to 3.78 for photon energy 1 to 100 keV. However, the air-kermas for BeO are 0.76-0 to 93 for energy region 1 to 100 keV and near to unity for energy in the range 100 keV-15 MeV. It is observed that the air-kermas for OSL dosimeters are independent upon chemical composition for photon energy in the range 100 keV-4 MeV.
7.2  GEL DOSIMETERS

7.2.1  CALCULATION DETAILS

To determine the photon buildup factors for gel dosimeters, we have selected sixteen gel dosimeters as given in Table 7.2.1. The EBF, EABF and air-kerma are calculated using the above eqs (4.14)-(4.16) and (4.29), respectively.

Similar to above, the EABF and EBF for the gel dosimeters are computed using G-P fitting method for photon energy in the range 0.015-15 MeV. The variations of EABF for gel dosimeters with photon energy at penetration depths 5, 10, 20, 40 mfp are shown in figures 7.2.1(a)-(b). The variations of EBF for the gel dosimeters with penetration depths at photon energies 0.015, 0.15, 1.5 and 15 MeV are shown in figures 7.2.2(a)-(b). The equivalencies of gel dosimeters with PMMA phantom and water are shown in figures 7.2.3(a)-(c). The air-kermas for the gel dosimeters are shown in figure 7.2.4. The photon buildup factors and air-kermas for the gel dosimeters have been reported by Singh and Badiger\textsuperscript{[191]}.  

7.2.2  RESULTS AND DISCUSSION

Variations of EABF for the gel dosimeters with photon energy at penetration depths 5, 10, 20 and 40 mfp are shown in the figures 7.2.1(a)-(b). The variations of EBF for the gel dosimeters with penetration depths at photon energies 0.015, 0.15, 1.5 and 15 MeV are shown in the figures 7.2.2(a)-(b). It is found to be EABF and EBF for the gel dosimeters are showing a similar trend up to photon energy 3 MeV similar as for the OSL, concretes and other mixtures and compounds. The variation of EABF and EBF for gel dosimeters can also be explained by partial photon interaction processes as the above.

It is also found to be that the EABF and EBF for BANG-1 are the highest whereas the lowest for Fricke. A very large difference in EABF and EBF observed below and above the photon energy 1.5 MeV, and become almost independent to energy for large penetration depths at 1.5 MeV. The reason is that Compton scattering interaction is less dominant as compared with pair production processes in high energy and $Z_{eq}$ for all the dosimeters are found constant (~6.5) except BANG-1 and Fricke.
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Table 7.2.1: Elemental compositions of gel dosimeters
Figure 7.2.1a: Energy absorption buildup factors versus photon energy for gel dosimeters at penetration depths 5 and 10 mfp

The EABF and EBF for the gel dosimeters increase with penetration depth initially and afterwards trend towards constant, except for the high energy photons (15 MeV). The EABF and EBF for the gel dosimeters are observed nearly linear with penetration depths at high energy (15 MeV). The maximum EABF and EBF for the gel dosimeters are due to low-Z (water, gelatin, BIS and acrylamide compositions) in BANG-1 which contains only H, C, N and O elements. However, Frické contains de-ionised water, ferrous ion, sulfuric acid, air and gel. The larger fractional compositions of sulfur and iron elements increase the \( Z_{eq} \) which result in reduction of the buildup factors for the Fricke. It is found to be that the difference between EABF and EBF for the gel dosimeters decrease with increase in the photon energy. At low energy (~0.15 MeV), the EABF and EBF for the gel dosimeters increase due to multiple scattering events.
The variation of air-kerma for the gel dosimeters is shown in the *figure 7.2.4* for photon energy in the range 1 keV-15 MeV. In general the air-kermas for the gel dosimeters are found to be unity (0.8<air-kerma<1.2) except for the PRESAGE. It is to be noted that the air-kerma variation for PRESAGE is having a sharp peak at 40 keV and minima at 15 keV. It is observed that the air-kermas are higher for Fricke and PRESAGE compared with the remaining dosimeters due to the presence of $^{32}$S, $^{35}$Cl, $^{35}$Br and $^{56}$Fe elements (see the Table 7.2.1).
Figure 7.2.2a: Exposure buildup factors versus penetration depths for gel dosimeters at photon energy 0.015 and 0.15MeV
Figure 7.2.2b: Exposure buildup factors versus penetration depths for gel dosimeters at photon energy 1.5 and 15 MeV
Figure 7.2.3a: Ratio of EABF of Fricke to water and PMMA phantom
Figure 7.2.3b: Ratio of EABF of BANG-1 to water and PMMA phantom
Figure 7.2.3c: Ratio of EABF of nPAG to water and PMMA phantom

Figure 7.2.4: Air-kerma versus photon energy for gel dosimeter
7.3 SOLID STATE NUCLEAR TRACK DETECTORS

7.3.1 CALCULATION DETAILS

To determine the photon buildup factors for solid state nuclear track detector (SSNTD), we have considered Apatite, Diopside, Merrillite, Phlogopite, Oligoclase, Titanite, Glass phosphate and CR-39. The EBF and EABF are calculated using the above eqs (4.14)-(4.16).

Similar to above, the EABF and EBF for the SSNTDs are computed using G-P fitting method for photon energy in the range 0.015-15 MeV. The variations of EABF and EBF for the SSNTDs with photon energy at penetration depths 5, 10, 20, 40 mfp are shown in figures 7.3.1 (a)-(b) and 7.3.2(a)-(b), respectively. The EABF and EBF for the solid state nuclear track detectors have been reported by Singh et al.[192].

7.3.2 RESULTS AND DISCUSSION

The variations of EABF and EBF for SSNTDs for photon energy in the range 0.015-15 MeV are shown in the figures 7.3.1(a)-(b) and 7.3.2(a)-(b). It is to be noted that the EABF and EBF for the SSNTDs are minimum for low-and high-energy photon whereas the highest in the intermediate-energy. This type of variation can be explained similar to the above different types of materials. The EABF_{max} for SSNTDs are found at energy 0.3, 0.2, 0.3, 0.2, 0.2, 0.4, 0.4 and 0.1 MeV for Apatite, Diopside, Merrillite, Phlogopite, Oligoclase, Titanite, Glass phosphate and CR-39, respectively. The analysis shows that the highest EABF and EBF are for CR-39 in low-and intermediate energy region below 3 MeV. The pattern of buildup factors becomes reverse in high energy region (>3MeV) which can be explained by chemical compositions of the detector materials.

Similar to other materials, the buildup factors for the SSNTDs increase with the penetration depths as shown for penetration depths 5, 10, 20 and 40 mfp in the figures 7.3.1(a)-(b) and 7.3.2(a)-(b). It can be seen that the buildup factors for the Glass phosphate are the lowest and the highest for CR-39 in low penetration depth up to 10 mfp. This can be explained by Z_{eq} of the SSNTDs for low energy photons. The small buildup factors are due to dominance of photoelectric effect which results in the complete removal of low energy photons thereby not allowing them to buildup in the medium. Thus, Glass phosphate (with the highest Z_{eq}) shows the lowest buildup factors.

The buildup factors for SSNTDs are found to be roughly constant (~unity) at 0.015 MeV photon energy which increase with the penetration depth. Analysis signifies that the buildup factors for CR-39 are the lowest at large penetration depths (>10 mfp) for photon energy beyond 3 MeV. This type of variation of buildup factors can be explained by chemical compositions and pair production similar to the above.
Figure 7.3.1a: Energy absorption buildup factors for solid state nuclear track detectors at penetration depths 5 and 10 mfp
Figure 7.3.1b: Energy absorption buildup factors for solid state nuclear track detectors at penetration depths 20 and 40 mfp
Figure 7.3.2a: Exposure buildup factors for solid state nuclear track detectors at penetration depths 5 and 10 mfp
Figure 7.3.2b: Exposure buildup factors for solid state nuclear track detectors at penetration depths 20 and 40 mfp
7.4 THERMOLUMINESCENT DOSIMETERS

7.4.1 CALCULATION DETAILS

To determine the photon buildup factors for sulfate based thermoluminescent dosimeters (TLDs), we have considered SrSO₄, BaSO₄, MgSO₄, MnSO₄, FeSO₄ and ZnSO₄. The EBF and EABF are calculated using the above eqs (4.14)-(4.16). The effective atomic numbers and air-kerma for the TLDs are calculated using eqs (4.22) and (4.29), respectively.

Similar to above, the EABF and EBF for the TLDs are computed using G-P fitting method for photon energy in the range 0.015-15 MeV. The effective atomic numbers for the TLDs with photon energy at penetration depths 5, 10, 20, 40 mfp are shown in figures 7.4.2 (a)-(b) and 7.4.3 (a)-(b), respectively. The air-kermas for the TLDs are shown in figure 7.4.4. The photon buildup factors for TLDs have been reported by Singh and Badiger[193].

7.4.2 RESULTS AND DISCUSSION

The variation of effective atomic numbers for the TLDs in the energy range 1 keV-15 MeV is shown in the figure 7.4.1. In the figure 7.1.1, effective atomic numbers of breast, cortical bone and soft tissues (as given in ICRU-44[78]) are also plotted. The effective atomic numbers for MgSO₄ are found to be the lowest which are slightly higher than cortical bone in Compton scattering region whereas lower than it in photoelectric absorption region. It observed that the effective atomic numbers for BaSO₄ are the highest in the entire photon energy region. The lowest effective atomic numbers for all the TLDs are observed at around 1 MeV energy. The variation of the effective atomic numbers can be explained using partial photon interaction processes. It is observed that the MgSO₄ is found to be the radiologically tissue equivalent material.

The variation of EABF and EBF for TLDs with photon energy at penetration depths 5, 10, 20 and 40 mfp are shown in the figures 7.4.2(a)-(b) and 7.4.3(a)-(b), respectively. The EABF and EBF for TLDs are found to be maximum in the intermediate photon energy region whereas minimum in low-and high-energies. The variation trend of the buildup factors is observed similar up to photon energy of 3 MeV. The variation of the EABF and EBF for the TLDs can be explained similar to above using chemical compositions and penetration depths. The EABF and EBF for MgSO₄ are found to be the highest below 3 MeV and the lowest above 3 MeV. At the same time the variation pattern for BaSO₄ is found in reverse order.

From the figures 7.4.2(a)-(b) and 7.4.3(a)-(b), it is to be noted that the EABF for the TLDs are higher than the EBF. There are two peaks in EABF and EBF for BaSO₄ at 40 keV and 60 keV energies. But the height of the peaks is larger for EBF than EABF. It is found that the EABF for the MgSO₄ is lesser than the BeO.
Figure 7.4.1: Effective atomic numbers for thermoluminescent dosimeters and some human organs

Figure 7.4.2a: Energy absorption buildup factors versus photon energy for thermoluminescent dosimeters at penetration depths 5 and 10 mfp
The variation of air-kerma for the TLDs for the photon energy range 1 keV-15 MeV is shown in the figure 7.4.4. It is to be noted that the air-kermas for MgSO₄ are the lowest among all the TLDs. It is also to be noted that the air-kermas for all the TLDs reach to near to unity at photon energy 1 MeV. The air-kermas for BaSO₄ reach up to 95.20 at the photon energy 50 keV. However, the air-kerma for MgSO₄ is 3.74 at same energy. It is observed that the air-kermas for TLDs are independent on photon energy in the range 1-3 MeV.
Figure 7.4.3a: Exposure buildup factors versus photon energy for thermoluminescent dosimeters at penetration depths 5 and 10 mfp
Figure 7.4.3b: Exposure buildup factors versus photon energy for thermoluminescent dosimeters at penetration depths 20 and 40 mfp

Figure 7.4.4: Air-kerma versus photon energy of thermoluminescent dosimeters
7.5 GAS BASED DETECTORS

7.5.1 CALCULATION DETAILS

To determine the photon interaction properties for gases, we have considered carbon dioxide, methane, acetylene, propane, butane and pentane. The \( \mu/p \), effective atomic numbers and electron densities for these gases are calculated using above eqs (4.5), (4.22) and (4.23), respectively.

Similar to above, the \( \mu/p \), effective atomic numbers and electron densities for the gases calculated and are shown in figures 7.5.1, 7.5.2 and 7.5.3, respectively. The gamma-rays interactions properties of these gases have been reported by Singh and Badiger\(^\text{[194]}\).

7.5.2 RESULTS AND DISCUSSION

The variation of \( \mu/p \) for the gases for photon energy in the range 1 keV-15 MeV is shown in the figure 7.5.1. From the figure 7.5.1, the variation of \( \mu/p \) can be explained by partial photon interaction parameters as the above. The atomic number of the constituent elements (carbon and hydrogen) for all the gases like CH\(_4\), C\(_2\)H\(_2\), C\(_3\)H\(_8\), C\(_4\)H\(_{10}\) and C\(_5\)H\(_{12}\) are same except CO\(_2\). Therefore, the \( \mu/p \) for the gases are almost same order in the photoelectric absorption region. In the intermediate energy region, the Compton scattering is dominant interaction and the cross-section is directly proportional to atomic number and inversely proportional to energy. Hence the \( \mu/p \) for all the gases reduces gradually in energy from 0.1 to 15 MeV.

The variation of effective atomic numbers for the gases in the energy range 1 keV-15 MeV is shown in the figure 7.5.2. The figure 7.5.2 shows that the effective atomic numbers for the gases are approximately constant in low-energy photon, reach minima in intermediate energy region. The effective atomic numbers for CO\(_2\) gas is comparatively high in all energies whereas minimum for methane. The effective atomic numbers for CO\(_2\) gas is more or less constant above 100 keV energy and doesn’t show any sharp reduction trend similar to the other gases. It is to be found that effective atomic numbers for CO\(_2\) are most appropriate as ICRU tissues (7 to 8). Other hydrocarbon gases show sharp reduction of effective atomic numbers at 10 keV which are far away from ICRU tissues. The effective atomic numbers for these gases also have been compared values with XmuDat program and found to be 7.58, 5.19, 5.74, 5.41, 5.43 and 5.45 for CO\(_2\), CH\(_4\), C\(_2\)H\(_2\), C\(_3\)H\(_8\), C\(_4\)H\(_{10}\) and C\(_5\)H\(_{12}\), respectively. Therefore, the CO\(_2\) gas is most suitable tissue equivalent gas for gamma-ray radiation detection.

The variation of effective electron densities for these gases with photon energy is linearly dependent on effective atomic number therefore it follows variation of the effective atomic numbers. The effective electron densities for these gases are shown in the figure 7.5.3 which shows that the effective electron densities for CO\(_2\) gas are approximately constant and lower as compared with the other gases. The effective electron densities for CH\(_4\), C\(_2\)H\(_2\), C\(_3\)H\(_8\), C\(_4\)H\(_{10}\) and C\(_5\)H\(_{12}\) are 11.15×10\(^{23}\)-7.93×10\(^{23}\), 5.53×10\(^{23}\)-4.99×10\(^{23}\), 8.95×10\(^{23}\)-7.00×10\(^{23}\), 8.68×10\(^{23}\)-8.24×10\(^{23}\) and 8.64×10\(^{23}\)-6.75×10\(^{23}\), respectively in photon energy in the range 1-10 keV. We also observe that the effective electron densities for all the gases gradually increase above 10 MeV photon energy. The effective electron densities for these gases using XmuDat program are found to be 3.55×10\(^{20}\), 2.50×10\(^{20}\), 3.52×10\(^{20}\), 1.63×10\(^{20}\), 8.78×10\(^{20}\) and 2.20×10\(^{23}\) for CO\(_2\), CH\(_4\), C\(_2\)H\(_2\), C\(_3\)H\(_8\), C\(_4\)H\(_{10}\) and C\(_5\)H\(_{12}\), respectively.

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Figure 7.5.1: Mass attenuation coefficients versus photon energy for gases

Figure 7.5.2: Effective atomic numbers versus photon energy for gases

Figure 7.5.3: Effective electron densities versus photon energy for gases