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Determination of Gamma-Ray Depth-Dose Distribution in a Polyethylene Sphere Phantom*

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Abstract

A result of the study to determine the depth-dose distribution along the central axis of a polyethylene sphere in diameter of 30cm is described.

Depth-dose distribution in the polyethylene sphere for broad beam of monoenergetic photons has been experimentally determined with thermoluminescent dosimeter as a cavity dosimeter. The conversion of dose absorbed in the LiF TLD to dose in the surrounding medium was carried out on the basis of Burlin's generalized cavity theory. Presented in graphical forms are the results obtained. The maximum absorbed doses in the sphere were observed at the depth of about 0.3cm and 0.5cm from the surface of the sphere for the gamma-rays of ^{137}Cs and ^{60}Co, respectively.

요 약

30cm 직경 포리에티렌 구체내의 길이에 따른 선량분포중 최대흡수선량인 흡수선량지수를 주어진 감마방사선장내에서 열형광선량계를 이용하여 결정하였다.

열형광선량계내의 흡수선량과 주위 매질내의 흡수선량간의 환산은 Burlin의 general cavity theory에 의거하였다. ^{60}Co과 ^{137}Cs에 의한 방사선장에서 구체내 최대흡수선량은 구체표면으로 부터 각각 0.5cm 및 0.3cm에 나타났으며 이 결과는 이론적으로 예상한 분포특성과 아주 근사하였다.

1. Introduction

The permissible levels for radiation protection are stated in terms of dose equivalent. Hence, this quantity, together with the underlying concept of absorbed dose, is of primary importance. However, the values of the dose equivalent in an organ can rarely be determined and must usually be derived from measurement of other quantities and at other locations. It is frequently necessary to specify radiation levels by means of a term that furnishes at least an approximate indication of the maximum absorbed dose that might be received if an individual were at some particular location.

In the environs of gamma or neutron sources, exposure or kerma determined at some point in free air can usually serve as an adequate basis for estimation of the maximum dose equivalent produced in the human body by indirectly ionizing radiations. However, these concepts are not applicable to

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directly ionizing radiations. On the other hand, the mean absorbed dose in some finite specified mass may be a useful index of the maximum absorbed dose in the human body at the same location, but the relation between the maximum and the mean absorbed dose depends upon the magnitude of the mass as well as upon the type of radiation encountered. Therefore, the mean absorbed dose in any particular mass cannot serve as an index of the maximum absorbed dose for all radiations.

To meet the need for the characterization of ambient radiation levels at any location for purposes of radiation protection, the quantities, absorbed dose index, D_I, and dose equivalent index, H_I, have been recently defined by ICRU[1]. The absorbed dose index, D_I, at a point is the maximum absorbed dose within a 30cm diameter sphere centered at this point and consisting of material equivalent to soft tissue with a density of 1 $g \cdot cm^{-3}$ and the dose equivalent index at a point is the maximum dose equivalent within the same as that of the absorbed dose index. Equivalence of the tissue is also defined by ICRU with the composition of 76.2% O, 11.1% C, 10.1% H and 2.6% N.

As a preliminary investigation for the determination of such indices an attempt was made for getting information of depth-dose distribution within the 30cm diameter polyethylene sphere since the depth-dose distribution drawn up in this work must be of primary importance in determining the indices. The depth-dose distribution in the sphere for normally incident broad beam of ^{60}Co and ^{137}Cs gamma rays were measured using a thermoluminescent dosimeter. The conversion of dose absorbed in the TLD to dose in the surrounding medium was carried out on the basis of Burlin's cavity theory.

2. Basic Theory of TLD Cavity Dosimetry

Measurement of the absorbed dose at a point of interest in a medium, particularly near the surface or an interface in ani nhomogeneous medium, is sometimes exceedingly difficult. Existing theories[2-3] of determining the absorbed dose in a medium using most standard measurement instruments such as ionization chamber, calorimeter and chemical dosimeter, have been elaborated for incident photons, with the entire dose assumed to come from the secondary electrons. In this case, the electron spectrum set up in the medium was assumed to be not modified by the presence of the gas in the cavity. In practice, the basic assumption noted above results in the cavity being limited to small dimensions especially for low energy photons.

In the present work, theoretical deduction of gamma-ray absorbed dose in a polyethylene sphere from TLD readings has been attempted, applying Ehrlich's approach[4] based on Burlin's generalized cavity theory[5] which permits its use with solid and liquid state dosimeters by means of the equation

$$f_z(T_o, \Delta) = \frac{(Z/A)_c}{(Z/A)_m}\left\{1+\frac{d}{T_o}\left[\int_{\Delta}^{T_o} R_m(T_o, T)\cdot\left(\frac{B_c(T)}{B_m(T)}-1\right)dT+\Delta\cdot R_m(T_o,\Delta)\left(\frac{B_c(\Delta)}{B_m(\Delta)}-1\right)\right]+(1-d)\left(\frac{(\mu_{en}/\rho)_c}{(\mu_{en}/\rho)_m}\cdot\frac{(Z/A)_m}{(Z/A)_c}-1\right)\right\} \quad \cdots\cdots 1)$$

where $f_z(T_o, \Delta)$ is the ratio of energy dissipation per gram of cavity gas to the energy dissipation per gram of wall material,

T_o is the initial energy of the electrons,

Z is the atomic number,

A is the atomic weight,

$R(T_o, T)$ is the ratio of the total electron flux to the primary electron flux

at an energy T when the initial energy of the electrons is T_o,

$B(T)$ is the stopping number of electrons of energy T,

Δ is the energy of an electron which will, on average, just cross the cavity,

$(\mu_{en}/\rho)_c$ and $(\mu_{en}/\rho)_m$ are the mass energy absorption coefficients of the cavity material and the medium, respectively, and d is a weighting factor which represents the fraction of the total electron energy produced in the cavity that escapes from the cavity, and $(1-d)$ the fraction of the electron energy absorbed in the cavity. A rough estimate of the relative contributions of the absorbed dose due to the electrons produced in the wall and those produced in the cavity should suffice for an estimate of the weighting factor, d. For this study, d was determined as

$$d=\int_o^g e^{-\beta x}\,dx \Big/ \int_o^g dx=(1-e^{-\beta g})/\beta g$$

and $$1-d=\int_o^g (1-e^{-\beta x})dx \Big/ \int_o^g dx$$
$$=(\beta g+e^{-\beta g}-1)/\beta g \qquad \cdots\cdots 2)$$

where β is effective mass absorption coefficient of the electron spectrum, and g is average path length of electrons crossing the cavity.

As Burlin did, Ehrlich assumed that the range of the Compton electrons produced by incident gamma-rays in the dosimeter is comparable to the TLD cavity dimension (our TLD is $3.2\times3.2\times0.9\text{mm}^3$), which means that the absorbed dose in the TLD cavity stems not only from the energy of the electrons produced in the cavity wall (polyethylene), but also from the electrons produced in the TLD cavity proper.

Under this condition, the absorbed dose in the TLD should lie between

$$D_{\text{TLD}}^{(1)}=D_{\text{Poly}}\cdot S_{\text{poly}}^{\text{TLD}} \qquad \cdots\cdots 3)$$

for cavity dimensions small compared to the range of the Compton electrons, and

$$D_{\text{TLD}}^{(2)}=D_{\text{Poly}}\cdot {}_{en}\mu_{\text{poly}}^{\text{TLD}} \qquad \cdots\cdots 4)$$

for cavity dimensions large compared to the electron range. Here, the μ represent relative energy absorption coefficents and the S, relative stopping power, all taken for estimated photon and electron energies at the position of the dosimeter cavity. D_{Poly}, the absorbed dose in the polyethylene layer surrounding the TLD cavity, is given by

$$D_{\text{Poly}}=0.869\cdot {}_{en}\mu_{\text{air}}^{\text{poly}}\cdot X\cdot 0.965 \qquad \cdots\cdots 5)$$

where 0.869 is the absorbed dose in air (in rads) per unit exposure (in R), and the factor 0.965 is a correction for the attenuation of the primary photons in the polyethylene, which experimentally found to be equal to $\exp(-\mu_{\text{poly}}\cdot t_{\text{poly}})$, μ_{poly} and t_{poly} being the attenuation coefficients for the incident photons and the wall thickness, respectively.

In line with Burlin's approach, D_{TLD} for incident gamma radiation best representing the actual exposure geometry was estimated as

$$D_{\text{TLD}}=d\,D_{\text{TLD}}^{(1)}+(1-d)\,D_{\text{TLD}}^{(2)} \qquad \cdots\cdots 6)$$

where d is the weighting factor given by Eq. 2. The estimate reported by others[6] yielded weighting factors of small TLD cavity for ^{60}Co and ^{137}Cs gamm-arays to be 0.311 and 0.157, respectively.

Having thus established absorbed dose in the TLD, the absorbed dose at the point of interest in the polyethylene, D_m in rad, is estimated from the following relation, assuming response of TLD over a wide range of energies of incident gamma-rays to be constant,

$$D_m=S_{\text{TLD}}^{m}\cdot D_{\text{TLD}} \qquad \cdots\cdots 7)$$

where S_{TLD}^{m} is in fact identical with the reciprocal of the S_m^{TLD}, which is a weighted average over the electron energy spectrum at

the position of the dosimeter. Calculation of S_{poly}^{TLD} was carried out using the formula[7]

$$\bar{S}_{poly}^{TLD}(E_o)=\frac{1}{\bar{S}_{TLD}^{Poly}(E_o)}=\frac{1}{E_o}\times\int_0^{E^o}\frac{(S/\rho)_{coll,\,TLD}}{(S/\rho)_{coll,\,Poly}}dE\cdot \quad \cdots\cdots 8)$$

Here $(S/\rho)_{coll.}$ indicates mass stopping power due to energy loss by collisions. The numerical integration was carried out using Simpson's rule, with relevant data from the ICRU Report[8]. Resulting values of S are

$\bar{S}_{poly}^{TLD}\simeq 1.142$ for ^{60}Co gamma-rays

and $\simeq 1.005$ for ^{137}Cs gamma-rays,

respectively.

In order to estimate the relative energy absorption coefficient, ${}_{en}\mu_{poly}^{TLD}$, it was necessary to calculate mass energy absorption coefficient, ${}_{en}\mu/\rho$, of LiF TLD, since the numerical data had not been available, while those for the polyethylene were appeared in the literatures[9]. For calculating $({}_{en}\mu/\rho)_{TLD}$, the following equation[10] was used.

$$\frac{{}_{en}\mu}{\rho}=\frac{\tau}{\rho}-\left(\frac{\tau^K}{\rho}\right)\cdot\left(\frac{F_K\bar{E}_K}{h\nu}\right)+\left(\frac{\sigma}{\rho}\right)f_c+\left(\frac{\kappa}{\rho}\right)f_\kappa \quad \cdots\cdots 9)$$

Here, $\tau-\tau^K\left(\frac{F_K\bar{E}_K}{h\nu}\right)$ is an approximation of photoelectric component of mass energy transfer coefficient, $(\tau/\rho)f_\tau^*$, based on the assumption of predominant ejection of electrons above K-edge, with F_K and $\bar{E}_K$ being fluorescence yield and average energy of fluorescence in the K-series, respectively. $\left(\frac{\sigma}{\rho}\right)f_c$ and $\left(\frac{\kappa}{\rho}\right)f_\kappa$ are Compton and pair-production components of the mass energy transfer coefficients, whereas f_c and f_κ are average functions of photon energy going into electronic collision loss by Compton scattering and into pair-production, respectively. The terms of $\frac{\tau^K}{\rho}$ and $\frac{\kappa}{\rho}$ are in practice minor enough to neglect in our calculation.

Compton cross section, ${}_e\sigma$, was calculated for ^{60}Co and ^{137}Cs gamma-rays using klein-Nishina formula[11],

$${}_e\sigma=2\pi r_0^2\left\{\frac{1+\alpha}{\alpha^2}\left[\frac{2(1+\alpha)}{1+2\alpha}-\frac{1}{\alpha}ln(1+2\alpha)\right]+\frac{1}{2\alpha}ln(1+2\alpha)-(1+2\alpha)-\frac{1+3}{(1+2\alpha)^2}\right\} \quad \cdots\cdots 10)$$

where r_0 is classical electron radius, e^2/mc^2, and $\alpha=\frac{h\nu}{mc^2}$. The numerical values obtained are

${}_e\sigma=1.887\times10^{-25}$cm^2/electron for ^{60}Co gamma-rays

and $=2.557\times10^{-25}$cm^2/electron for ^{137}Cs gamma-rays.

Resultant total mass attenuation coefficients, $\frac{\sigma}{\rho}$ ($\sigma={}_e\sigma\frac{\rho NZ}{A}$, where N is Avogadro's number) of LiF TLD for 1.25 MeV and 0.661 MeV gamma-rays are 4.872×10^{-2} cm^2/gm and 6.605×10^{-2} cm^2/gm, respectively. Density of the TLD was taken as 2.64gm/cm^3 [12]. Numerical values of f_c for the TLD were estimated as 0.467 and 0.381 for ^{60}Co and ^{137}Cs gamma-rays, respectively, by means of interpolation of the data given by R. T. Berger[10].

Calculation of τ was carried out using Gray's empirical equation[11]

$$\log\tau=\bar{3}.6505+1.0\log\lambda+0.480(\log\lambda)^2 \quad \cdots\cdots 11)$$

where τ is given in cm^{-1} and wavelength of the incident gamma-rays, λ, is in X-units (10^{-11}cm). Numerical values obtained are

$\frac{\tau_a}{\rho}=6.7503\times10^{-8}$ cm^2/gm for ^{60}Co gamma-rays

and,

$\frac{\tau_a}{\rho}=2.6173\times10^{-7}$ cm^2/gm for ^{137}Cs gamma-rays.

The mass energy absorption coefficients of the TLD for ^{60}Co and ^{137}Cs thus obtained are

$$\left[\frac{_{en}\mu}{\rho}\right]_{Co}=2.275\times10^{-2}\ cm^2/gm$$

and

$$\left[\frac{_{en}\mu}{\rho}\right]_{Cs}=2.514\times10^{-2}\ cm^2/gm,$$

respectively.

Resultant relative mass energy absorption coefficients, $_{en}\mu^{TLD}_{poly}$ for the two different gamma-rays in energy are

$$\left[_{en}\mu^{TLD}_{poly}\right]_{Co}=0.746$$

and

$$\left[_{en}\mu^{TLD}_{soly}\right]_{Cs}=0.752$$

With all the data obtained, the absorbed dose in the polyethylene sphere, D_m in Eq. 7, can be deduced as a linear function of exposure, X, observed by TLD in the medium at the position of the cavity. That is

$$\left.\begin{aligned}D_m&=0.732X\ \text{for}\ ^{60}Co\ \text{gamma-rays}\\&=0.755X\ \text{for}\ ^{137}Cs\ \text{gamma-rays}\end{aligned}\right\}\quad\cdots\cdots12)$$

These relationships are of practical use, if necessary, in computing the dose absorbed in the polyethylene sphere directly from exposure observed by TLD embedded in the sphere.

3. Experimental Apparatus and Procedures

The experimental arrangement for measuring the depth dose distribution in a given gamma-radiation field is shown in Fig. 1. The gamma-ray source used were 0.75 Ci ^{60}Co, and 4 Ci ^{137}Cs, respectively. A 30cm diameter polyethylene sphere employed in this work was one of the Bonner neutron spectrometer's assembly and consisted of material approximately equivalent to soft tissue with a density of around 1 g/cm^3. The sphere has a stepped opening which is going through the center and has three

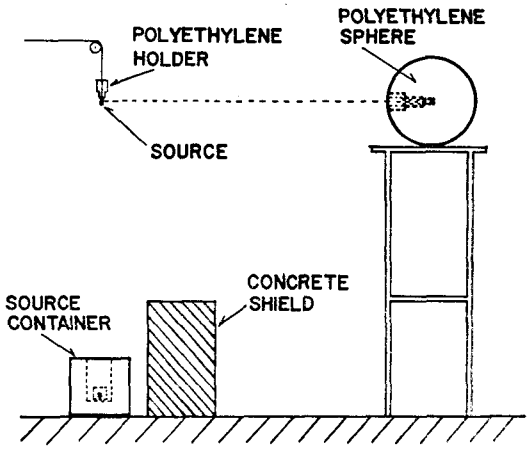

Fig. 1. Experimental Arrangement for Measuring the gamma-ray absorbed dose distribution in 30cm diameter polyethylene sphere.

different diameters of 14.3mm, 18.8mm and 51mm as shown in Fig. 2. The plug-in having

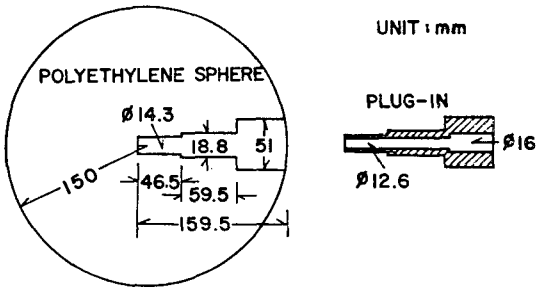

Fig. 2. Cross sectional view of 30cm dia. polyethylene sphere and plug-in.

two different opening along the central axis was fabricated so as to fit tightly to the stepped opening of the sphere and used varying the depth with piecewise polyethylene tablets and rods as an absorber. Some of the absorbers with thickness of 1mm to 100 mm are shown in Photo 1. Using these various absorber thickness, it was possible to vary the depth at which the detectors were placed in successive experimental runs. Fig. 3. shows the exploded view of the detector holder and the combined absorber assembly.

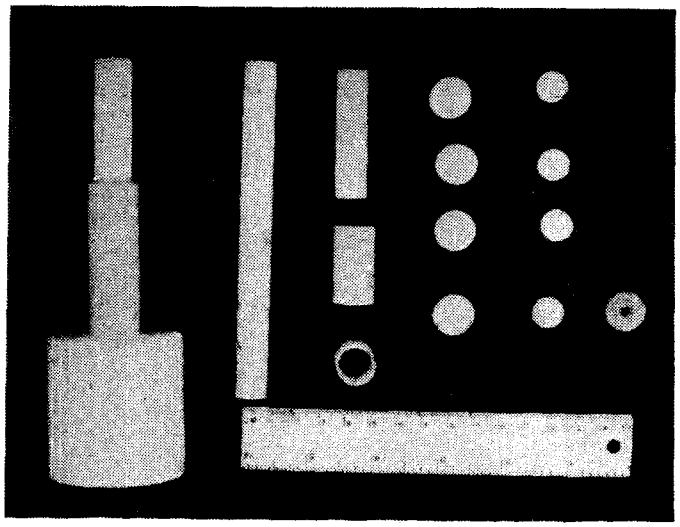

Photo 1. Piecewise polyethylene tablets and rods used for measuring the Depth-Dose distribution

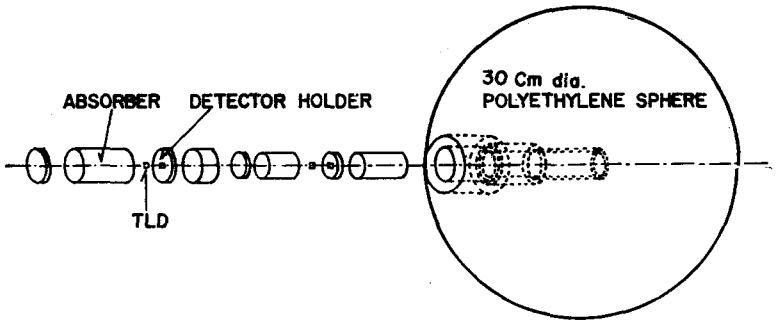

Fig. 3. Exploded view of detector holder and absorber assemblies.

The thickness of each absorber disk was determined with a measuring instrument having an expanded-scale optical readout.

The gamma-ray dosimeter used in this experiment is a extruded LiF TLD-700 obtained from Harshaw Chemical Co., whose dimensions are $1/8'' \times 1/8'' \times 0.035''$. As quoted by the producer, TLD-700 contains 99.993% ^{7}Li isotope. The physical and dosimetric characteristics of TLD-700 have well established and reported in many literatures[13-14].

The sensitivity of each dosimeter had been determined before the experiments were initiated, as small sensitivity changes of TLD frequently occur. Calibration of the detector was performed in both ^{60}Co and ^{137}Cs radiation fields. Electronic equilibrium was provided by placing additional polyethylene plates of 3mm in thickness on each side of the dosimeter being calibrated.

During the course of the experiment, the gamma-ray sources were suspended by a string in air at a distance of at least 150cm from the scattering objects such as the floor, ceiling and walls of the laboratory to minimize the possible contribution of scattered radiations. The distance from the center of the source to the center of the polyethylene sphere was maintained to be 115cm. Each dosimeter embedded in the different depth of

the sphere was separately irradiated for 1 hr., regardless of differences in dose due to the depth, that provided corresponding exposure rates of 998 mR/hr. and 655 mR/hr. for ^{137}Cs and ^{60}Co sources, respectively, at the center point of the sphere.

Five successive experimental runs at each measuring point in the sphere were performed in order to evaluate the reproducibility and statistical fluctuations in the measurement. Each experimental run was followed by careful annealing of the TLD element at 400°C to avoid possible contribution of spurious and/or residual thermoluminescence. The annealing procedure used was the same as that suggested by Cameron[15], i.e., 1 hr. heating at 400°C and then 24 hrs. custody of 80°C. Thermoluminescence was measured with Harshaw Model 2000 reader. For consistent results in any TLD measurement, the same conditions had been kept for all readings.

4. Results and Discussion

The results obtained in the determination of gamma-ray depth dose distribution for the photons emitted from ^{137}Cs and ^{60}Co, respectively, are shown in Fig. 4 and Fig. 5. The maxima of the depth-dose distributions occurred at about 0.3cm and 0.5cm, for ^{137}Cs and ^{60}Co gamma-rays, respectively, from the surface of the sphere. The ordinates of the Figs. were normalized to the surface dose, while the data points and relevant error bars were calculated from the values obtained by five successive experimental runs at each measuring point in the sphere. The results obtained in this work showed a reasonable range of statistical fluctuation and hence fairly good reproducibility.

The TLD readout system, Harshaw Model 2000, was disigned to provide output data in terms of electronic charge. Thus, inter-calibration of TL unit of coulomb into dose unit was necessary to be done not only for converting the readout data directly into dose, but also for certifying the linearity in relationship between TL output and dose.

The conversions of the dose absorbed in the surrounding medium was carried out on the assumption that the TLD is nearly equal to the medium in effective atomic number, with the implication of the electron spectrum

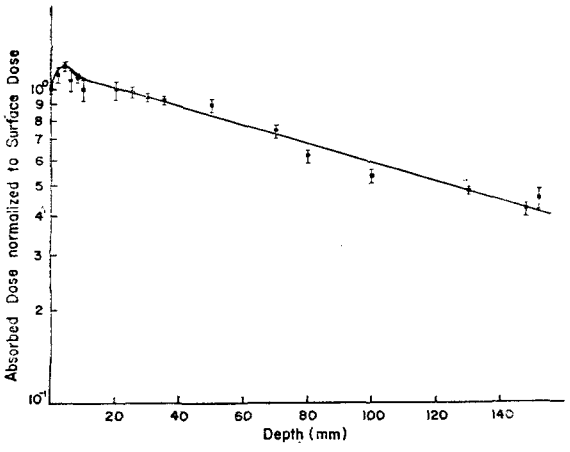

Fig. 4. Depth dose Distribution in 30cm dia. polyethylene sphere for broad beam of ^{60}Co.

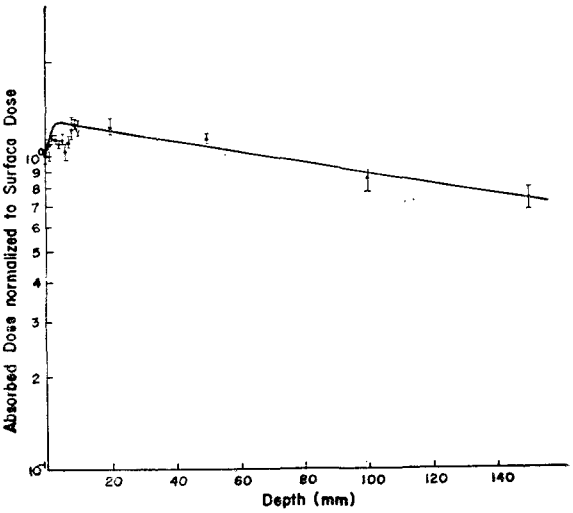

Fig. 5. Depth dose distribution in 30cm dia. polyethylene sphere for broad beam of ^{137}Cs.

established in the medium being remained unchanged by the presence of the TLD. At an interface, however, the electron energy spectrum is dependent on the absorber materials on both sides of the TLD. In this case where the TLD was surrounded by a single absorber of polyethylene, cavity theory requirements were assumed to be met. When the sphere is homogeneously composed of polyethylene, the TLD at the interface can be considered as an extended radiation-sensitive portion of the polyethylene layer because their energy absorbing properties are nearly equal. Therefore, as a first approximation the constant stopping-power ratios were used for each absorbing material adjacent to the interface to convert the measured dose in a TLD to the dose absorbed in the surrounding medium in each of the adjacent media.

As can be seen in Figs. 4 and 5, the several experimental data obtained in the electron build-up region before passing through the transition point deviated far from the smoothing curves, mainly due to neglecting a correction of non-electronic equilibrium and the possible effect of scattered radiations. The dose beyond the relative depth-dose maxima are, however, decreased with increasing depth, following the exponential attenuation law suggested by Spencer[16]. In a short word, the experimental data have the same general characteristics as the theory predicts.

5. Conclusions

Preliminary experiment for the determination of gamma-ray absorbed dose index in a given gamma-ray field has been carried out using polyethylene in place of tissue equivalent material. As aresult of the study it is primarily figured out that the absorbed dose index, which is in fact maximum depth dose in a polyethylene of 30cm in diameter, appears to be about 1.5 times as high as the surface dose at depth of 0.5cm for ^{60}Co and 1.4 times at depth of 0.3cm for ^{137}Cs, respectively. The absorbed dose in the medium was deduced directly from exposures observed by TLD embedded in the sphere using the Eq. 12 derived theoretically in line with Burline's approach to his modified cavity theory. These absorbed dose indices can be considered as the corresponding dose equivalent indices because the quality factor for gamma-rays with energies below 3 MeV has been well known to be 1.

An applicability of the index to practical radiation protection purposes as a means of characterizing the radiation field and as an aid to practice in the special circumstances where it is difficult to estimate the maximum absorbed dose and dose equivalent in the externally irradiated human body at the point of interest in air will be dealt with a further work in details.

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