SPECTRA OF SCATTERED RADIATION AT POINTS OFF THE BEAM AXIS

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ABSTRACT

In radiological physics, a knowledge of the spectral distribution of radiation reaching a point is very important. Although the dose gives the amount of radiation at the point, it is the spectral distribution which determines the effects, for instance, the energy absorbed by the irradiated medium.

In an irradiated medium radiation reaching a point consists of primary and scattered radiation. The scattered radiation becomes more important as the depth is increased.

In this investigation, the spectral distributions of scattered radiation at 1.47 cm inside, at 1.88 cm outside the boundary of the field and at the central axis were measured with a scintillation spectrometer for two qualities of X-rays, 280 KVP, HVL of 2.5 mm Cu and 140 KVP, HVL of 1.45 mm Al. A circular beam of 100 cm² at FSD of 60 cm was used. Measurements were carried out at 5 cm depth for 280 KVP and 2 cm depth for 140 KVP.

It was found that for 280 KVP radiation, the shapes of the integrated spectra inside the field, outside the field and at the centre are nearly the same. However, the dose received at 1.47 cm inside is 73% of that at the centre and 1.88 cm outside is 37% of that at the centre. It should be pointed out that at the centre, the scattered radiation contributes about half the total dose.

For 140 KVP radiation, the peak of the scattered spectrum becomes broader as the distance from the centre is increased. The dose received

at 1.47 cm inside is 83% of that at the centre and 1.88 cm outside is 25% of that at the centre. For the central point the scattered radiation accounts for approximately 50% of the total dose received.

Comparisons were made with doses calculated by a method suggested by Clarkson together with the depth dose data. Reasonable agreement was found.

I. INTRODUCTION

In order to understand the effects of radiation on an irradiated medium, the spectral distribution of the radiation at the point in question is required. The radiation reaching a point within an irradiated medium consists of primary radiation which reaches the point without interaction and the scattered radiation which has undergone one or more Compton scatterings. The scattered radiation will, in general be incident on the point from all directions and the spectral distributions will be different in each direction. For most applications of spectral information in radiological physics the direction of incidence of the radiation is immaterial. Such applications include calculations of absorbed dose, ionization in a small cavity and distribution of linear ion density or LET. All that is required in these cases is the spectral distribution integrated over all angles. As an illustration consider the calculation of absorbed dose. Suppose that the spectral distribution incident at some point with photon energy k (KeV) at angle $\vec{\Omega}$ is $N(k, \vec{\Omega})$ photons per cm^2 per steradian per photon energy interval (KeV). The area is always taken perpendicular to $\vec{\Omega}$. Let $\mu_a(k)$ be the real absorption coefficient of the material in cm^2 per g. Then the energy absorbed in the material from photons incident at angle $\vec{\Omega}$ is $k \cdot N(k, \vec{\Omega}) \cdot \mu_a(k)$ KeV per g per steradian per KeV. The energy absorbed from photons travelling in all directions is

$$\int_{\Omega} k \cdot N(k, \vec{\Omega}) \mu_a(k) d\vec{\Omega} = k \cdot \mu_a(k) \int_{\Omega} N(k, \vec{\Omega}) d\vec{\Omega}.$$

The integral on the right hand side of the equation represents simply the spectrum integrated over all angles.

With a scintillation spectrometer of the total-absorption type one can measure the spectrum of the radiation incident on a small area ΔA within a small solid angle $\Delta \Omega$ where ΔA and $\Delta \Omega$ are determined by the geometry of the collimating system. That is, one measures a quantity proportional to $N(k, \vec{\Omega})$ at a number of angles and at a number of photon energies. Most of the measurements up to the present time (1-4) have been made for points on the central axis of a circular beam of radiation with an apparatus which could be rotated only about an axis at right angles to the beam. If one represents the angle between the incident beam and the measured scattered beam by Θ and the angle of rotation about the beam axis by φ (see Fig. I) one can write the integrated spectra as

$$N(k) = \int_{\Omega} N(k, \vec{\Omega}) d\vec{\Omega} = \int_0^{\pi} \int_0^{2\pi} N(k, \vec{\Omega}) \sin\Theta d\varphi d\Theta.$$

However, for the central axis of a circular field $N(k, \vec{\Omega})$ does not depend on φ and, therefore

$$N(k) = \int_0^{\pi} 2\pi \sin\Theta N(k, \vec{\Omega}) d\Theta.$$

In the present investigation the apparatus has been designed so that both Θ and φ may be varied. With this apparatus it is possible to obtain integrated spectra for points where there is no radial symmetry. This thesis reports measurements of the spectral distributions of scattered radiation at points inside and outside the boundary of a circular beam of X-rays for two different qualities, 280 KVP, HVL 2.5 mm of Cu and 140 KVP, HVL 1.45 mm Al. The spectral distribution of scattered radiation at the central axis of the beam was also measured for comparison purposes.

II. APPARATUS

The apparatus used is basically the same as that described by T.J. Griffith (1) and is shown in Fig. I. The apparatus consists of a lucite tank 45 cm in diameter and 30 cm long mounted on a steel frame. Various amounts of water can be put into the tank. A small lucite tube with a closed end is mounted midway between the ends of the tank and extends from the centre axis of the tank to the curved surface. A shutter with a 1/2 " hole in the middle is mounted outside the tank and followed by a collimating system and a housing for the detecting system. The shutter is incorporated to facilitate the background counting. To measure the background, the shutter is replaced by a solid lead block so that photons passing through the lucite tube will not reach the detecting system. A hole is drilled through the shielding to admit a beam of radiation for calibration purposes. The whole apparatus, including the cylinder, can be rotated about the axis of the cylinder in order to vary the angle θ .

The apparatus described above may be used for measurements at points on a vertical axis of radial symmetry but must be modified for less symmetrical geometries. Such a modification was accomplished as follows:

On the steel frame, a small pivoted screw jack was mounted directly below the end of the lucite tube. In actual measurements, the whole apparatus is raised slightly so that it is pivoted by the screw jack. Most of the weight of the apparatus is carried by the

APPARATUS

HOUSING FOR
CRYSTAL &
PHOTO-MULTIPLIER

TO
ANALYZING
SYSTEM

PIVOT

FIGURE I

pivot while the four casters keep it from tilting. This enables the apparatus to be rotated about a vertical axis through the end of the lucite tube.

In Fig. I, the scattering angle and azimuthal angle are defined. The scattering angle, Θ , is defined as usual, that is, the angle between the direction of incident photon and that of the scattered photon. The scattering angle, Θ is zero when the direction of both is the same. The azimuthal angle is the angle produced by rotating the whole apparatus about the vertical axis through the centre of the tank. φ is zero when the lucite tube sees a minimum amount of irradiated field as shown in Fig. II.

Photons striking the end of the lucite tube were collimated and then incident on a 2" diameter and 1 5/8" long NaI(Tl) crystal. The crystal had a very thin window, 0.001" Al and was obtained from Harshaw Company. The collimating system was such that only a portion of the photons striking the end of the lucite tube was accepted. The light pulses produced in the crystal by the photons were detected by a Dumont K1234 10-stage photomultiplier. A positive high voltage of about 1000 volts, obtained from a Baird-Atomic Model 312 power supply, was supplied to the anode of the photomultiplier with the cathode at ground potential. The output pulse was coupled to a 6J6 cathode follower for impedance matching. The output, having been amplified by a Baird-Atomic Model 204-B linear amplifier, was fed to a Baird-Atomic Model 510 pulse height analyzer, and then to a Baird-Atomic Model 131 A scaler. A block diagram of the whole system together with circuit diagram of

FIGURE II

cathode follower is shown in Fig. III.

Using the apparatus described, the spectra of scattered radiation at the centre and at the points 1.47 cm inside and 1.88 cm outside the boundary of a 100 cm² circular field at a focal skin distance (the distance between the target and the surface of the water) of 60 cm were measured. Measurements were carried out at 5.0 cm depth for 280 KVP X-rays, and at 2.0 cm depth for 140 KVP X-rays. Both kinds of radiation were obtained from a Picker Vanguard machine in the Saskatoon Cancer Clinic.

FIGURE III

III. CALIBRATION

A calibration curve is necessary to convert the base line voltage readings on the pulse height analyzer into photon energy units (KeV). The gamma-rays from Ba^{133} and K-characteristic X-rays from various materials were used as energy calibration sources. Ba^{133} emits two gamma-rays of 79 and 355 KeV. The gain of the amplifier was adjusted so that the centre of the 355 KeV-peak was obtained at a base line setting on the analyzer of 60 v using a channel width of 2 volts. Then the base line voltage setting corresponding to the 79 KeV gamma-ray was recorded.

To obtain the characteristic X-rays of various materials, the materials were bombarded by X-rays from a General Electric Maximar machine and the K-characteristic X-rays from these materials were detected by the NaI(Tl) crystal at approximately 90 degrees from the incident beam (See Fig. IV).

Since $\text{K}\alpha_1$ line has a greater intensity than $\text{K}\alpha_2$ line, approximately 3 to 1, the energy of the $\text{K}\alpha_1$ line was used as K-characteristic X-ray energy of the various materials.

A list of materials used in the experiment together with their K-characteristic X-ray energies (5) and corresponding base line voltage setting is shown in the following table.

TABLE I: MATERIALS USED FOR CALIBRATION

Material	Characteristic X-Ray Energy (KeV)	Base Line Voltage
Zirconium	15.8	1.45
Tin	25.3	3.30
Barium	32.2	4.52
Cerium	34.7	4.96
Tungsten	59.3	9.30
Lead	75.0	12.22
	<u>γ-Rays (KeV)</u>	
Ba ¹³³	79	13.3
Ba ¹³³	355	60.0

The Calibration curve so obtained is shown in Fig. V. It can be seen that the curve is nearly linear except near the low energy end. The curvature of this curve will be discussed in a later section (see Treatment of Data).

FIGURE IV

FIGURE V

IV. METHOD OF ALIGNMENT

It is very important especially for the points near the boundary of the field to position the apparatus correctly. At first, the head of the X-ray machine was adjusted so that the beam was directed vertically downward. The apparatus was moved under the machine and the height of the latter was adjusted to give the desired focal skin distance, in this case, 60 cm. It was now necessary to position the apparatus so that the end of the lucite tube was at the geometrical centre of the beam. The positioning for the central axis point was done as follows:

The apparatus was moved away and a plumb-bob was hung from the centre of the diaphragm which limited the size of the field. The position of the plumb-bob was marked on the floor. Then the apparatus was positioned so that the pivot point coincided with the "mark" on the floor (see Figs. I and VI). Since the pivot is directly below the end of the lucite tube, this positioning would place it at the centre of the beam.

It was found earlier, by exposing an X-ray film in the beam that the field had a rather large and non-symmetrical penumbra. In order to see the effect of the irregular penumbra on the scattered spectra from different directions in a horizontal plane, spectra were measured for various azimuthal angles φ . It was found that these spectra had nearly the same shape and magnitude. This confirms our assumption that the radiation is radially symmetrical for the central axis point.

FIGURE VI

Although the penumbra effect can be disregarded in the measurement of scattered radiation at the central axis, it cannot be overlooked for the points near the boundary. If the measurements were taken near the edge where the penumbra is greatest, the results would be erroneous. For instance, a point outside the boundary is actually inside the penumbra. The penumbra effect was minimized by choosing the part of the boundary where it is least and by using a trial and error method as follows:

After the position of the plumb-bob was marked on the floor, the pivot on the apparatus was made to coincide with a point at an appropriate distance away from the "mark" on the floor. Then the apparatus was orientated by geometry so that the lucite tube saw a minimum amount of the field. This would correspond to $\varphi = 0$ if the penumbra did not exist. From the geometry of the system it can be seen that the spectrum at $\varphi = 90^\circ$ should be the same as that at $\varphi = 270^\circ$. This fact was used to orientate the apparatus to conform to the definition. For a fixed scattering angle θ , say 90° , the spectrum at $\varphi = 90^\circ$ was taken. Then the apparatus was rotated 180° and another spectrum was taken. If both spectra were identical, the φ orientation would be correct. If, however, they differed, a spectrum at a new φ value, slightly different from 90° , say 95° , was taken and compared with that obtained at 275° . This process was repeated until an orientation such that both spectra were nearly identical. Then a correction was applied to the zero reading on the φ scale. The above procedure also corrected for the non-uniformity of the field near the point in question.

To ensure the point outside the boundary was indeed outside the irradiated area, a Baldwin-Farmer sub-standard dosimeter was used to detect the amount of radiation at the point in question with the X-ray machine turned on before the apparatus was in its place. It was found that when the dosimeter was placed outside the expected boundary, the reading was very small indicating that the point was indeed outside the primary beam.

V. PROCEDURE

After the apparatus was correctly orientated, field area and depth of water were properly set, spectra were taken for $\theta = 50^\circ$, 70° , 90° , 120° and 135° for each value of φ . Spectra were measured at $\varphi = 0^\circ$, 45° , 90° , 135° and 180° . For the central point, spectra at $\theta = 18^\circ$, 30° , 60° , 90° , 120° and 135° were taken.

In order to obtain a spectral distribution, the base line voltage setting on the pulse height analyzer was varied and the counts for fifteen seconds at each base line voltage setting were taken. The channel width was set constant at 2 volts throughout the whole experiment.

Background readings were taken with the shutter replaced by a solid lead block and the X-ray machine turned on. It was found that the background was nearly the same whether the X-ray machine was on or off indicating that the system was well-shielded. Background readings were negligible above 45 KeV.

The long term stability of the spectrometer was very good; however, the calibration was checked every hour or so by testing if the 355 KeV gamma-ray from Ba^{133} would still give a 60 volt base line reading. If it was found that it had drifted, the gain of the linear amplifier was adjusted until the peak appeared at 60 volts.

For the 280 KVP X-rays, the output of the machine was quite constant; however, for the 140 KVP, it was found that the output varied slowly. To correct for this variation, a large ionization

chamber was inserted between X-ray target and the phantom. The ionization chamber was connected to a monitor circuit which would give an indication of ionization current. All the readings would be normalized to an arbitrary monitor reading.

Some of the spectra with background subtracted are shown in Figs. VIIa and VIIb.

FIGURE VIIa

FIGURE VIIb

VI. TREATMENT OF DATA

The spectra were converted from base line voltage to energy units (KeV) by a calibration curve. It was noted that the calibration curve was not a straight line, but slightly curved at the low energy end. The ordinates of the measured spectra were in units of relative counts per second per unit channel width. The non-linearity of the calibration curve effectively changes the size of the photon energy interval per unit channel width. Therefore, it was necessary to correct for the difference of slope in the calibration curve. The calibration curve was divided into intervals and the slopes at the mid-points of these intervals were measured. The slope was assumed to be constant throughout any interval and all the ordinate readings in the spectra were normalized to the slope at 355 KeV. Table II shows the slope and correction factors.

TABLE II: CORRECTION FACTORS
FOR NON-LINEARITY OF CALIBRATION CURVE

Energy Range (KeV)	Correction Factor
15 - 55	1.13
65 - 85	1.11
95 - 105	1.08
115 - 155	1.05
165 and up	1.00

The spectra were then corrected for the limited resolution of the photomultiplier tube by an approximate method (6). The effect of this correction was an increase of the peak height of a spectrum with a decrease at both ends. This would be expected since this correction was the reverse of Gaussian spreading. In a Gaussian spreading some of the photons from the peak would appear at energies higher or lower than the peak energy. So the reverse would show an increase in peak height.

The spectra were then corrected for loss of energy from the crystal. This correction had been discussed fully in a paper by Rawson and Cormack (7). The 20 KeV intervals in the matrix worked out by Rawson and Cormack were not fine enough for this work. Therefore, a similar matrix with 10 KeV intervals was constructed for this correction. For these energies most of the energy loss is due to the escape of iodine X-rays.

After these corrections a double integration, over φ and θ , was performed to obtain the integrated spectrum for each point in question. The integration over all φ was performed first. This was done by plotting the relative number of counts per 15 seconds against angle φ while energy and scattering angle θ were held constant. This plotting produced families of curves. A few of these curves are shown in Fig. VIII. The integration was performed by measuring the areas under them with a planimeter. The values of areas would give $\int_0^{2\pi} N(k, \vec{\Omega}) d\varphi$ where $N(k, \vec{\Omega}) d\varphi$ is the number of photons with a particular energy at a particular scattering angle, θ with azimuthal

FIGURE VIII

angles between φ and $\varphi + d\varphi$. The integration over θ was done by multiplying $\int_0^{2\pi} N(k, \bar{\Omega}) d\varphi$ by $\sin \theta$, plotting against θ as shown in Fig. IX and measuring the enclosed areas with a planimeter. These values would give $\int_0^{\pi} \int_0^{2\pi} N(k, \bar{\Omega}) \sin \theta d\varphi d\theta$, photons scattered from all directions.

Since the radiation is independent of φ for the point on the central axis, the integration over φ was done simply by multiplying by 2π . Other than this difference, the procedure in treating the data was the same as described above.

The fully integrated spectra are shown in Figs. Xa and Xb and are tabulated in Table III.

TABLE III: SCATTERED SPECTRA

F.S.D. = 60 cm, Area = 100 cm², N(k) = No. of Photons/cm²/sec/KeV

Photon Energy (KeV)	280 KVP, Depth = 5 cm			140 KVP, Depth = 2 cm		
	Centre N(k)	1.47 cm Inside N(k)	1.88 cm Outside N(k)	Centre N(k)	1.47 cm Inside N(k)	1.88 cm Outside N(k)
25	187	73	88	622	500	62
35	715	502	395	2138	1733	472
45	1700	1427	843	1712	1378	445
55	3280	2520	1354	1514	1294	411
65	4380	3165	1727	818	824	220
75	4670	3420	1708	359	338	104
85	4300	3185	1474	186	158	40
95	3521	2510	1172	50		
105	2805	2028	1027			
115	2080	1469	733			
125	1589	1088	555			
135	1152	802	370			
145	848	577	270			
155	662	427	181			
165	359	302	101			
175	251	214	78			
185	189	110	39

FIGURE IX

FIGURE Xa

FIGURE Xb

VII. DISCUSSION OF RESULTS

A. General

The following discussion applies to both 280 KVP and 140 KVP radiation. For the points outside the irradiated field the spectra appear to be nearly independent of scattering angle θ , for $\varphi = 0^\circ$, 45° and 90° . The curves for different θ would fall on top of each other and so have not been plotted. The radiation spectrum appears to be independent of φ also from $\varphi = 0^\circ$ to $\varphi = 90^\circ$. Fig. VIII shows the counting rate at various energies plotted against φ for $\theta = 90^\circ$. In view of the above observations, all radiation scattered in from outside the field appears to be independent of direction. As seen in Fig. VIII the counting rate increases sharply between $\varphi = 90^\circ$ and 135° . There probably is a discontinuity at the point where the spectrometer begins to accept radiation from the irradiated field. In Fig. VIII it should be pointed out that only the portions of the curves from $\varphi = 0^\circ$ to $\varphi = 180^\circ$ were actually measured, the rest of the curves being obtained by reflection about $\varphi = 180^\circ$.

B. 280 KVP

As seen in Fig. Xa the shapes of the integrated spectra inside the field, outside the field and at the centre were nearly the same, except that the peak for the point outside is shifted slightly towards the lower energy end. It will be noted that there is a large decrease

in the amount of scattered radiation as the boundary of the field is crossed.

In order to determine the dose received at the various points, the relative number of photons per cm^2 per sec per KeV was converted into roentgens per sec per KeV, plotted against energy and then integrated over all energies. It was found that the dose at 1.47cm inside the field was 73% of that received at the centre and at 1.88cm outside, 37% of that at the centre.

Doses received at the points off the beam axis were calculated by a method put forth by Clarkson (8) and using the depth dose data of Johns et al (9). This method involves dividing the irradiated area into sectors with the point in question as common origin. The mean radius of each sector is measured. The contribution of scattered radiation from each sector is equal to $\frac{\Delta\omega}{360}$ of the scattered radiation from a circular field of the same radius where $\Delta\omega$ is the size of the sector in degrees. By adding up the contributions from all sectors, the scattered radiation at the point in question can be obtained. If a point is outside the irradiated area, the contribution from a sector will be the difference between that corresponding to the total radius and that corresponding to the portion of the radius lying outside the field. The scattered radiation dosage at the points off the beam axis was calculated with 10-degree intervals. The data were normalized to a dose at the centre of 100 roentgens. The results are shown in Table IV.

TABLE IV: SCATTERED DOSE: 280 KVP

DOSE IN ROENTGENS

	Experimental Results	From Depth Dose Data	From Bruce's Data		
	(Total)	(Total)	Total	Once- Scattered	Multiply- Scattered
Centre	100	100	104	55	49
1.47 cm Inside	73	73	69	42	27
1.88 cm Outside	37	21	—	—	—

It can be seen that the agreement is very good for the point inside the field. However, there is a large discrepancy between the values for the outside point. This discrepancy can be explained at least partly by the large and unreliable extrapolation of the depth dose data and back-scatter factors required for this point (8).

Bruce (10) has worked out tables for calculating scattered radiation spectra from primary spectral data. Using a primary spectrum measured by Cormack et al (11), the scattered spectrum at the centre was calculated from tables based on Bruce's data. Although Bruce worked out the scattered spectra for points at the central axis only, the scattered spectra at points off the beam axis may be found by the following method. The irradiated area was divided up into sectors as in Clarkson's method (8) and the contributions from each sector were summed up. In this case the contribution from each sector

takes the form of a spectrum instead of a dose.

The measured spectra were normalized so that the measured and the calculated spectra for the central point would have the same peak height. The comparison is shown in Fig. XI. It can be seen that for the central point the measured spectrum is shifted somewhat to higher energies. For the point inside the field, the magnitude agrees very well, but the shift is much more pronounced. The increase in the discrepancy can be partly attributed to the interpolations and extrapolations from Bruce's calculations. Although the experimental spectra and those calculated from Bruce's tables do not agree very well, the total doses calculated from these spectra are in reasonable agreement as can be seen in Table IV. For the point outside the irradiated area more interpolations and extrapolations would be required. Therefore, it was thought that such a comparison was not worthwhile and was therefore not attempted.

Since Bruce had calculated the once-scattered and the multiply-scattered photons separately, it is interesting to see what portion of the spectrum was due to the once-scattered photons. Graphs showing the separation are shown in Figs. XIIa and XIIb. The dose corresponding to the once-scattered and to the multiply-scattered radiation is given in Table IV. The contribution of once-scattered photons to the total dose received consisted of 47% for the central point compared to 39.5% for the point 1.47 cm inside the field. Such a difference would be expected since a greater portion of the photons have to travel farther to reach the point near the edge of the beam. Probably the

FIGURE XI

FIGURE XIIa

FIGURE XI**b**

once-scattered photons will contribute a still lower percentage for the point outside the field.

C. 140 KVP

As seen in Fig. VIIb there seem to be two peaks in the scattered spectra. They are probably due to the single-scattered photons from the primary peaks which occur at approximately 35 and 60 KeV (12). The energies of the scattered peaks agree roughly with those given by the Compton scattering formula. No shift in these peaks was noted as the scattering angle θ was varied. This would be expected because the energy of the scattered photons varies very little with the scattering angle for these low incident energies, 35 and 60 KeV, and the resolution was not good enough to show the change. These scattered peaks also appear in the integrated spectra, but more smeared out.

Unlike the scattered spectra for the 280 KVP, the shape of the measured spectrum as well as its magnitude changes with increasing distance from the beam centre (see Fig. Xb). As the boundary is crossed the magnitude is greatly reduced. The percentage of reduction was more than that given by the 280 KVP radiation. Martin and Evans (13) have measured the scattered dose outside the irradiated field as a function of distance from the centre of the beam. They showed that as the distance increases the dose falls off more rapidly for the softer radiations than for harder ones. Our calculations confirm their results qualitatively.

A comparison of the dose calculated from our measured spectra

with that from depth dose data was made for the central point and the inside point only, since the depth dose data are not adequate to make calculations for the outside point. Since Jennings data (14) give maximum focal skin distances of 30 cm the data had to be extrapolated to a focal skin distance of 60 cm. This was done by the method described by Johns, Bruce and Reid (15). From Bruce's investigations, the ratio between the total dose and the primary dose at that depth is constant without regard to the focal skin distance provided that the depth and area at that depth are the same.

FIGURE XIII
FOCAL SKIN DISTANCE EXTRAPOLATION

$$\frac{(\text{Total Dose})_1}{(\text{Primary Dose})_1} = \text{constant}$$

To have the same area at depth d , A_2 corresponding to f_2 must be reduced by a factor $\left(\frac{f_1}{f_1+d}\right)^2 \left(\frac{f_2+d}{f_2}\right)^2$. The primary dose corresponding to f_2 will also be reduced by the same factor. Then

$$\frac{(\text{TOTAL DOSE})_2}{\left(\frac{f_1}{f_1+d}\right)^2 \left(\frac{f_2+d}{f_2}\right)^2 (\text{PRIMARY})_1} = \text{constant.}$$

From these considerations, extrapolation to a new focal skin distance f_2 will be carried out as follows:

The percentage depth dose data for focal skin distance of f_1 were plotted against area. Values corresponding to an area of

$$A_2 \left(\frac{f_1}{f_1+d}\right)^2 \left(\frac{f_2+d}{f_2}\right)^2 \text{ were recorded. These values were then}$$

divided by $\left(\frac{f_1}{f_1+d}\right)^2 \left(\frac{f_2+d}{f_2}\right)^2$ to obtain the percentage depth dose for f_2 .

The remainder of the calculation of the dose at the point near the beam edge was the same as that for 280 KVP radiation. It was again normalized so that the dose at the centre was equal to 100 roentgens. The results are shown in Table V.

TABLE V: SCATTERED DOSE: 140 KVP
DOSE IN ROENTGENS

	Experimental Results	Calculated From Depth Dose Data
Centre	100	100
1.47 cm Inside	83	77
1.88 cm Outside	25	—

It can be seen that the agreement is reasonably good although not so good as the results for 280 KVP X-rays. Part of the discrepancy can be attributed to the inaccuracy of the percentage depth dose data. A comparison of data obtained by Jennings and those by Johns et al (16) shows deviations of the order of 10%.

Bruce's (10) tables are not applicable to radiations in these energies because the lowest incident energy that Bruce considered was 50 KeV while the primary of 140 KVP radiation had a peak height at about 35 KeV (12).

SUMMARY

Scattered radiation spectra at both sides of the boundary and at the geometrical centre of an X-ray beam were measured with a scintillation spectrometer. Two types of radiations were used, 280 KVP with HVL of 2.5 mm Cu and 140 KVP with HVL of 1.45 mm Al.

The dose received at 1.47 cm inside the beam edge was 73% of that at the centre and 1.88 cm outside was 37% of that at the centre for the 280 KVP radiation. For 140 KVP radiation, the dose at 1.47 cm inside and 1.88 cm outside was found to be 83% and 25% of that at the centre respectively.

Comparisons were made between the measured spectra and those calculated from Bruce's tables for the 280 KVP radiation. The measured spectra agree fairly well both in magnitude and shape with the calculated values. The doses received at these points were compared with those calculated from depth dose data and found to be in fair agreement.

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