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Experimental Study on the Determination of Absorbed dose Index*

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Abstract

The prime purpose of this study is to realize an index quantity, absorbed dose index, defined by the ICRU for the characterization of ambient radiation level at any location for the purpose of radiation protection.

The experiment has been designed to be carried out in two phases, namely, preliminary and main experiment. In the primary study a 30cm diameter sphere of polyethylene was used, while in the main experiment that of tissue equivalent material was fabricated and used. Both experiments were performed in the gamma-ray fields of ^{137}Cs and ^{60}Co, and in a neutron beam of thermal column of the TRIGA MARK-II research reactor.

In the measurement of gamma-ray absorbed dose TLD-700 (^{7}LiF) chips were used, and for the neutron dose both Au activation foils and TLD chips (TLD-600 (^{6}LiF) and TLD-700 for the discrimination of gamma-ray contribution) were used.

Theoretical assessment of the absorbed dose in the sphere phantom has been carried out in accordance with the Ehrlich's idea that deduced on the basis of Burlin's cavity theory in the case of gamma-ray irradiation. For the analysis of neutron dose fluence-KERMA rate conversion method was used. The explanation on the dose assessment is given in detail.

Results obtained were numerically and statistically analyzed and the depth dose distributions are presented in the graphic forms with normalized values. In the concluding remarks, the possibility and difficulty of realizing the index quantity, including questions and problems to be solved are mentioned.

1. Introduction

For the characterization of ambient radiation levels at any location for the purpose of radiation protection, ICRU has recently defined "absorbed dose index" and "dose equivalent index", which are the maximum absorbed dose and the corresponding dose equivalent within a 30cm diameter sphere consisting of material equivalent to soft tissue with a density of $1g/cm^3$ and centered at a point of interest in a radiation field.[1)]

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These quantities in consideration of radiation protection may be an adequate approximation to the numerical values of the maximum dose and maximum dose equivalent in the human body, and will meet the necessity of specifying ambient radiation levels that furnishes at least an approximate indication of the maximum absorbed dose that might be received if an individual were at some particular location. This maximum is of particular interest because critical organs can be found at almost any depth in the body.

The purpose of this study is to experimentally determine the absorbed dose index, which is underlying basis of the dose equivalent, in monoenergetic gamma-rays and reactor beam neutron fields, and to evaluate the practical applicability of the quantities in interpreting the survey data obtained by conventional health physics instruments in a certain radiation field.

The experimental study has been carried out in two different phases namely, the preliminary and the main experiments. In the former experiments, polyethylene sphere was used while in the latter, a sphere of tissue equivalent material is used.

The depth dose distributions in the spheres irradiated in ^{137}Cs and ^{60}Co gamma-ray fields were measured by thermoluminescent dosimeters. For reactor beam neutrons, the measurements of the dose distribution as a function of depth were made by activation detector together with TLD. Theoretical assessment has been carried out for the dose measured by those detectors embedded in the spheres.

2. Experiments

a) Preliminary Study

1) In Gamma-ray Fields.

The experimental arrangement for the preliminary measurement of the depth dose distribution in the gamma-ray fields is shown in Fig. 1.

The gamma-ray sources were suspended by a string in air at a distance of at least 150cm from the floor, ceiling and walls of the irradiation room in order to minimize possible effect of scattered photons. The distance from the center of the

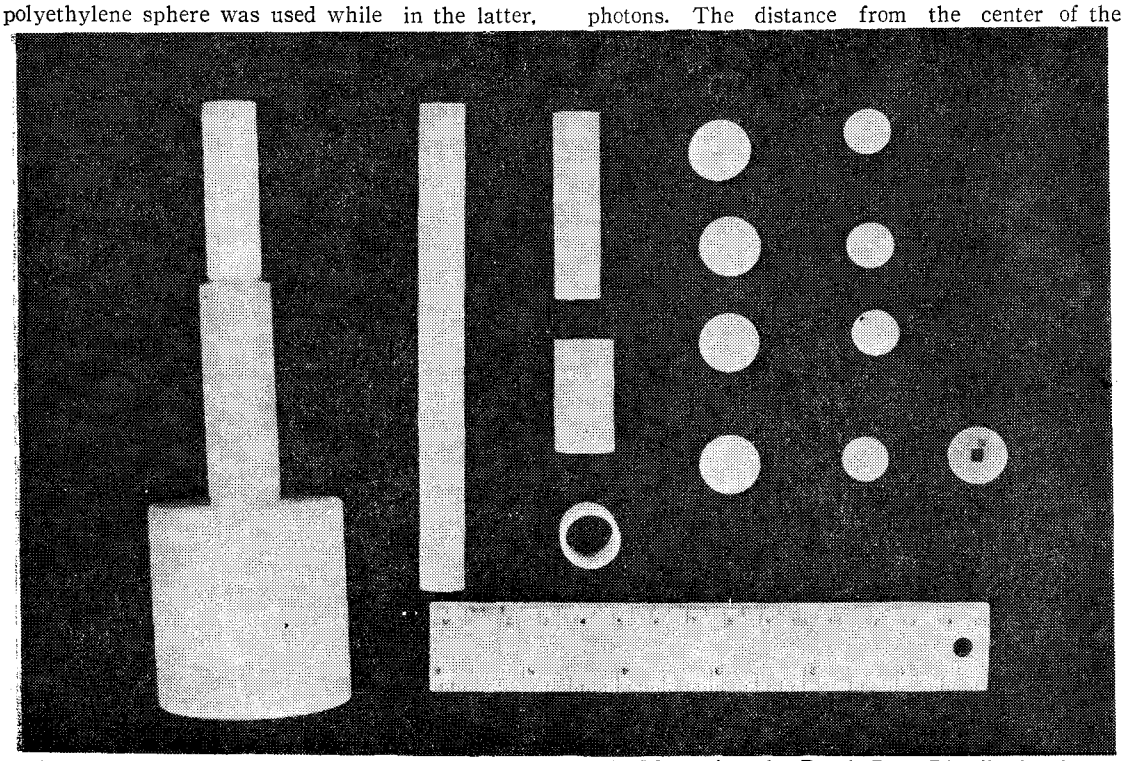

Photo 1. Piece-wise Polyethylene Elements for the Use in Measuring the Depth Dose Distribution in Polyethylene Sphere.

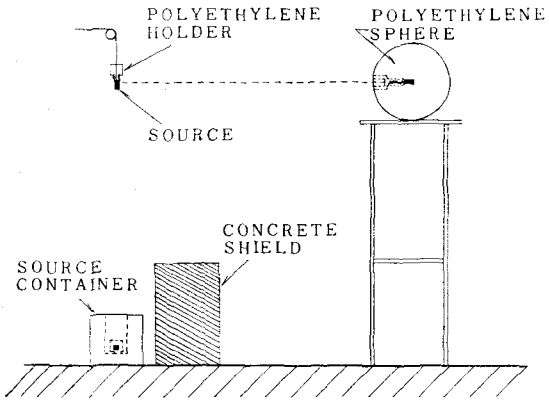

Fig. 1. Experimental Arrangement for Measuring the Gamma-ray Absorbed dose Distribution in 30cm Diameter Polyethylene Sphere.

source to that of the polyethylene sphere was kept to be 100cm.

The sources used were a ^{60}Co source of 130 mCi and a ^{137}Cs of 4 Ci, respectively. The dimension of the active part of the sources are in the order of a few millimeter that are small enough to be taken into account as a point source in this experiment. In this study, a polyethylene sphere of 30cm in diameter which is one of the Bonner spheres

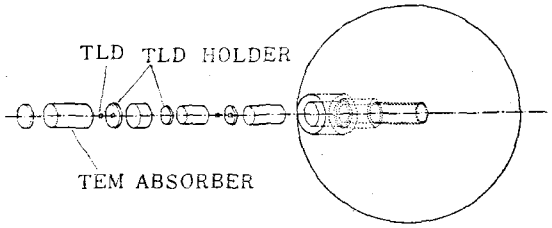

Fig. 2. Exploded view of Detector Holder and Absorber Assemblies.

neutron spectrometer assembly has been employed. The sphere has an opening directing to the center of itself. Piecewise polyethylene tablets and rods to be used for the measurement of the depth dose distribution were fabricated in our laboratory, and some of them are as shown in photo 1. Fig. 2 shows the exploded view of the detector holder and absorber assembly.

The detector used for gamma-ray dose measurement was TLD 700, ^{7}LiF chip of $1/8'' \times 1/8'' \times 0.035''$ produced by Harshow Chemical Co. The detectors have been interposed along the center line of the polyethylene tablet. The TLD reader used is that of Harshaw Model 2000.

The TLDs embedded in the various depths of the sphere were irradiated for 1 hour each, regar-

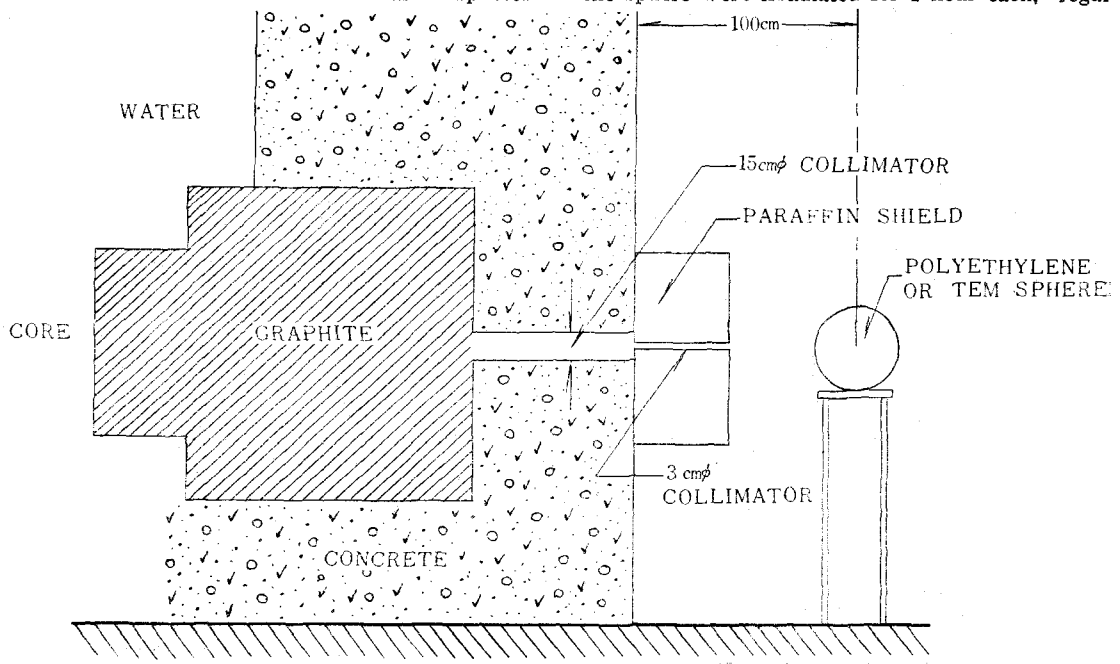

Fig. 3. Experimental Arrangement for Measuring Neutron Depth Dose Distribution in a Spherical Phantom of Polyethylene or TEM of 30cm in Diameter

dless of difference in dose due to the different depth in the sphere.

Five successive experimental runs at each measuring point in the sphere were carried out for the evaluation of the reproducibility and statistical fluctuations in the data obtained. In every experimental run, careful annealing of the TLD element at 400°C was performed prior to the dose measurement in order to avoid possible contribution of spurious or residual thermoluminescence.

ii) In Neutron Field

Neutrons from the thermal column of TRIGA Mark-II research reactor were used for the preliminary experiment of determining neutron absorbed dose index. Fig. 3 shows the experimental arrangement for the measurement of neutron depth dose distribution in the polyethylene sphere of 30cm in diameter. The thermal column consists of 122×122 ×167cm³ graphite and 107cm thick concrete shielding door which has a hole of 15cm in diameter and 107cm in length at about its center. The outer face of the column is again provided with 50cm thick paraffin shield with a hole of 3cm in diameter whose center coincide with that of the hole on the concrete door. The center of the polyethylene sphere was placed at a distance of 50cm from the opening of the hole on the center line of the collimated beam.

For the detection of neutrons, activation foils made by the Reactor Experiment Inc. and TLD-600, ^{6}LiF chip of 1/8″×1/8″×0.035″ produced by Harshaw Chemical Co. were used together with TLD-700 for the discrimination of gamma-ray contribution from the read out of TLD by means of gamma originated TL subtracting method.[2,3]

Bare and cadmium-covered gold foils were employed for the measurement of thermal and intermediate energy neutrons. The physical and nuclear properties of the gold foils are summarized in Table 1. Threshold detectors such as indium and aluminum foils were also subjected to irradiation in the thermal column neutron beam. Since, however, the flux density of fast neutrons was too small to obtain reliable experimental results, the dose due to thermal and intermediate energy neutrons will henceforth be considered in this work. The activity induced in the foil is measured by means of photopeak counting using 3″×3″ NaI(Tl) cylindrical

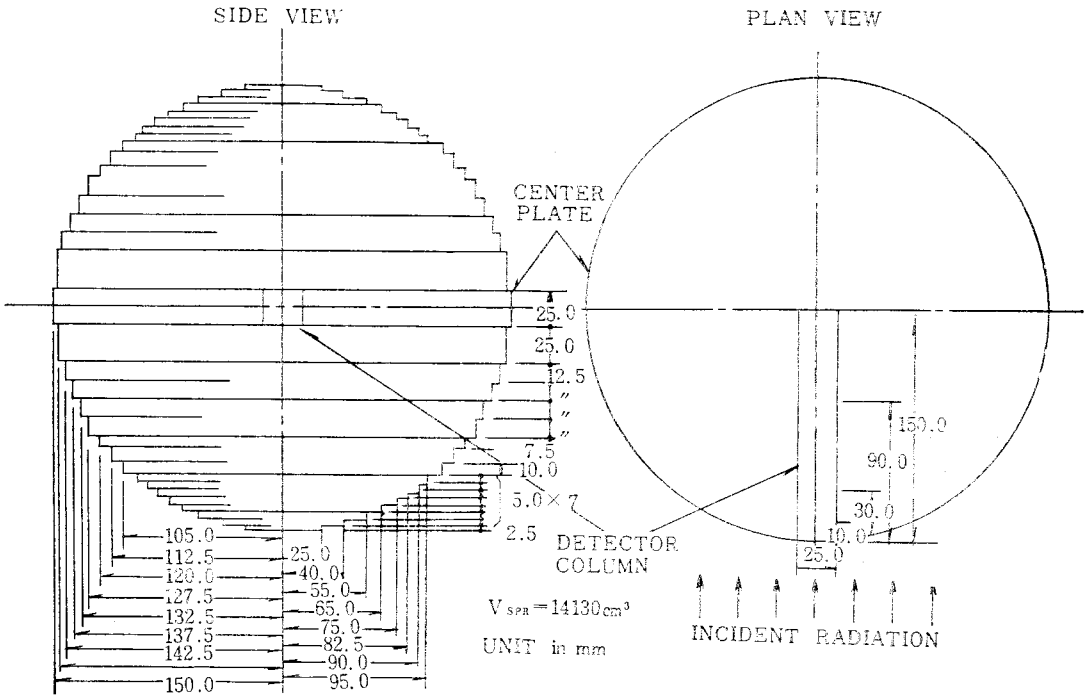

Fig. 4. Stepped sphere of tissue equivalent material

Table 1. Physical and Nuclear Properties of Gold Foil for $^{197}Au(n, r)$ Reaction

Dimension : 1.27cm dia.×0.00127cm thick
Weight : 0.0234g
Purity : 99.992%
Isotopic abundance : 100%
Half-life : 2.7days
Gamma energy : 0.412MeV
Photon yield per decay : 99.975%

scintillation detector associated with 400 channel pulse height analyzer, Hitachi Model RAH-403. The TLD contributed to the major portion of the information by providing data covering the range of 5cm in depth to the center of the sphere phantom, while the activation foils covered the range from the surface to 5cm in depth. This is done because activity of gold foils irradiated at a depth of beyond 5cm in the sphere was too low to give us useful data even if the irradiation was performed for five hours which is the longest duration available at a time. Bare and 0.5mm Cd-covered gold foils embedded in the sphere were irradiated for three to five hours to the neutron beams from the reactor TRIGA Mark-II operated at steady power of 250 KW. TLD, on the other hand, were subjected to irradiation for five to ten minutes in the identical beams of neutrons.

b) Main Experiment

i) Design and Fabrication of the TEM Sphere

As described before, a "perfect" polyethylene sphere of 30cm in diameter, which is one of the Bonner neutron spectrometer, has been used in the preliminary experiment for the determination of absorbed dose index in a radiation field. This sphere may be reasonably acceptable for the determination of the index in a photon field in consideration of the effective atomic number and its density, and thus polyethylene has commonly been used in place of tissue equivalent material (TEM) for X-and gamma-ray dosimetry.

However, for more realistic determination of absorbed dose in TEM defined by ICRU[1], in particular for the determination of absorbed dose in a neutron field, polyethylene is no longer satisfactory to be considered as tissue equivalent, because tissue equivalence in composition of ICRU definition takes 76.2% O, 11.1% C, 10.1% H, and 2.6% N, whereas polyethylene is simply composed of C and H in the form of $(CH_2)_n$.

TEM produced by Alderson Laboratories International, Inc. in the United States was purchased through the Agency. This material was produced not in the form of a sphere, but in the form of circular plate of 2.5cm in thickness, and rod of 3cm in diameter. Two different diameters of the plates are 35 and 25cm, respectively, and the rod is 20cm in length.

Because of great difficulty in fabricating perfect sphere with those plates, due to the absence of copy attachment to the lathe of our machine shop, it was decided to design and make an approximate "stepped" sphere. The details are as shown in Fig. 4. Detectors for the depth dose measurement are to be arranged, in the detector column, vertically to the direction of incident radiation. The stepped approximation of the sphere was justified through a series of *a priori* experiment carried out for clarifying whether there is any difference in depth dose distribution between the "perfect" and the "stepped" spheres in an identical radiation field. For this experiment a stepped sphere of polyethylene in the same dimensions as shown in Fig. 4 was first made. The depth dose distributions in both perfect and stepped spheres were measured in ^{60}Co and ^{137}Cs gamma-ray fields using TLD-700 chips.

According to the comparative study of the perfect and stepped spheres, depth dose distributions in the two are found to be in good agreement within tolerable statistical error. Standard deviations were calculated for data obtained in every specified depth. Observed range of the standard deviations is summarized in Table 2. This range of deviation in the observed data is quite acceptable for our further experiment.

On the other hand, the volume of the stepped sphere is figured out 14,130cm^3 as easily can be estimated from Fig. 4, while that of the perfect

Table 2. Range of the Standard Deviatio in Depth Dose Measured using TLD-700 Embedded in Two Different Polyethylene Sphere.

Gamma-ray field	Sphere / Range	Perfect sphere[1)]	Stepped sphere[2)]
Co-60	Minimum	0.4%	0.5%
	Maximum	7.5%	7.1%
	Average	2.56%	2.98%
Cs-137	Minimum	0.3%	0.8%
	Maximum	5.3%	4.9%
	Average	2.17%	2.78%

1) Whole number of S.D. observed are 22 in each gamma-ray field.
2) Whole number of S.D. observed are 23 in each gamma-ray field.

sphere of 30cm in diameter is 14,137cm³. This shows also that the stepped sphere is quite satisfactory for our study so far as the volumetry is concerned.

ii) Experiment in Gamma-ray Field

In order to measure the gamma-ray depth dose distribution in the sphere phantom of tissue equivalent material, gamma-ray fields of different monoenergies were provided using 4 Ci ^{137}Cs and 0.56 Ci ^{60}Co sources separately embedded in a newly constructed collimating lead castle. The arrangement for the experiment is shown in Fig. 5. This type of arrangement is used because of a great advantage of minimizing unnecessary exposure to experimental workers, as well as eliminating the contribution of scattered photons from the walls, ceiling and floor of the exposure room. Thickness of the lead castle was designed so as to be more than 15cm from the source position to all directions except for the collimating hole. Such a collimated output gamma-ray beam, however, normally includes a certain amount of secondary photons scattered from the surrounding inside walls of lead castle. Contribution of the scattered photons to the collimated beam under a similar condition has been evaluated to amount a few percent[4)], while another study on the similar lead castle showed that the relative contribution of the scattered photons to total exposure rate is about 2.25% regardless of distance from the source to the detecting position.[5)]

In measuring the gamma-ray depth dose in the sphere phantom, 3.18×3.18×0.89mm TLD-700 ribbons made by Harshaw Chemical Co. were used with an arrangement shown in Fig. 6. Depth doses were measured at an interval of 1mm in first 10mm from the surface of the sphers, 5mm in depth of 10 to 40mm, 10mm in that of 40 to 70mm, and 20mm in between the depth of 70 and 150mm. In each measurement, namely at each depth, four TLD chips were used for the reasonable evaluation of statistical significance of the result.

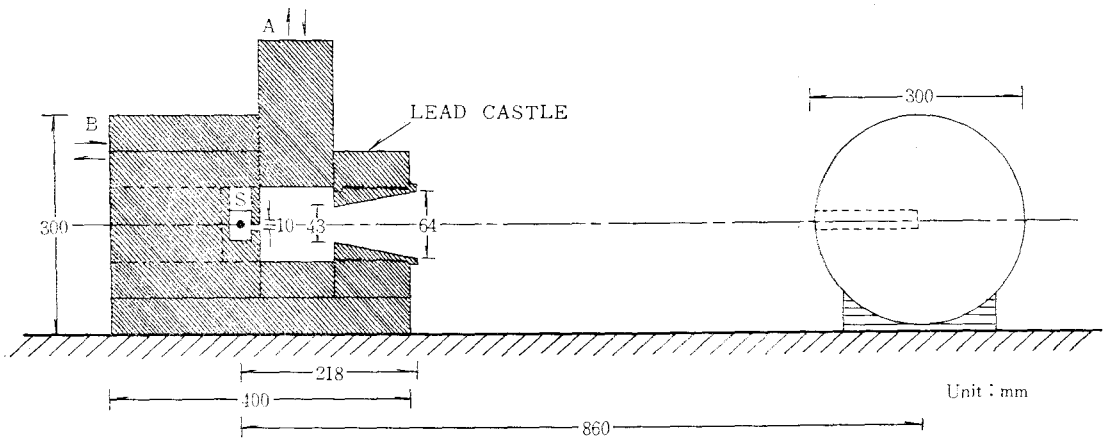

Fig. 5. Experimental arrangement for the measurement of Gamma-ray Depth dose in a spherical phantom of tissue equivalent material

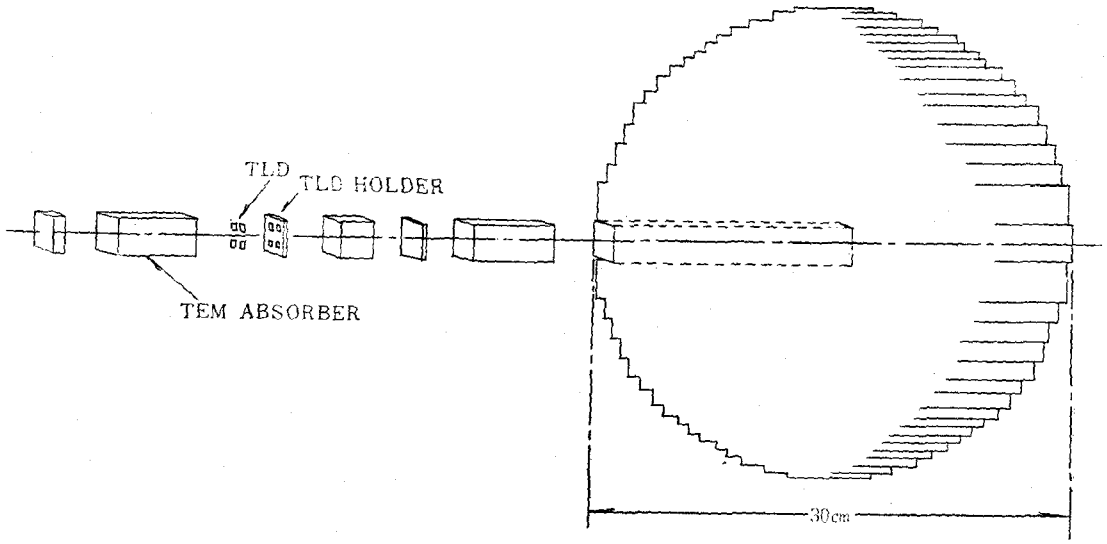

Fig. 6. Exploded view of detector holder and absorber assembly for the measurement of depth dose in a spherical phantom of tissue equivalent material using TLD chips

Center of the sphere phantom was located at 86cm from the source on the central axis of the conically collimated radiation beam, where the cross section of the radiation beam coincides with the largest cross section of the sphere.

One hour was kept for irradiation at each depth and this would result total exposure of 0.74R at the location of the center point of the sphere when ^{60}Co source was embedded in the lead castle, while an exposure of 1.32R would be resulted at the same point in the case of ^{137}Cs.

iii) Experiment in Neutron Field

Measurement of depth dose in a phantom located in neutron field, in practice, necessitates first to measure the neutron fluence at a depth of interest in the phantom. For carrying out this work, neutrons from thermal column of TRIGA Mark-II research reactor were used. Experimental setup is as shown in Fig. 3.

The sphere phantom of tissue equivalent material was placed at 50cm from the opening of the collimated beam and the reactor has been operated at steady power of 250KW during the course of the experiment. In this work two different type of detectors were used. One is neutron sensitive TLD and the other is Au activation foil.

TLD-600 ribbons(3.18×3.18×0.89mm) made by Harshaw Chemical Co. were used and contribution of the reactor gamma-rays to this TLD is discriminated by means of substracting the readout of TLD-700 from that of TLD-600 irradiated under the same condition.[2,3] Thus, in the measurement of neutron depth dose distribution in the sphere, two series of identical measurement had to be carried out using TLD-600 and TLD-700, respectively. The depth intervals at which the fluences were measured using TLD were same as done in gamma-ray depth dose measurement. At each depth, four ribbons were embedded and the detectors were irradiated for ten minutes in the neutron beam.

Bare and Cd-covered gold foils were embedded at depths of 1, 3, 5, 7, 10, 15, 30 and 50mm from the surface of the sphere phantom along with the center line of the neutron beam, which passes through the center point of the sphere. Irradiation time was established from 5 to 8 hours according to the depth at which the neutron fluences were measured.

For a numerical evaluation of the neutron albedo for the sphere phantom, the foils were also subjected to irradiation at the surface of the sphere with and without the existence of the phantom.

The activity induced in the gold foils was measured 30 minutes after the end of the irradiation

by a 3″×3″ NaI(Tl) scintillation detector associated with a 400 channel pulse height analyzer (Hitachi Model RAH-403). From the spectrum obtained, the photopeaks due to 0.412 MeV gamma-ray were evaluated using numerical values of peak-to-total ratio and absolute detection efficiency deduced, for our detector, from published data.[6,7]

3. Theoretical Assessment of Absorbed Dose.

a) For Gamma-ray Dose.

Theoretical deduction of gamma-ray absorbed dose in a polyethylene sphere (This might also be valid for the sphere of TEM in the light of effective atomic number) from the data obtained by TLD-700 (^{7}LiF) embedded in it has been attempted by applying Ehrlich's method.[8] This is essentially based on Burlin's generalized cavity theory[9] which assumes the range of electrons produced by the incident gamma-rays in the dosimeter comparable to the cavity dimensions.

As Burlin did, Ehrlich assumed that the range of the Compton electrons produced by incident gamma-ray in the dosimeter is comparable to the TLD cavity dimension (our TLD is 3.18×3.18×0.89mm^3), which means that the absorbed dose in the TLD cavity stems not only from the cavity wall (polyethylene or TEM), but also from the electrons produced in the TLD cavity proper.

Under this conditions she thought the absorbed dose in the TLD should lie

$$D^{(1)}_{TLD}=D_{poly}\cdot S^{TLD}_{poly}\cdots\cdots(1)$$

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

$$D^{(2)}_{TLD}=D_{poly}\cdot {}_{en}\mu^{TLD}_{poly}\cdots\cdots(2)$$

for cavity dimensions large compared to the electron range.

Here, the μ represents relative mass energy absorption coefficient and the S, reative 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 to TLD cavity is given by

$$D_{poly}=0.869\ {}_{en}\mu^{poly}_{air}\cdot X\cdot 0.965\cdots\cdots(3)$$

where 0.869 is the absorbed dose in air (in rad) 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 $\exp(-\mu_{poly}\cdot t_{poly})$, μ_{poly} and t_{poly} being the attenuation coefficient for the incident photons and the wall thickness, respectively.

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

$$D_{TLD}=dD^{(1)}_{TLD}+(1-d)D^{(2)}_{TLD}\cdots\cdots(4)$$

where d is a weighting factor given by the equation

$$\left.\begin{aligned} d&=\int_0^g e^{-\beta g}dx\Big/\int_0^g dx=(1-e^{-\beta g})/\beta g \\ \text{and}\quad 1-d&=\int_0^g (1-e^{-\beta x})dx\Big/\int_0^g dx=(\beta g+e^{-\beta g}-1)/\beta g \end{aligned}\right\}\cdots\cdots(5)$$

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

Published numerical values of d for the LiF TLD[10], 0.311 and 0.156 in the case of ^{60}Co and ^{137}Cs gamma-rays, respectively, were used in our work.

The absorbed dose in the polyethylene, D_m, is then estimated by

$$D_m=S^m_{TLD}\cdot D^{TLD}\cdots\cdots(6)$$

where S^m_{TLD} is in fact identical with the reciprocal of the S^{TLD}_{poly}.

In calculating $\bar{S}^{TLD}_{poly}$, which is a weighted average over the electron energy spectrum at the position of the dosimeter, the formula[11]

$$\bar{S}^{TLD}_{poly}(E_0)=\frac{1}{\bar{S}^{poly}_{TLD}(E_0)}=\frac{1}{E_0}\int_0^{E_0}\frac{(S/\rho)_{coll.\ TLD}}{(S/\rho)_{coll.\ poly}}dE\cdots\cdots(7)$$

was used. Here, $(S/\rho)_{coll}$ indicates mass stopping power due to energy loss by collisions. Using the numerical values of $(S/\rho)_{coll.\ poly}$ and $(S/\rho)_{coll.\ LiF}$ appeared in an ICRU Report[12], as a function of electron energy, numerical integration was carried out according to Simpson's rule. Resultant S values

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 are not available, while those for the polyethylene were appeared in the literature[13]. For calculating $({}_{en}\mu/\rho)_{TLD}$, the following equation[14] was used.

$$\frac{{}_{en}\mu}{\rho} = \frac{\tau}{\rho} - \left(\frac{\tau^k}{\rho}\right)\left(\frac{F_k E_k}{h\nu}\right) + \left(\frac{\sigma}{\rho}\right) f_c + \left(\frac{k}{\rho}\right) f_k \quad \cdots\cdots(8)$$

Here, $\tau - \tau^k\left(\frac{F_k E_k}{h\nu}\right)$ 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 E_k being fluorescence yield and average energy of fluorescence in the K-series, respectively. $(\sigma/\rho)f_c$ and $(k/\rho)f_k$ are Compton and pair-production components of the mass energy transfer coefficients, wheres f_c and f_k are average fractions of photon energy going into electronic collision loss by Compton scattering and into pair-production, respectively. The terms of τ^k/ρ and k/ρ are in practice minor enough to neglect in our calculation.

Compton cross section, σ_c, was calculated for ^{60}Co and ^{137}Cs gamma-rays using Klein-Nishina formula,[15]

$$\sigma_c = 2\pi r_0 \left\{ \frac{1+\alpha}{\alpha^2} \left[\frac{2(1+\alpha)}{1+2\alpha} - \frac{1}{\alpha}\ln(1+2\alpha) \right] + \frac{1}{2\alpha}\ln(1+2\alpha) - \frac{1+3\alpha}{(1+2\alpha)^2} \right\} \quad \cdots\cdots(9)$$

where r_0 is classical electron radius, e^2/mc^2, and $\alpha = h\nu/mc^2$. The numerical values obtained are $\sigma_c = 1.387\times10^{-25}$ cm^2/electrons for ^{60}Co gamma-rays, and $\sigma_c = 2.559\times10^{-25}$ cm^2/electrons for ^{137}Cs gamma rays. Resultant total mass attenuation coefficients, σ/ρ ($\sigma = \sigma_c \cdot \rho \cdot NZ/A$, 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 an 2.64g/cm.[16] 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.

Calculation of τ was carried out using Gray's empirical equation[15],

$$\log\tau_a = 3.6505 + 1.0\log\lambda + 0.480(\log\lambda)^2 \cdots\cdots(10)$$

where τ_a is given in cm^{-1} and wavelength of the incident gamma-rays, λ, is in X-units (10^{-11}cm). Obtained numerical values of τ/ρ ($\tau = \tau_a \rho N/A$) are 6.75×10^{-8}cm/gm and 2.62×10^{-7}cm/gr for ^{60}Co and ^{137}Cs gamma-rays, respectively. In light of the order of magnitude, these values are obviousely negligible compared to those of σ/ρ.

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

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

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

respectively. Resultant relative mass energy absorption coefficients, for the two different gamma-rays in energy are

$[{}_{en}\mu_{poly}^{TLD}]_{Co} = 0.746$

and $[{}_{en}\mu_{poly}^{TLD}]_{Cs} = 0.752$.

With all the data obtained, the absorbed dose in the polyethylene sphere, D_m(*Eq.* 6), can be deduced as a linear function of exposure, X, observed by TLD in the medium at the position of the cavity. That is

$D_m = 0.732X$ for ^{60}Co gamma-rays

$= 0.755X$ for ^{137}Cs gamma-rays. $\cdots\cdots(11)$

This simple and basic relations will be effectively used in the assessment of absorbed dose in the polyethylene and TEM sphere from embedded TLD data.

b) For Neutron Dose (KERMA)

It is common to assume the neutron energy spectrum being composed of three different components, namely; 1) fast neutron component with the form of a virgin fission spectrum (^{235}U+thermal fission neutron spectrum), 2) slowing down neutrons proportional to 1/E, and 3) thermal neutron component with a Maxwellian distribution of velocities appropriate to the temperature of 20°C. For the slowing down neutrons, the lower and upper limits of the spectrum were taken as 0.12 eV and 1.0

MeV, respectively. The lower limit was determined according to Westcott[17], while the upper limit was chosen arbitrarily but is nearly corresponding to the maximum point of virgin fission neutron spectrum.

The fluence-dose (KERMA) conversion factor was calculated on the basis of NBS Handbook 63[18], ICRU Report 13[19], and NCRP Report No. 38[20] and the results are presented for three spectrum component in Table 3. Neglecting the fast neutron flux density in the beam of the thermal column, thermal and intermediate energy neutron flux densities were determined by means of cadmium cut-off technique.[21]

4. Results and Discussion

a) Results obtained in the Preliminary Study

In the preliminary study for the measurement of gamma-ray absorbed dose index, a reasonable range of statistical fluctuation and hence fairly good reproducibility was shown. Figs. 7 and 8 show the results obtained in the gamma-ray fields of ^{137}Cs and ^{60}Co, respectively.

The ordinates of the figures 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.

Some experimental data in the depth dose distribution deviate from the expected values. This might happen because of serveral factors such as lack of charged particle equilibrium (near the surface), difference in sensitivity of individual TLD element, etc. The dose distribution beyond the maxima, however, decrease with increasing depth approximately following the exponential law suggested by Spencer.[22]

Table 3. KERMA and KERMA Equivalent Conversion Factors per unit Fluence of Neutron from Spectrum Componets

Spectrum component	Thermal $\int_0^\infty D(E)\frac{E}{E_0^2}e^{-E/E_0}dE$	Intermediate $\frac{1}{15.93}\int_{0.12ev}^{1Mev} D(E)\frac{1}{E}dE$	Fast $\int_0^\infty D(E)N_f(E)\,dE$
KERMA [rads/(n/cm²)]	2.30×10^{-11}	2.56×10^{-10}	2.23×10^{-9}
KERMA equivalent [rems/(n/cm²)]	2.40×10^{-10}	2.93×10^{-9}	2.14×10^{-8}

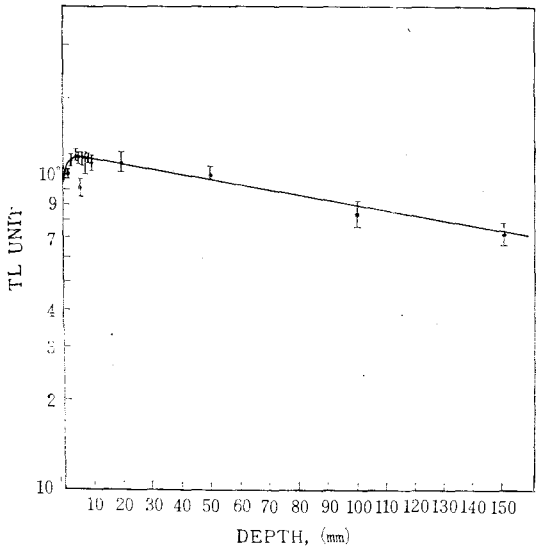

Fig. 7. Depth dose distribution in 30cm dia. polyethylene sphere for broad beam of ^{137}Cs.

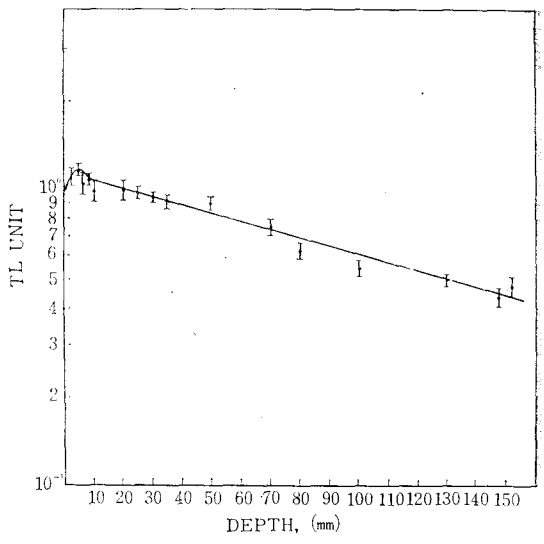

Fig. 8. Depth dose distribution in 30cm dia. polyethylene sphere for broad beam of ^{60}Co.

As a result of the study it is primarily figured out the absorbed dose index, which is in fact the maximum depth dose in a polyethylene sphere of 30cm in diameter appears at about 0.4 to 0.5cm in depth, and the maximum dose is about 1.3 times as high as the surface dose.

Neutron absorbed dose was determined by weighting field parameters such as fluence and energy spectrum in order to figure out the fluence-dose (KERMA) conversion factor. The field parameters were measured by activation foils. The data obtained with TLD elements were converted into absorbed dose through a crose-calibration with the values obtained by activation foils at the depth of 5cm in the polyethylene sphere.

The thermal and intermediate energy neutron flux densities thus measured were 9.08×10^{5}n/cm²-sec and 2.66×10^{5}n/cm²-sec at the surface of the sphere which subsequently lead to 2.09×10^{-5} rads and 6.80×10^{-5} rads, respectively, according to the estimation on the basis of fluence-dose conversion factor given in Table 2. The effect of scattered neutrons at the surface of the sphere has been taken into account in determining the surface dose. This is achieved by measuring the difference of the activity induced in the activation foils when they were irradiated with and without the presence of the sphere. The apparent dose (the dose due to the incident and scattered neutrons) seemed to be about 50% higher than that due to the incident neutrons only.

In this way, the depth dose variation in the sphere was obtained and the results are shown in Fig. 9. All the experimentally obtained values were normalized to that measured at the surface of the sphere. The bald circles indicate the data obtained by activation foils, while the bald rectangulars represent those measured by TLD. With maximum dose at the surface of the sphere, the dose decreases with increasing depth. From the surface up to about 1cm in depth, a sharp decrease is observed. This might be explained as a result of variation in component ratio between thermal and intermediate energy neutrons by the absorption process.

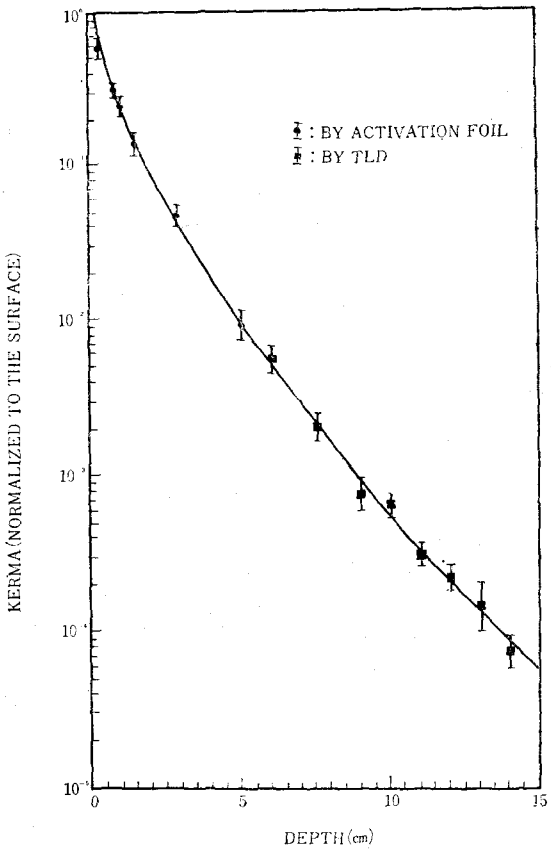

Fig. 9. Depth dose distribution in 30cm diameter polyethylene sphere for beamport neutron from thermal column of TRIGA Mark-II reactor

b) On the Theoretical Assessment of Absorbed Dose.

In accordance with the Ehrlich's idea that is formulated essentially based on Burlin's cavity theory, and with calculation of mass energy absorption coefficient of the LiF TLD through broad survey and collection of relevant published data, it was possible to derive a simple linear equation which enables us to deduce gamm-ray absorbed dose in a polyethylene sphere from the data obtained by embedded TLD. That is expressed as equation 11. This relationship is also valid for the sphere of tissue equivalent material in the light of effective

atomic number of polyethylene and TEM. Practical assessment of gamma-ray absorbed dose from the data obtained by TLD has been carried out using this relationship.

The absorbed dose, KERMA in fact, in the sphere phantom irradiated to reactor neutron beams has been assessed on the basis of references 18 through 20.

c) Results obtained in the Main Experiment.

Data obtained in gamma-ray depth dose distribution in TEM sphere phantom using TLD-700, which had been read out in terms of nanocoulomb, was converted into exposure with the unit of R. For this conversion calibration of the TLD has been carried out in an open air using a ^{226}Ra standard source of 13.7 mCi in activity. Resultant calibration curve is as shown in Fig. 10.

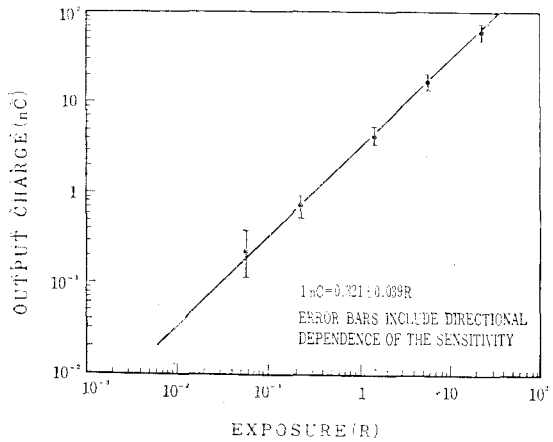

Fig. 10. Calibration curve for TLD-700 (^{7}LiF) for gamma-ray exposure

Since the energy dependence of the TLD sensitivity in measuring exposure is well-known to be consistant in the energy range of about 100 KeV up to 10 MeV,[23] the output charge-exposure calibration curve shown in Fig. 10 is valid for the gamma-rays from ^{137}Cs and ^{60}Co sources. The data obtained in terms of electronic charge was first to be converted into exposure, and the conversion of exposure into absorbed dose was then followed using the equation 11 derived on the basis of cavity theory.

Thus determined absorbed dose rates at the surface of the sphere phantom were 1.72 rad/hr in the field of ^{137}Cs gamma-rays and 0.51 rad/hr in that of ^{60}Co, respectively, for the particular geometry of the experimental arrangement shown in Fig. 5. The maximum absorbed dose rate in the sphere phantom were observed at the depth of 1mm and the dose rate was 1.93 rad/hr in the case of ^{137}Cs, while it was observed at 3mm in

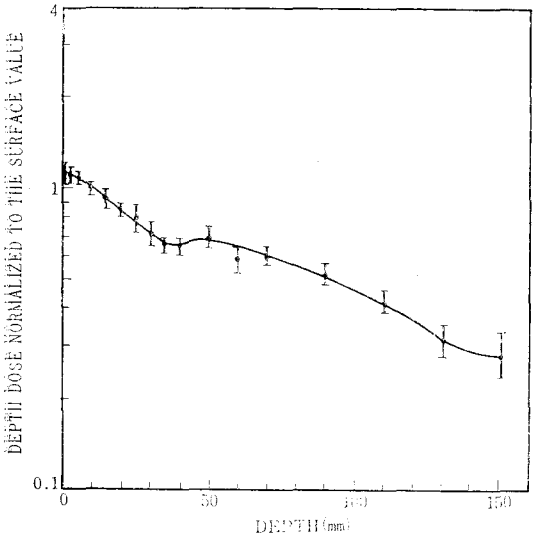

Fig. 11. Depth dose distribution in the TEM sphere of 30cm in diameter irradiated to ^{137}Cs gamma-ray beam.

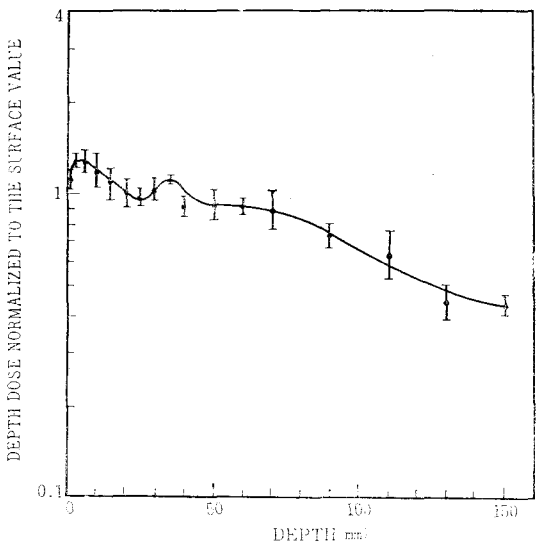

Fig. 12. Depth dose distribution in the TEM sphere of 30cm in diameter irradiated to ^{60}Co gamma-ray beam

depth with the dose rate of 0.64 rad/hr in the case of ^{60}Co. The maximum values observed are 1.12 and 1.27 times as high as that of surface dose rates in the case of ^{137}Cs and ^{60}Cs, respectively. The results are shown in Figs. 11 and 12. All the values in the ordinates were normalized to the surface dose. As shown in the figures the variations of the dose rate with depth in the sphere are not consistent, and two peaks are shown in each figure. The second peak in depth dose distribution were observed at the depth of 5cm in the case of ^{137}Cs and 3.5cm in the irradiation of ^{60}Co gamma-rays.

It is generally known[24] that the magnitude of the absorbed dose in an extended medium resulting from an external source varies from point to point in the medium. And this variation results from; 1) the divergence of the radiation from the source, 2) the absorption and the scattering of the incident radiation in the medium, and 3) the build-up of associated charged particles for a given type and energy of radiation. Despite considering all these factors, it is quite ambiguous to explain the occurrence of two peaks in the depth dose distribution.

The absorbed dose (KERMA) in the TEM sphere due to the irradiation of neutrons of the TRIGA reactor thermal column has been measured using both Au activation foils and TLD (TLD-600 and TLD-700). Firstly, gamma-ray spectra of ^{198}Au produced by the activation of ^{197}Au foils in the neutron field were analyzed for the determination of neutron flux density at a point of interest in the phantom. For the foils used in this study, the flux density was calculated by

$$\phi = 3.313 \frac{A}{g(1-e^{-\lambda t_i})e^{-\lambda t_e}} (cm^{-2} \cdot s^{-1}) \cdots\cdots (12)$$

which was deduced from the well-known activation formular[25] using numerical data of nuclear characteristics of the foil,[26] and that of neutron capture cross section.[27,28] Here, g is the weight of ^{197}Au foil, λ is decay constant of ^{198}Au, and t_i and t_e are irradiation time and elapsed time after the end of irradiation, respectively. A is absolute disintegration rate of ^{198}Au which was determined by

$$A\ (dps) = 11.63S\ (cps) \cdots\cdots (13)$$

under our particular condition of source-detector arrangement. Here S denctes total count rate of 0.412 Mev photopeak area in the spectrum. Numerical constant connecting S and A is calculated using published data of photopeak efficiency[6] and total counting efficiency[7] for the detector employed in this study. Contribution of intermediate energy neutrons was quantified by evaluating the difference in activities of bare and Cd-covered gold foils. The measured flux densities were converted into KERMA rate using conversion factors given in Table 3. Beyond the depth of 15 mm in the sphere, the dose was evaluated from the TLD data, which cross-calibrated using the data obtained by Au foils at six different depth of 1 mm to 15 mm in the sphere. For this calibration TLD was used to measure the neutron dose at the same depth. The conversion factor obtained through the calibration was

$$C_d = (1.41 \pm 0.06) \times 10^{-4}\ rad/nC \cdots\cdots (14)$$

The measured depth doses (KERMA) in the sphere are plotted in Fig. 13 with values normalized to the surface dose rate (KERMA rate). As shown in

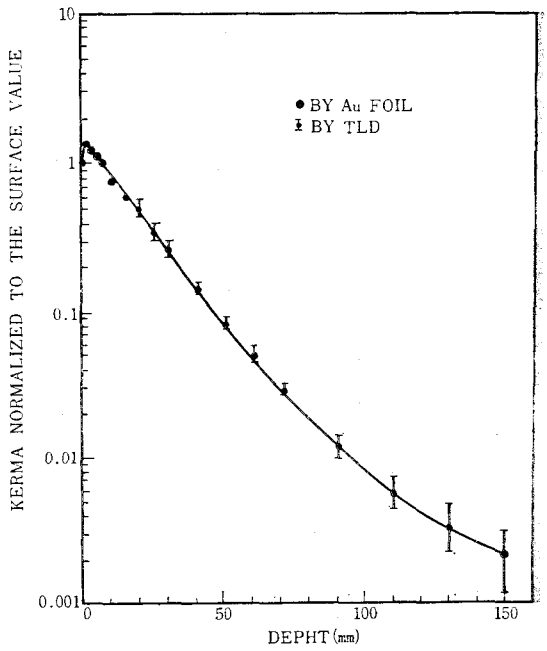

Fig. 13. depth dose distribution in the TEM sphere of 30cm in diameter irradiated to neutron beam from thermal column of the reactor triga mark-II

the figure, the maximum absorbed dose was observed at the depth of 1mm from the surface of the sphere. At this point the measured thermal and intermediate energy neutron flux densities were 6.47×10^{5} n/cm^{2}. sec and 1.82×10^{5} n/cm^{2}-sec, which corresponding to the KERMA rate of 1.36×10^{-5} rad/sec and 4.55×10^{-5} rad/sec, respectively. The total KERMA rate at the point is 5.91×10^{-5} rad/sec, and this is about 1.5 times as high as the KERMA rate at the surface of the sphere.

5. Concluding Remarks

The experimental realization of the ICRU definition of the index quantity, absorbed dose index, was rather complicated than it was expected at the beginning of this study. The work has been started in 1973, while the detailed explanation of the ICRU on the conceptual basis of the quantity[24] came out a few years later.

This study has been restricted to determine the index quantity in the unidirectional radiation field.

Through this study, however, an experimental and analytical basis for the determination of absorbed dose index in gamma-ray and neutron fields of specified energy were established. The basis includes the theoretical assessment of the absorbed dose from the data obtained by the detector that does not give us the dose itself, yet has strong advantage in the measurement of depth dose in a medium.

The second gain to be pointed out is that the possibility and the difficulty of realizing the index quantity have been revealed through the study. And it was also found that there are many questions and problems to be solved prior to practical application of the index quantity. Some of them are; 1) development of appropriate TEM sphere that fits to the ICRU definition, 2) development of the index quantity measurement technique in the low dose radiation field, including isotropy analysis, 3) assurance of the usefulness of the index quantity for the practical radiation protection purpose, in consideration of the complexity of the realization of the quantity in an arbitrary radiation field.

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吸收線量指數決定에 관한 實驗的 硏究

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要　　約

본 연구의 일차적 목적은 방사선 방호를 위하여 任意地點의 주변 방사선량의 수준을 特性짓는 방법의 하나로 ICRU가 定義한 흡수선량지수를 實測하는데 있는 바 이를 위한 실험은 예비실험과 본 실험의 두 단계로 나누어 수행하였다.

예비단계의 실험에서는 30cm 지름의 polyethylene球를 사용한 반면 본 실험에서는 人體組織等價物質의 球를 제작하였으며 두 실험 모두 ^{137}Cs 및 ^{60}Co 감마線場과 TRIGA Mark-Ⅱ 원자로의 熱中性子 column의 中性子工場에서 행하여졌다.

감마선 흡수선량측정에는 TCD-700 (^{7}LiF) chip을, 중성자선량측정에는 Au 放射化箔과 함께 TLD chip도 사용하였는데 이 경우에는 감마선의 기여를 판별해 내기 위하여 TLD-600 (^{6}LiF)과 TLD-700을 동시에 사용하였다.

감마선 照射의 경우 球 phantom內 흡수선량의 이론적 해석은 Burlin의 空洞理論에서 유도된 Erlich의 방법을 썼으며, 중성자 선량해석에는 fluence-KERMA 변환방법을 사용하였다. 이들 선량에 관하여서는 특히 자세히 설명하였다.

해석에 실험결과는 모두 통계적으로 처리·분석하였으며 특히 深部線量分布는 規格化한 값을 사용하여 圖表로 나타내는 한편, 결론에서는 방사선방호용 指數量 實測의 가능성과 難點을 설명하고 해결하여야 할 문제점들을 言及하였다.

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