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A Modified Conjugate Counting Technique for Quantitative Measurement of Radioactivity in Vivo

MASTER

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The quantitative measurement of organ and whole-body distribution of an internally dispersed radionuclide in human is important in making realistic radiation-absorbed dose estimates, studying biochemical transformations in health and disease, and developing clinical procedures indicative of abnormal functions. The conjugate counting method provides a means of obtaining such quantitative data. However, the accuracy of the quantitative measurement using the conventional method and instrumentation has been above or around 10%. This paper presents a modified conjugate counting method and a new instrumentation design which improves the accuracy to within 5%.

The first slide [1] shows the theoretical basis of the conventional conjugate counting technique. Suppose a uniform sheet source of thickness t is imbedded at a depth of d inside a uniform background of thickness D. If the attenuation of the photon emissions inside the medium is represented by the effective attenuation coefficient μ_{eff}, the detected counts of the upper and lower detectors and their geometric mean are given as shown, where A is the true activity density, S_o is the detector sensitivity, and D is the body thickness. The dependent on the source thickness t is given by the sinh term. Although the geometric mean is independent of the source depth d, the value of which can be obtained from the ratio of the conjugate counts as shown in the second to the last equation.

By using a constant effective attenuation coefficient μ_{eff}, the conventional conjugate counting method assumes that the detector response to a uniform sheet source is exponential as a function of depth inside the body. In practice, this situation is approximated when both the photon energy and the baseline setting are high such that the scatter contribution is negligible. However, the most commonly used radionuclides in nuclear medicine emit photons with relatively low energies such as the 140 keV photons of Tc-99m. As shown in the next slide [2], in these instances the scatter contribution in the detected photons cannot be neglected. The response curve to a uniform sheet distribution deviate from that of a straight line indicating contribution from scatter. A more accurate approximation to the response curve is a two-exponential fit as shown in the slide. The coefficients of the two-exponential approximation, a_1, a_2, μ_1 and μ_2 are determined by a least square fit to the experimental data for the specific energy photon emissions and baseline setting.

Based on the two-exponential approximation to the detector response, the conjugate counting method can be modified as shown in the next slide [3]. Here, the geometric mean is dependent on the sensitivity of the detector, the source geometry and the coefficients of the two-exponential approximation (a_1, a_2, μ_1 and μ_2). Also the geometric mean is dependent on the source depth d. In practical measurement, the sensitivity of the detector system S_o and the coefficients for the two-exponential approximation can be determined experimentally for specific photon energy and window setting. The body thickness can be estimated from transmission measurement. The source depth can be estimated from the ratio of the detected counts using the effective photon attenuation coefficient. Then if the source thickness t can be estimated, the true activity density A can be determined.

In order to obtain accurate quantitative data of organ distribution of radioactivity efficiently, a detector system with high sensitivity and relatively good spatial resolution is required. Furthermore, it is important that the spatial resolution be constant over the body thickness. The detectors chosen in our study are 5 cm x 5 cm NaI(Tl) detectors. The design of a constant-area focused collimator is shown in the next slide [4].

The collimator consists of a hexagonal array of 37 tantalum tubes which are arranged so that the center lines of the tubes are focused at a distance of 28 cm from the collimator face. The septa are filled with lead. By choosing tantalum tubes 7.62 cm (3 in) in length and 3 mm (.23 in) i.d., one obtains an almost constant radius of view for the collimator of about 2.5 cm up to the focal distance. This constant radius of view of the collimator design is important in the quantitative measurement.

The next slide [5] shows the measured geometric line spread function of the constant-area collimator at various distance Z from the collimator face. The measured FWHM (Full-Width-Half-Maximum) of the line spread function is fairly constant at about 2 cm between 14 and 21 cm from the collimator face and diverge slowly at both ends of this region.

In the next slide [6], we show the measured total line spread function of the constant-area collimator at various depths inside water. The measured FWHM also has a fairly constant value up to the focal distance.

The modified conjugate counting technique and the new detector-collimator design are essential in obtaining more accurate quantitative organ and whole-body distribution of radioactivity in vivo. The next slide [7] shows the schematic diagram of a whole-body scanning system designed and built in our laboratory. It consists of eight opposing pairs of 5 cm x 5 cm NaI(Tl) detectors arranged linearly for simultaneous conjugate counting. Each of the 16 detectors is fitted with the constant-area collimator described earlier. A position-encoded scanning bed moves the subject longitudinally and transversely between the detector arrays. A PDP/11-40 computer is interfaced with the whole-body scanning system for system control and data anlysis.

The completed whole-body scanning system is shown in the next slide [8]. The scanning bed moves the patient in and out of a well-shielded iron room for low background counting. The detector arrays are housed right behind the opening. The electronic circuitry cabinet is shown on the left.

We have conducted experiments to study the modified conjugate counting method and to verify the quantitative measurement technique. In the next slide [9], we show the effect of source depth on the geometric mean in different body thicknesses. The dashed curves, obtained when attenuation alone is considered, show an independence of source depth. The solid curves, which are derived from the two-exponential approximation, are in good agreement with the experimental data.

The next slide [10] shows the dependence of the geometric mean on the source thickness. The predictions from the two-exponential approximation also show good agreement with the experimental data.

To verify the quantitative measurement technique using the modified conjugate counting method, we measured the radioactivity in isolated sources of finite sizes by area scanning. The next slide [11] shows the experimental set up for the measurement. The four circular disk sources of different sizes can be placed at different depths inside a water phantom and scanned by the whole-body scanning system. The pixel size used in the scanned image is 1.6 cm. The total activity is given by the product of the activity density obtained from the conjugate counting technique and the area of the image pixel, summed over the region of interest.

The next slide [12] shows the fraction of recovery as a function of the radius of the circular regions of interest which are centered over the sources. It is shown that for all four sources of different sizes, the fraction of recovery is within 5% of total recovery if the area of interest is sufficiently large. The next slide [13] shows the fraction of recovery as a function of the radius of integration at different depths. The total recovery shown here is also better than 5%.

Similar experimentals were carried out using spherical sources [14]. Here, when assuming that the source thickness equals the radius of the spherical sources, we found similar accuracy in our quantitative measurement.

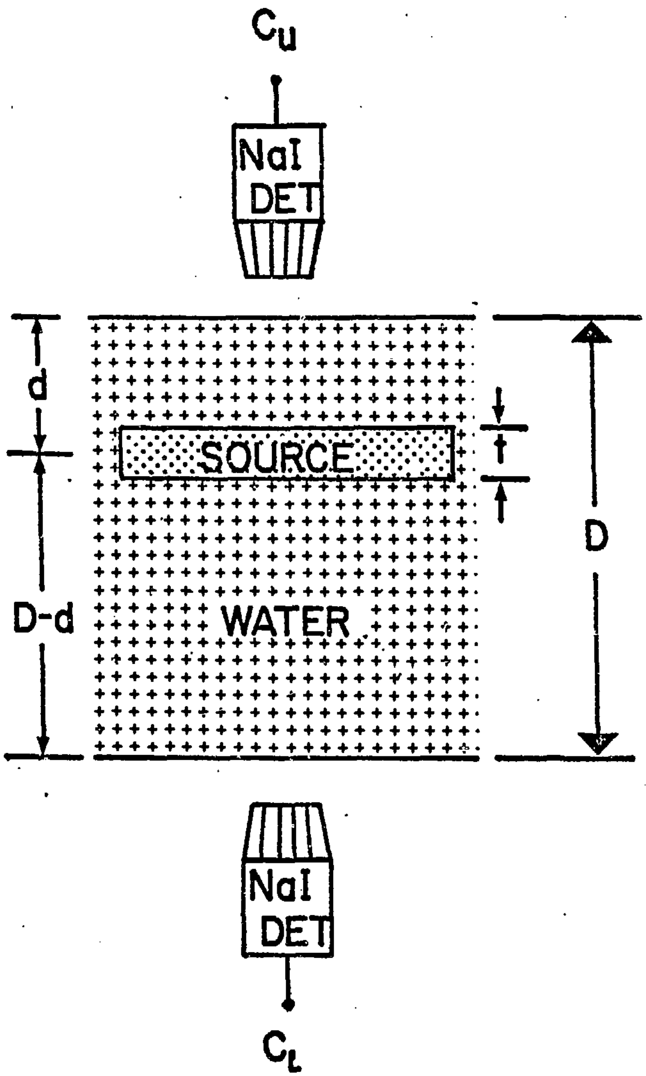
In the next slide [15], we show the humanoid phantom (REMCAL, Alderson Research Laboratories, Inc.) which was used to simulate and verify the quantitative measurement in human. The phantom has individual organ and whole-body compartments which can be filled with different levels of activity. The next slide [16] shows the scan images of a study which simulates the distribution of sodium pertechnetate at about 30 minutes. From left to right are the image obtained from the transmission scan showing the thickness of the phantom, the images obtained from the upper and lower detector arrays and the image of their geometric mean. The images are collected in 32 x 110 matrices with pixel size of 1.6 cm.

The conjugate counting method of quantitative measurement is applied on a per pixel basis. The body thickness is obtained from the corresponding pixel in the transmission image. The source depth is calculated from the ratio of the conjugate counts. A priori knowledge of the organ thickness is used, however, as the source thickness. The total activity in each organ is obtained by summing the results within the corresponding region of interest.

A comparison of the true and measured activity is shown in the next slide [18]. The error is within 5% in the stomach, bladder and whole body and 8% in the thyroid. This higher percentage error found in the thyroid can be attributed to the small dimension of the thyroid and the neck region.

In conclusion, the modified conjugate counting technique is applied in a whole-body scanning system to provide an efficient and accurate means of collecting absolute quantitative organ distribution data of radioactivity in humans. The collection of such data is important for the calculation of radiation absorbed dose and for biokinetic studies of radiopharmaceuticals in humans.

CONJUGATE COUNTING TECHNIQUE
(ATTENUATION ONLY)



UPPER DETECTOR COUNTS

$$C_U = S_0 \cdot A \cdot e^{-\mu_{eff} d} \cdot \frac{\sinh(\mu_{eff} t/2)}{(\mu_{eff} t/2)}$$

LOWER DETECTOR COUNTS

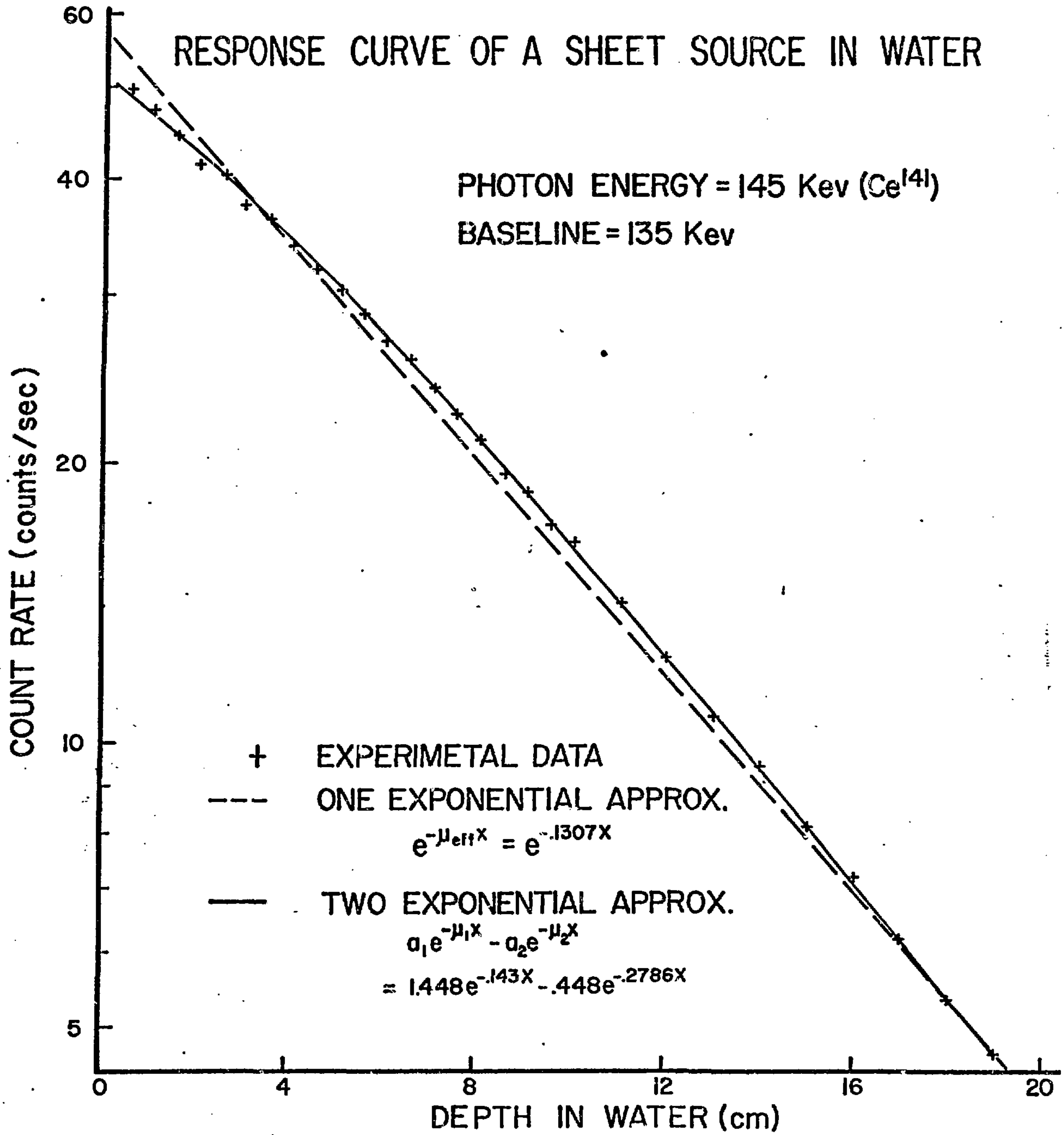
$$C_L = S_0 \cdot A \cdot e^{-\mu_{eff}(D-d)} \cdot \frac{\sinh(\mu_{eff} t/2)}{(\mu_{eff} t/2)}$$

SOURCE DEPTH

$$d = \frac{D}{2} - \frac{1}{2\mu_{eff}} \cdot \ln\left(\frac{C_U}{C_L}\right)$$

GEOMETRIC MEAN

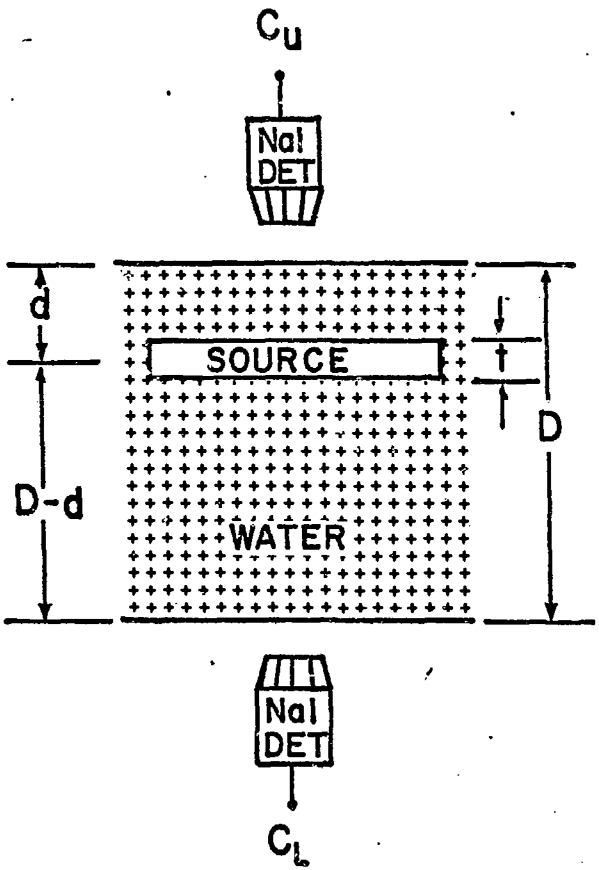
$$\sqrt{C_U \cdot C_L} = S_0 \cdot A \cdot e^{-\mu_{eff} D/2} \cdot \frac{\sinh(\mu_{eff} t/2)}{(\mu_{eff} t/2)}$$



RESPONSE CURVE OF A SHEET SOURCE IN WATER
PHOTON ENERGY = 145 Kev (Ce141)
BASELINE = 135 Kev
COUNT RATE (counts/sec)
60
40
20
10
5
DEPTH IN WATER (cm)
0
4
8
12
16
20
+ EXPERIMETAL DATA
ONE EXPONENTIAL APPROX.
$e^{-\mu_{eff}x} = e^{-.1307x}$
TWO EXPONENTIAL APPROX.
$a_1e^{-\mu_1x} - a_2e^{-\mu_2x}$
$= 1.448e^{-.143x} - .448e^{-.2786x}$

CONJUGATE COUNTING TECHNIQUE

(ATTENUATION AND SCATTER)



UPPER DETECTOR COUNTS

$$C_u = S_0 A \left[a_1 F_1 e^{-\mu_1 d} + a_2 F_2 e^{-\mu_2 d} \right]$$

LOWER DETECTOR COUNTS

$$C_L = S_0 A \left[a_1 F_1 e^{-\mu_1 (D-d)} + a_2 F_2 e^{-\mu_2 (D-d)} \right]$$

GEOMETRIC MEAN

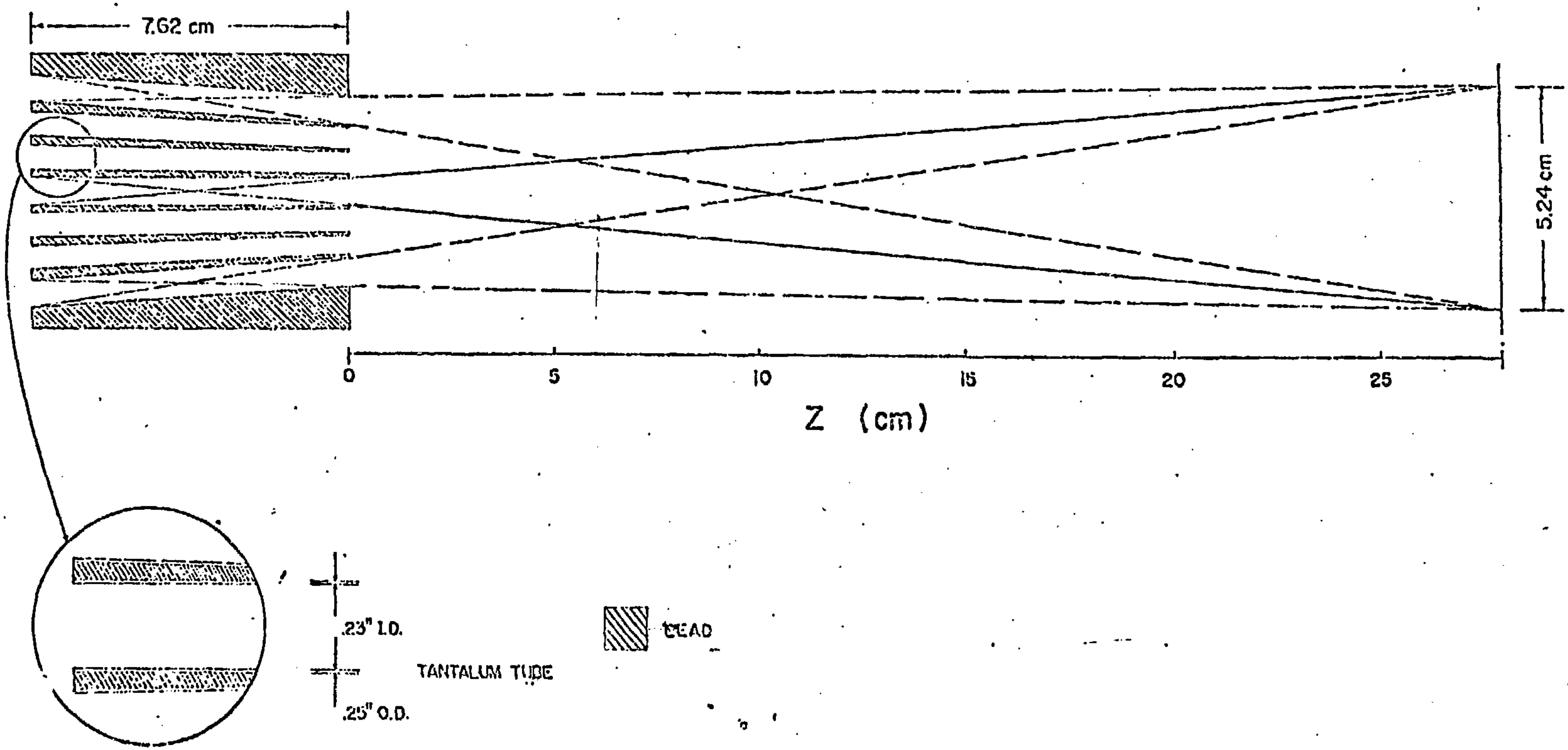
$$\sqrt{C_u C_L} = S_0 A \Big\{ a_1 F_1 e^{-\mu_1 D} \left[a_1 F_1 + a_2 F_2 e^{-(\mu_2 - \mu_1) d} \right]$$

$$+ a_2 F_2 e^{-\mu_1 D} \left[a_2 F_2 + a_1 F_1 e^{-(\mu_1 - \mu_2) d} \right] \Big\}^{1/2}$$

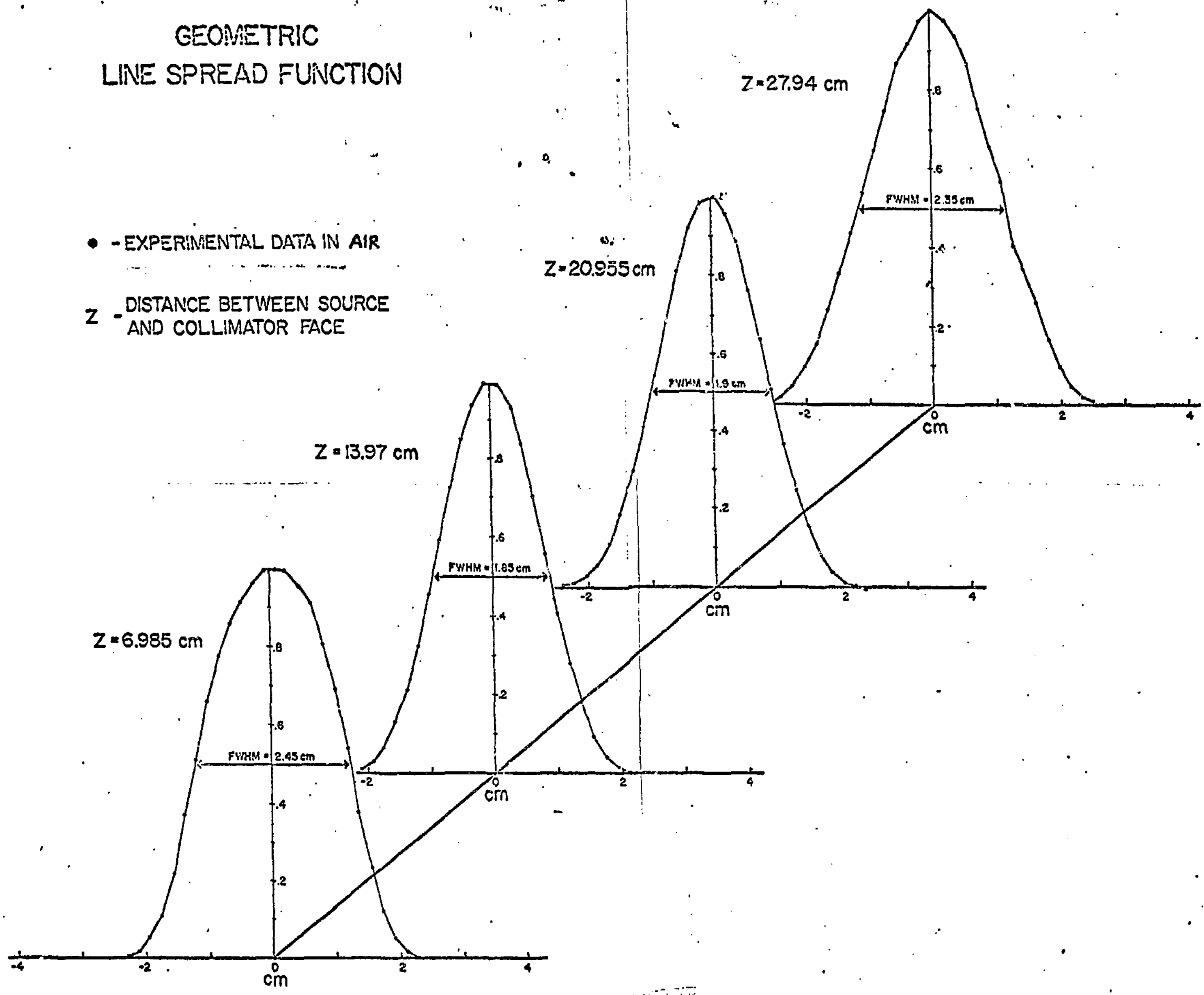
where: $F_i = \dfrac{\sinh(\mu_i t/2)}{(\mu_i t/2)}$ $\qquad i = 1, 2$

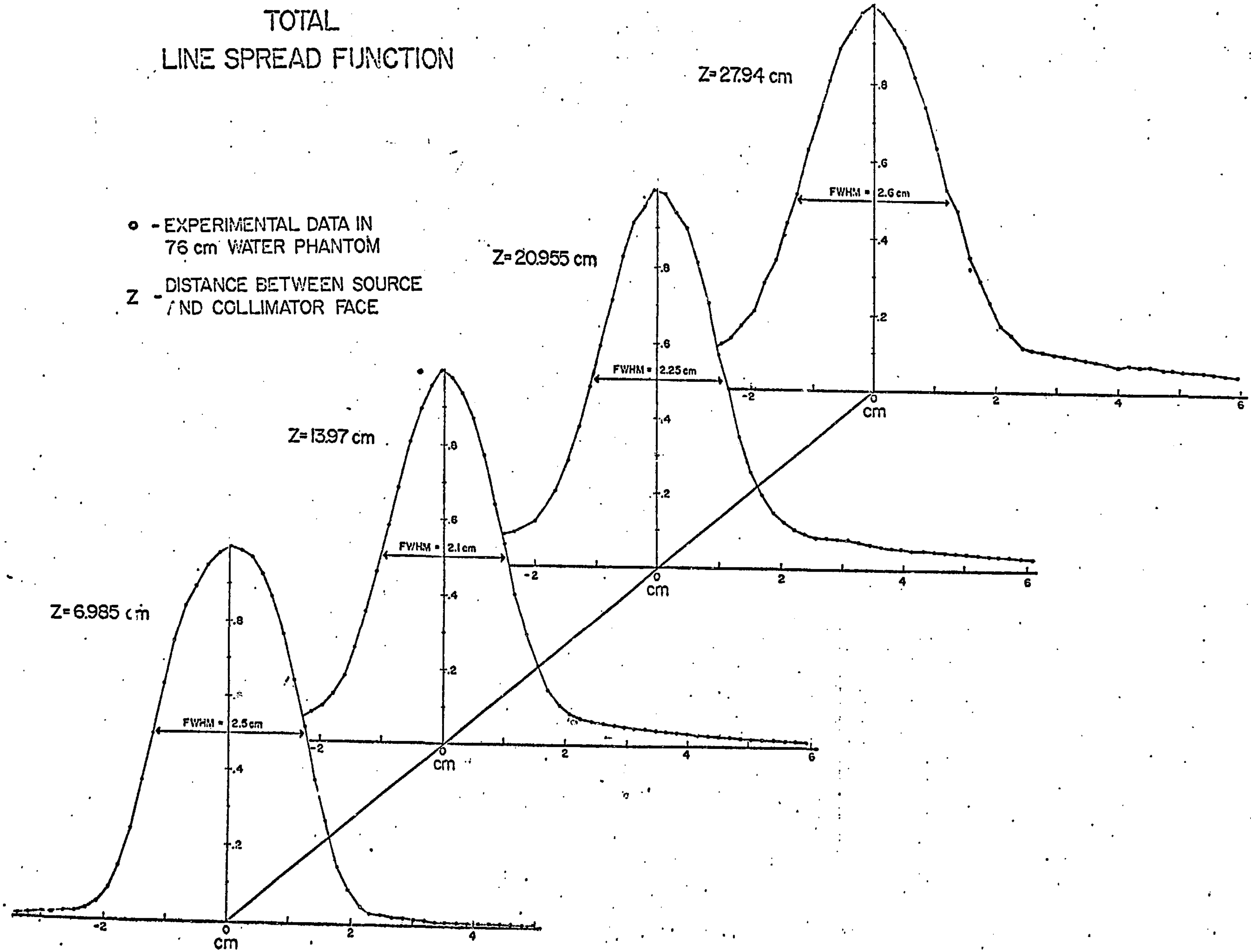
$$d \cong \frac{1}{2} D - \frac{1}{2\mu_{eff}} \ln\left(\frac{C_u}{C_L}\right)$$

CONSTANT-AREA STRAIGHT-HOLE FOCUSED COLLIMATOR
(37 HOLES)

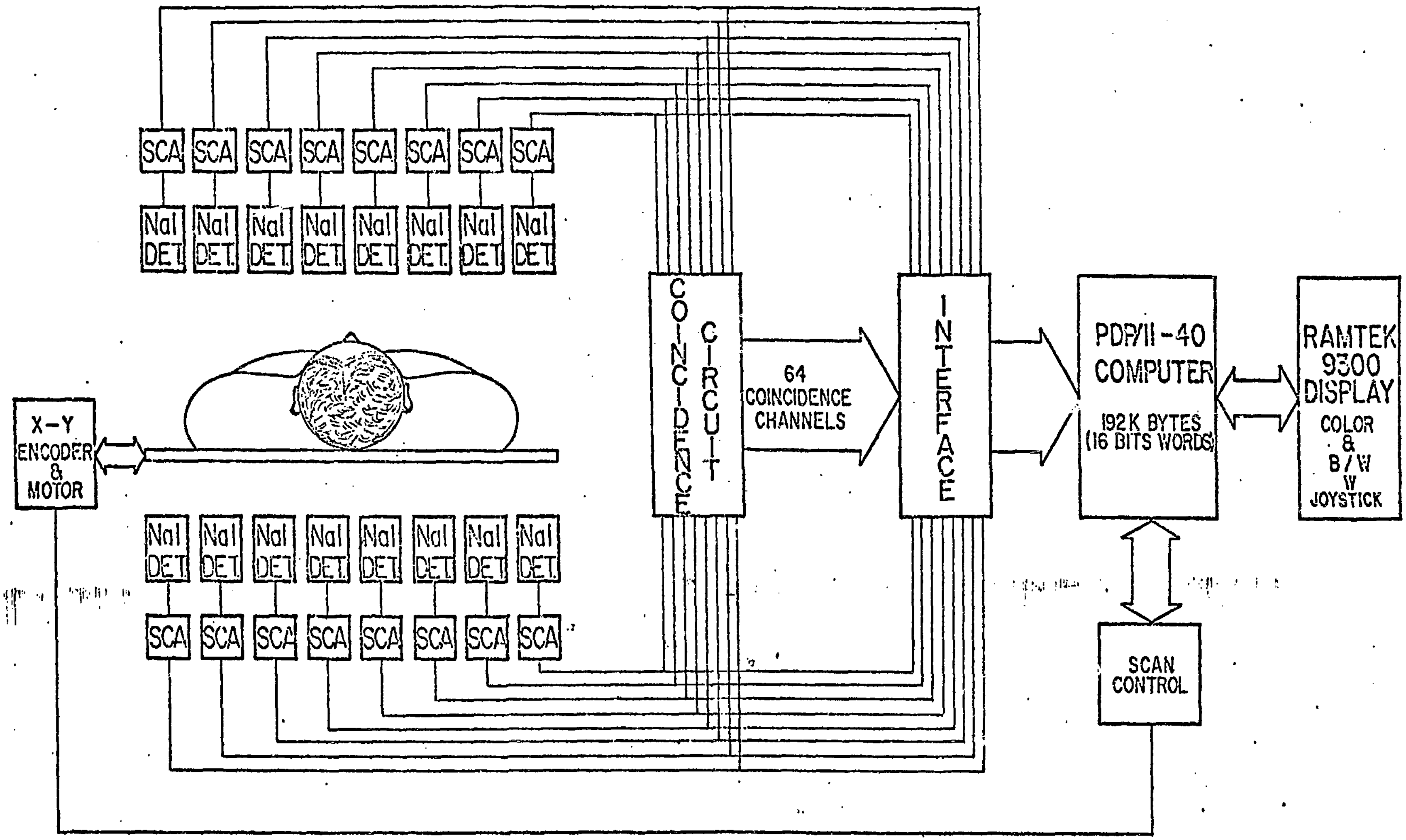


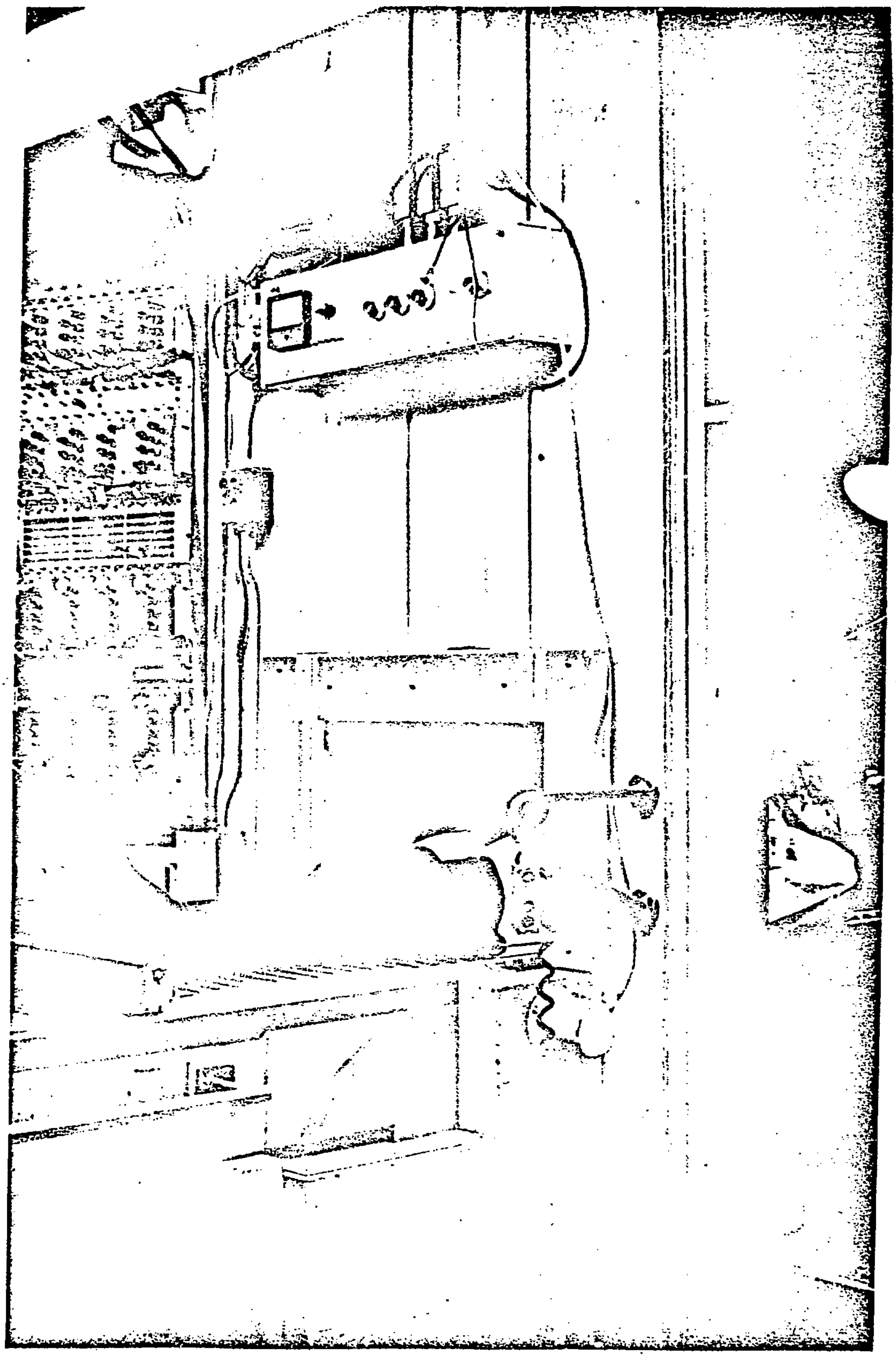
GEOMETRIC LINE SPREAD FUNCTION

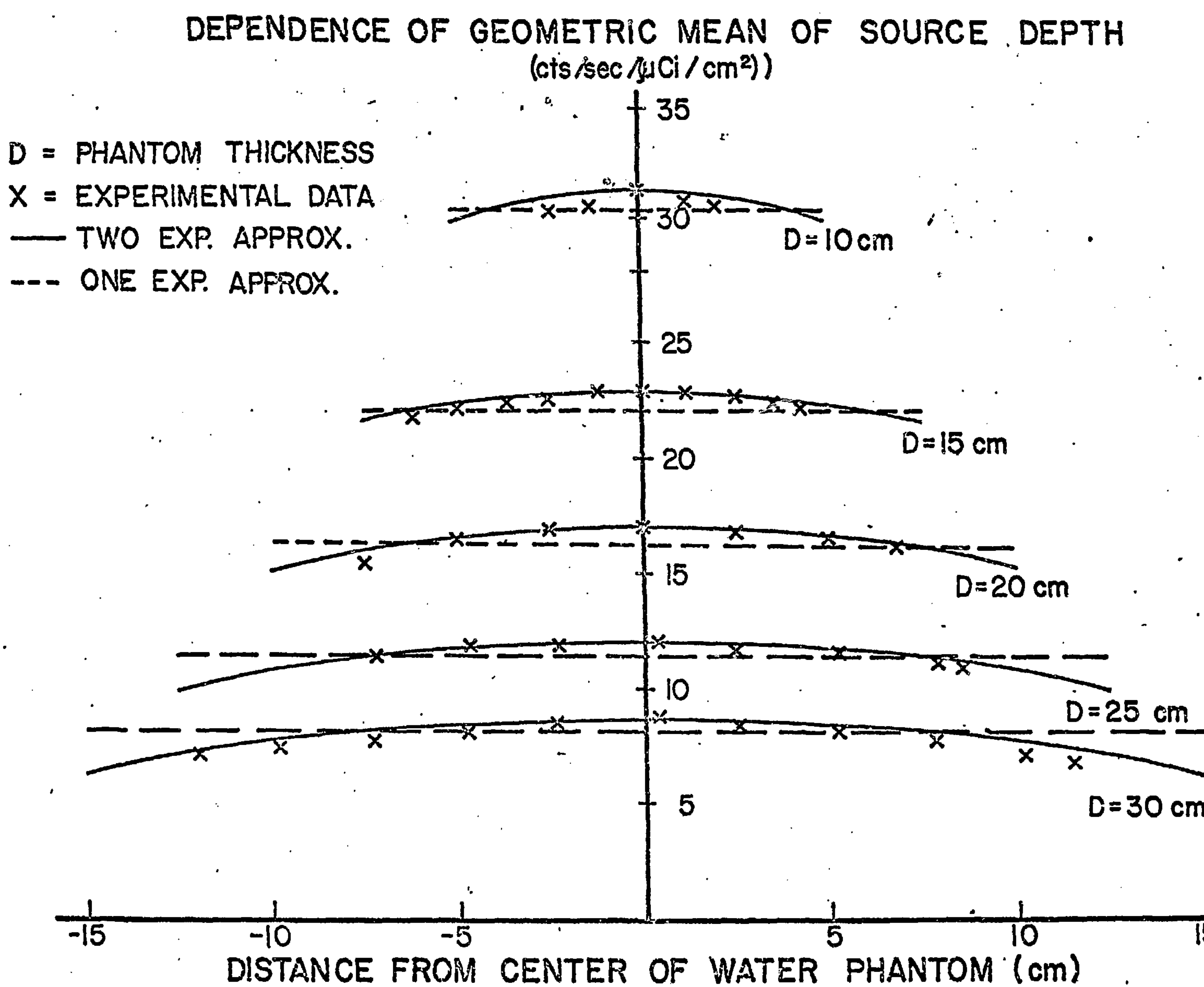


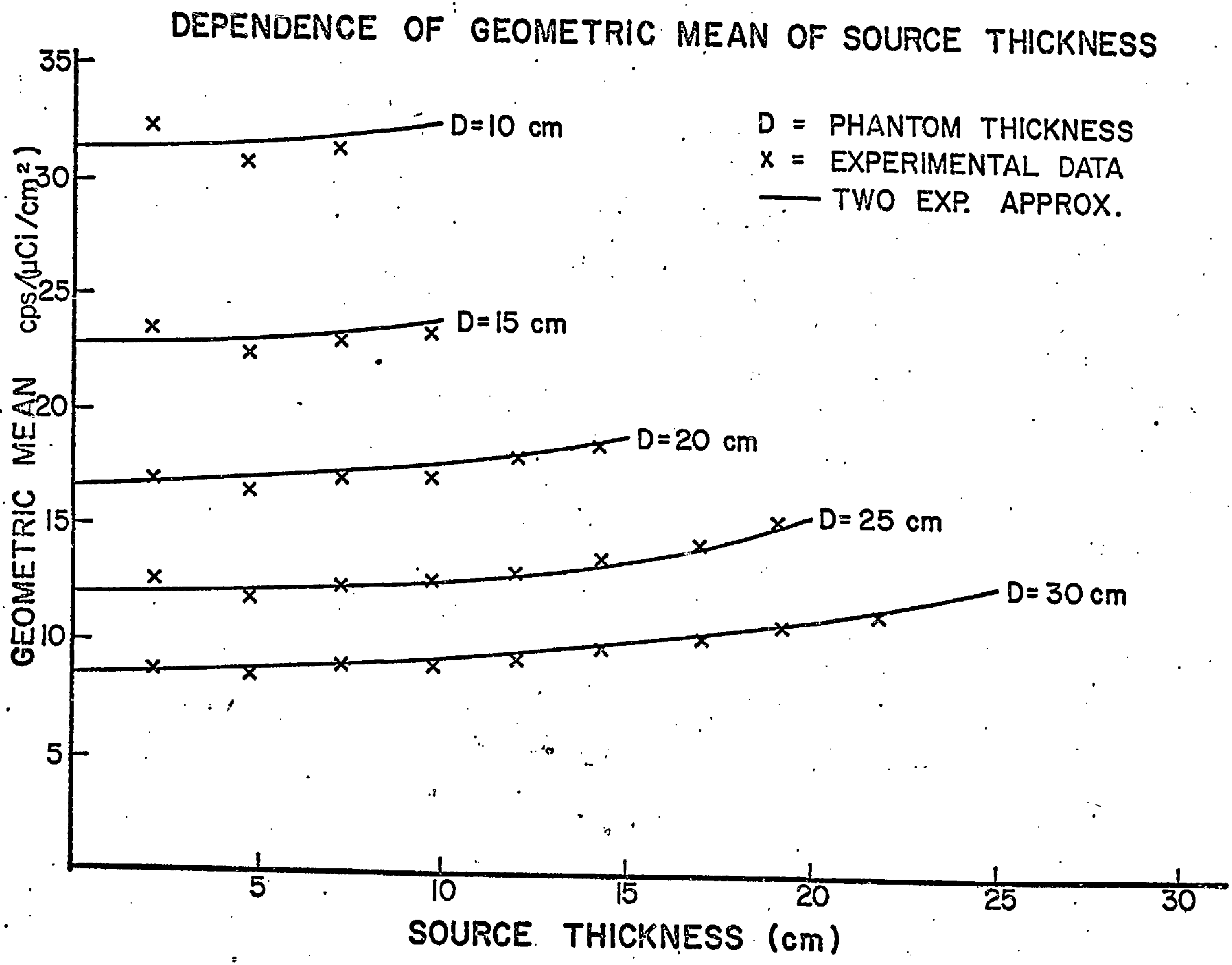

TOTAL
LINE SPREAD FUNCTION
o - EXPERIMENTAL DATA IN 76 cm WATER PHANTOM
Z - DISTANCE BETWEEN SOURCE AND COLLIMATOR FACE
Z= 27.94 cm
FWHM = 2.6 cm
Z= 20.955 cm
FWHM = 2.25 cm
Z= 13.97 cm
FWHM = 2.1 cm
Z= 6.985 cm
FWHM = 2.5 cm
cm

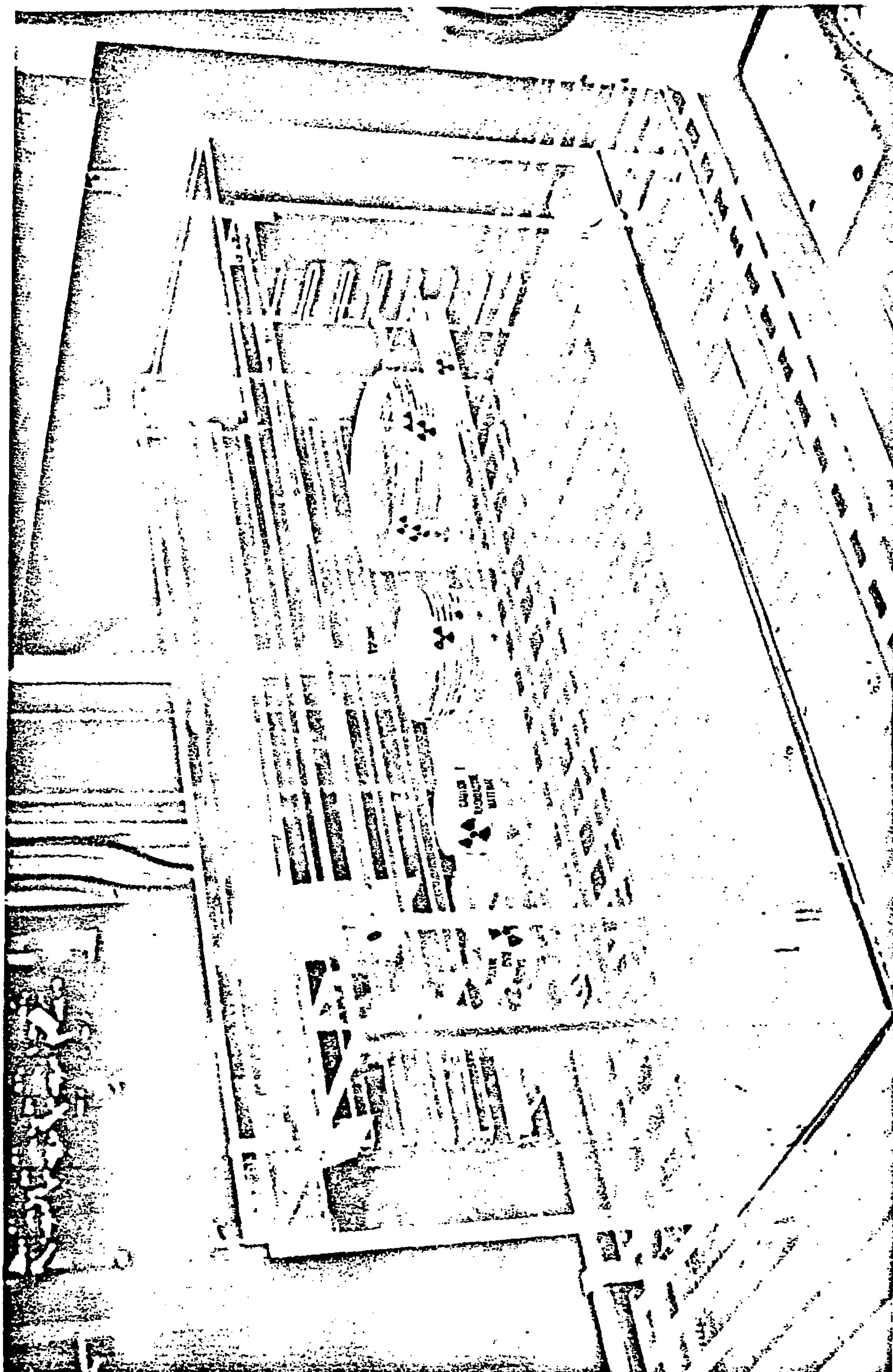
QUANTITATIVE CONJUGATE WHOLE-BODY SCANNING SYSTEM

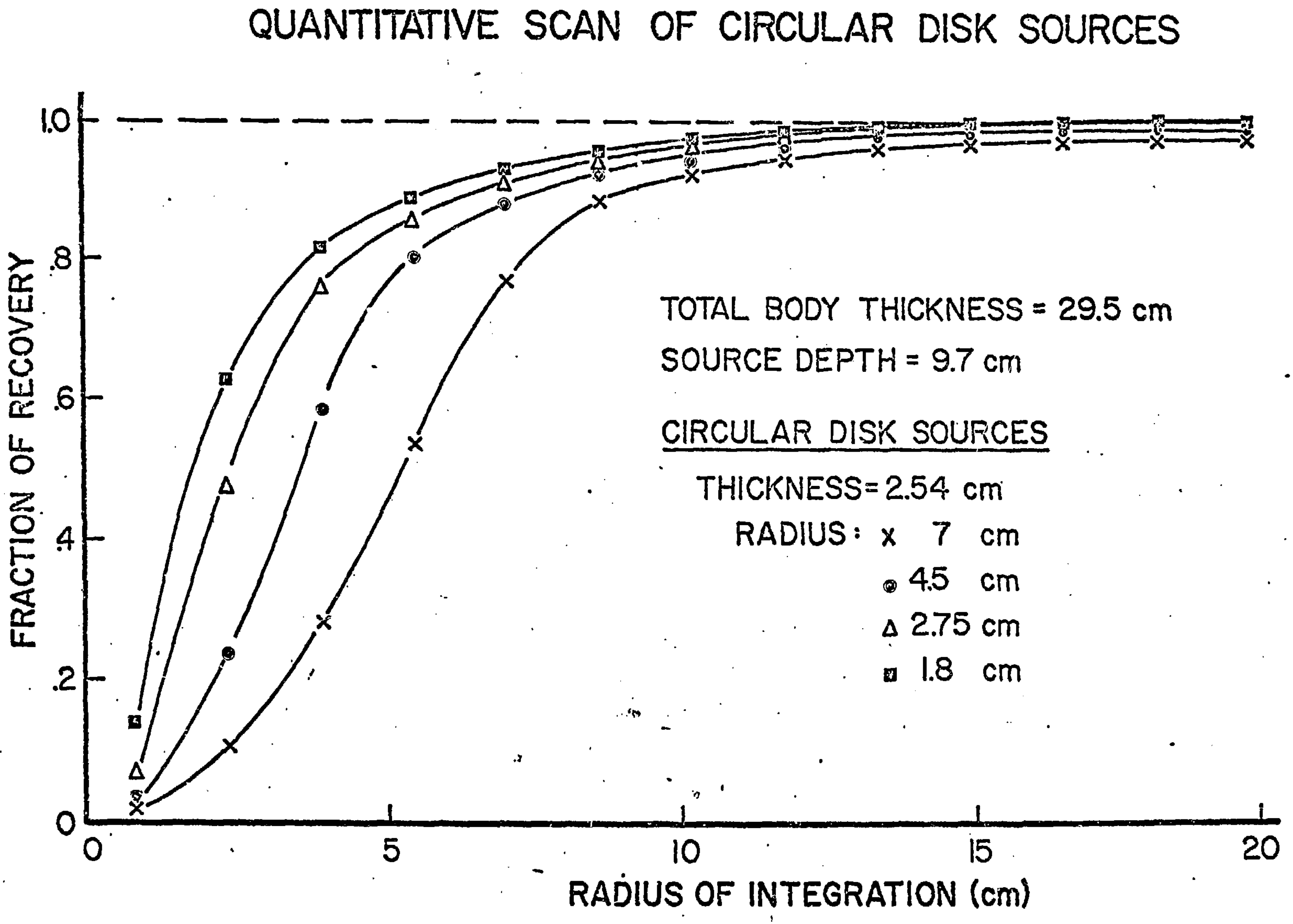




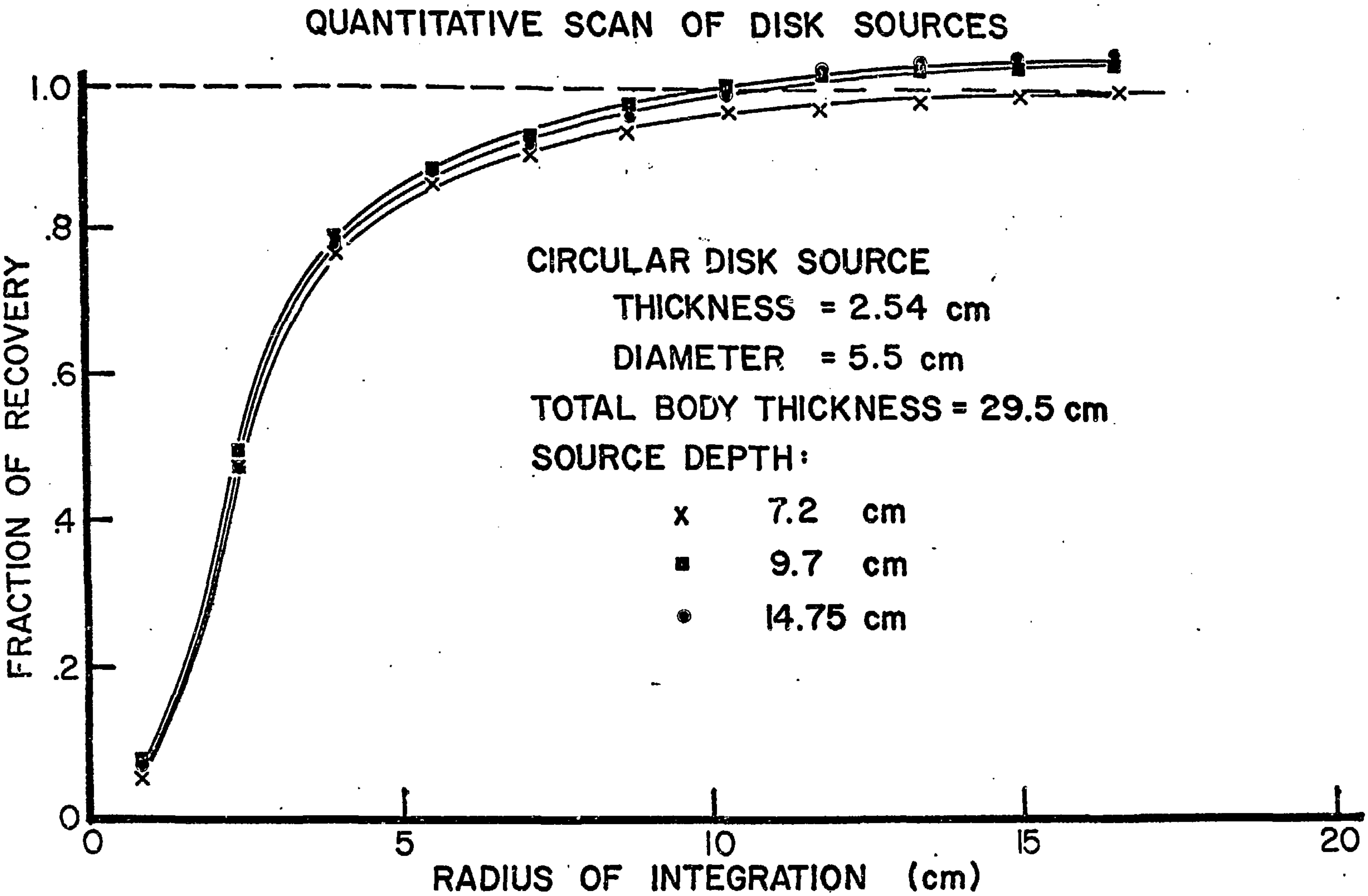

DEPENDENCE OF GEOMETRIC MEAN OF SOURCE DEPTH
(cts/sec/μCi/cm²))
D = PHANTOM THICKNESS
X = EXPERIMENTAL DATA
—— TWO EXP. APPROX.
--- ONE EXP. APPROX.
35
30
25
20
15
10
5
D=10 cm
D=15 cm
D=20 cm
D=25 cm
D=30 cm
-15
-10
-5
5
10
15
DISTANCE FROM CENTER OF WATER PHANTOM (cm)


DEPENDENCE OF GEOMETRIC MEAN OF SOURCE THICKNESS
D = PHANTOM THICKNESS
x = EXPERIMENTAL DATA
TWO EXP. APPROX.
D=10 cm
D=15 cm
D=20 cm
D=25 cm
D=30 cm
GEOMETRIC MEAN cps/(µCi/cm²)
SOURCE THICKNESS (cm)
35
30
25
20
15
10
5
5
10
15
20
25
30

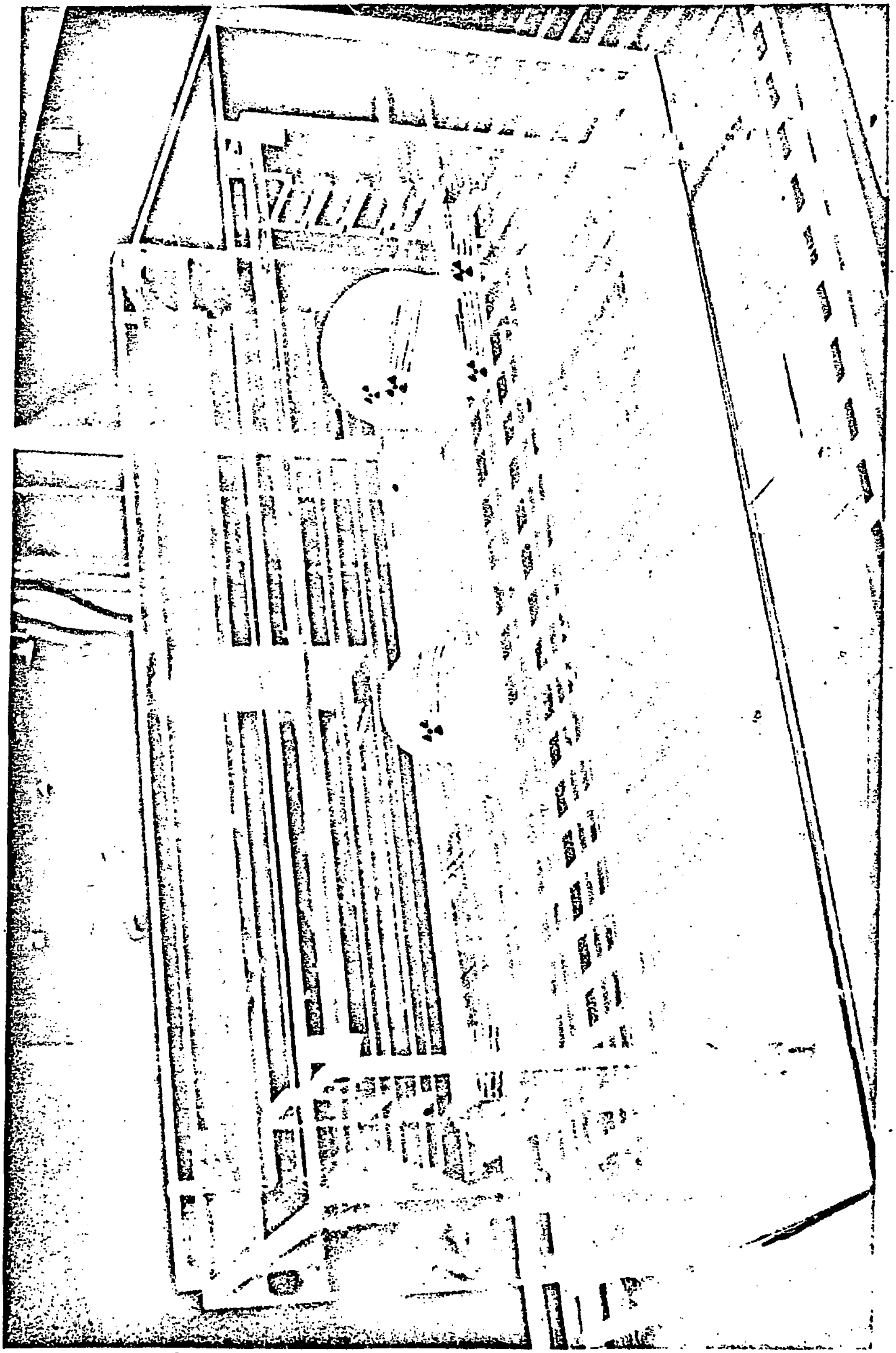


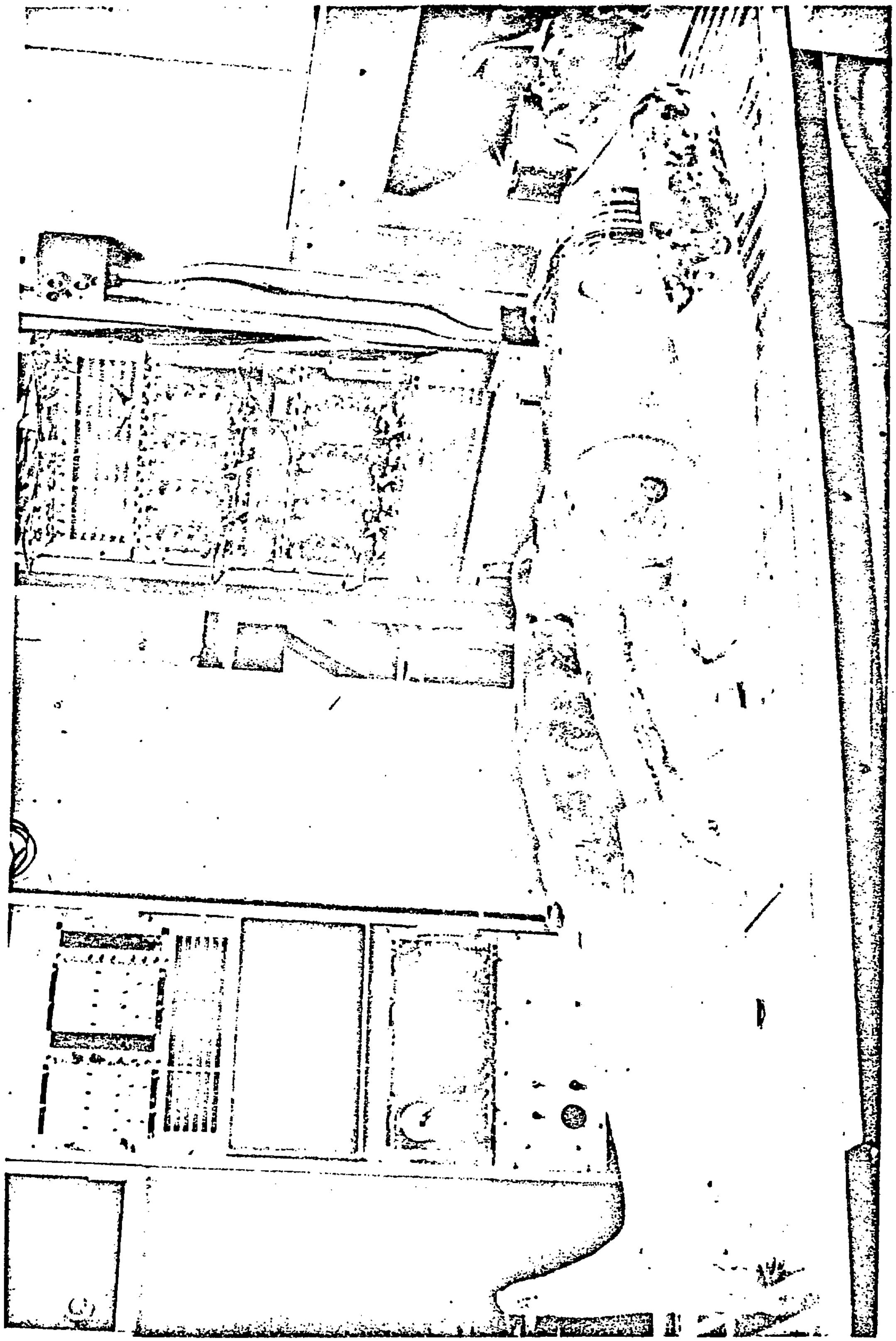


QUANTITATIVE SCAN OF CIRCULAR DISK SOURCES
FRACTION OF RECOVERY
1.0
.8
.6
.4
.2
0
0
5
10
15
20
RADIUS OF INTEGRATION (cm)
TOTAL BODY THICKNESS = 29.5 cm
SOURCE DEPTH = 9.7 cm
CIRCULAR DISK SOURCES
THICKNESS = 2.54 cm
RADIUS: x 7 cm
4.5 cm
2.75 cm
1.8 cm

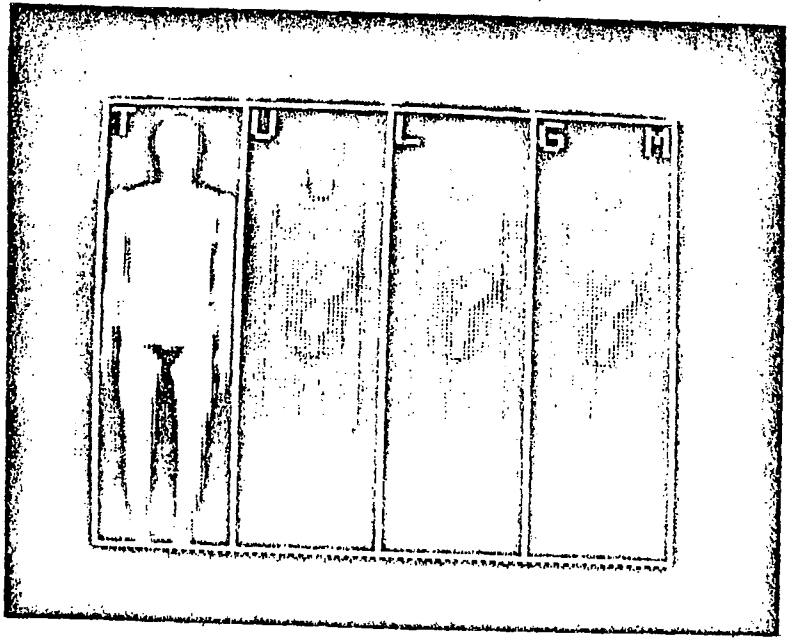


QUANTITATIVE SCAN OF DISK SOURCES
FRACTION OF RECOVERY
1.0
.8
.6
.4
.2
0
0
5
10
15
20
RADIUS OF INTEGRATION (cm)
CIRCULAR DISK SOURCE
THICKNESS = 2.54 cm
DIAMETER = 5.5 cm
TOTAL BODY THICKNESS = 29.5 cm
SOURCE DEPTH:
x 7.2 cm
■ 9.7 cm
● 14.75 cm





IMAGES OF WHOLE-BODY SCAN (ALDERSON PHANTOM)



T : TRANSMISSION IMAGE

U : IMAGE FROM UPPER DETECTOR ARRAY

L : IMAGE FROM LOWER DETECTOR ARRAY

GM : IMAGE OF GEOMETRIC MEAN

QUANTITATION OF WHOLE BODY SCAN (ALDERSON PHANTOM)

TISSUES	TRUE ACTIVITY	MEASURED ACTIVITY	% ERROR
THYROID	.0853 mCi	.0783 mCi	-8.2 %
BLADDER	.3898 mCi	.3909 mCi	+0.3 %
STOMACH	1.7061 mCi	1.7039 mCi	-0.1 %
WHOLE BODY	8.3677 mCi	8.6103 mCi	+2.9 %