ABSORPTION AND SCATTERING OF RADIUM GAMMA RADIATION IN WATER

by

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ABSTRACT

The first part of this thesis describes measurements made with medical radium sources to determine the ratio of the exposure in a large (essentially infinite) water "phantom" to the exposure at the same point in air, i.e., to determine the fractional transmission in an "infinite" water phantom. The fractional transmission was measured as a function of the distance between the radium sources and the measuring instrument. The radium used was sealed in platinum containers which absorbed the primary alpha and beta rays from the radium so that the exposures were due to gamma rays only. All measurements were made with small air-filled ionization chambers with plexiglas walls. Ionization currents were measured with these chambers in water and in air. The corrections which were required to determine the ratio of exposure in water to exposure in air from these measurements and the preliminary experiments necessary to determine the required corrections are described in the thesis. The fractional transmission through water is shown graphically as a function of the distance between source and point of measurement. Also, the relationship is described by an empirical equation. The curve drawn fits the experimental points obtained under a variety of conditions of measurement within the experimental error of 1/2 to 1%.

The second part of the thesis describes measurements of ionization currents made with an experimental set-up in which the ionization chamber was at a fixed distance vertically below the radium and the whole assembly was moved relative to the surface of a water phantom. From measurements made with the radium above the surface, in the surface and below the surface

of the water, it was possible (a) to obtain data which could be compared with the results of Part I and (b) to obtain correction factors which could be applied to the results of Part I to correct for reduced scatter when the radium was in the surface, rather than well immersed in water.

The results of the present experiment are compared with those of previous workers.

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INTRODUCTION

Small sealed radium sources are frequently used as sources of gamma radiation in the treatment of cancer. There are three methods of application: (a) "Interstitial" where the radium is implanted in the tissue to be treated, (b) "Intra-cavitary" where the radium is inserted into a body cavity by means of special radium applicators, (e.g., for treatment of cancer of the cervix uteri), and (c) "Moulds", for treatment of superficial lesions, where the radium sources are mounted on a surface, usually built up from tissue-equivalent material, which carries the radium at a fixed distance from the surface to be treated (e.g., for treatment of skin cancer). In the first two methods the radium sources are normally surrounded on all sides by soft tissue; in the third method of application there is usually tissue or tissue-equivalent material on one side of the radium only. Where the site of the lesion permits treatment with radium, it has the advantage over treatment with "external" x-ray or cobalt 60 sources in that the radiation source is located in or very close to the malignant tissue to be treated and the dose delivered to surrounding normal tissue is minimized.

Typical radium "needles" and "tubes" are linear sources containing 0.5 to 20 mg. of radium as a radium salt sealed in cylindrical platinum-iridium containers having a wall thickness of 0.5 to 1.0 mm. This wall thickness is sufficient to remove all primary alpha and beta rays. Hence treatment is due to gamma rays only, mainly from the RaB and RaC produced by the disintegration of radium.

When radium is used for gamma-ray therapy it is essential to be able to estimate the distribution of "absorbed dose"* over the treated volume.

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* The definition of absorbed dose adopted by the International Commission on Radiological Units and Measurements in 1962 (ICRU Report 10d) is as follows:

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In general, the absorbed dose at a point may be calculated if the "exposure"** at the point is known. Hence, the exposure must be determined as a step in finding the absorbed dose.

The gamma-ray exposure at a point in air due to a linear radium source (and, therefore, due to any array of linear sources) may be calculated by well established methods. The exposure rate in roentgens per hour at a distance r cm. in air from a point source of M mg. of radium shielded by 0.5 mm. of platinum is given by the equation

$$\text{Exposure rate} = C \frac{M}{r^2} \qquad (1)$$

where C is the specific gamma-ray constant of radium in equilibrium with its disintegration products and filtered by 0.5 mm. of platinum. This constant has been measured very carefully; the accepted value is 8.25 roentgen-cm.^{2} per mg.-hour (1,2). Sievert has evaluated the integrals which are required to calculate, from the basic equation 1, the exposure in air due to a linear radium source. Sievert's integrals include a correction for oblique transmission through the wall of the platinum container and a correction for

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> "The ABSORBED DOSE (D) is the quotient of ΔE by Δm where ΔE is the energy imparted by ionizing radiation to the matter in a volume element and Δm is the mass of matter in that volume element."

This is the quantity which is biologically significant. It is usually measured in rads where 1 rad = 0.01 joules per Kg.

** The definition of exposure adopted by the International Commission on Radiological Units and Measurements (Report 10d) is as follows:

> "The EXPOSURE (X) is the quotient of ΔQ by Δm where ΔQ is the sum of the electrical charges on all the ions of one sign produced in air when all the electrons (negatrons and positrons), liberated by photons in a volume element of air whose mass is Δm, are completely stopped in air."

Exposure is usually measured in roentgens where 1 roentgen = 2.58×10^{-4} coulombs per Kg. It is to be noted that exposure is a measure of the radiation only; a statement of the exposure at a point is a statement of the ability of the radiation reaching the point to produce ionization in air.

self-absorption in the radium salt can be included in the integrals (3,4,5). To determine the absorbed dose in radium therapy, however, it is necessary to know the exposure at different points in tissue, not in air. This requires a knowledge of the ratio of the exposure in tissue to the exposure in air for the same geometry. There is no practical method of calculating this ratio since the apparent absorption in water depends, in general, on true absorption and on multiple scattering. It is, therefore, necessary to measure the ratio of the two exposures. The experimental results will be valid only for the geometry in which the measurements are made.

Early experimental measurements by Bruzau (6) and by Griffith (7) indicated that the gamma-ray exposure from a radium source was the same in a "large water phantom"* as in air. This was explained on the assumption that, in large phantoms, scattering compensates completely for absorption. More recent experimental measurements have not confirmed Bruzau's and Griffith's results. Measurements have been reported by Ter-Pogossian, Ittner and Aly (8), by Van Dilla and Hine (9), by Wootton, Shalek and Fletcher (10) and by Kartha, Kenney and Cameron (11). All these investigators have found that the exposure in water is smaller than the exposure in air but their results have not been in good agreement. Further, all the measured values of the effective transmission are lower than values calculated by Hale (12) from published absorption coefficients (13) and published build-up factors (14). Most radium dosimetry to date has been based on the assumption that apparent absorption in tissue is negligible but recently attempts have been made to improve the

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* It is not practical to make measurements in soft tissue. Water is very nearly tissue-equivalent with respect to electron density and effective atomic number and is, therefore, the most universally accepted "phantom" material for exposure and absorbed dose measurements. If the measuring instrument and the radium source are surrounded in all directions by a thickness of water equal or nearly equal to the separation of the instrument and the source, then the phantom can be considered as essentially infinite.

accuracy of the dosimetry by correcting for tissue absorption (15,16). In view of these attempts, it appeared useful to try to improve the accuracy of the basic data.

The above measurements, made in large water phantoms, are applicable to the dosimetry of interstitial and intra-cavitary radium but not to the dosimetry of radium moulds. Some measurements of the apparent transmission through water made with geometry similar to that pertaining to radium moulds, i.e., with the radium sources in the surface of the phantom, have been reported by Roberts and Honeyburne (17) and by Cook (18,19). The results of Roberts and Honeyburne must be questioned since they found greater apparent transmission through water in the limited phantom than others have found using "infinite" phantoms. Cook made somewhat different measurements and it is, therefore, difficult to compare his results with other published data but where the comparison can be made his values of the apparent transmission through water are lower than those of other investigators. In view of these discrepancies, it appeared that there was need for more reliable data for limited phantoms, as well as for large phantoms, and that these data could be obtained most conveniently and most reliably by measuring correction factors to be applied to the data for large phantoms.

The purpose of the present project was, therefore, twofold.

(a) To repeat the measurements with radium gamma rays of the ratio of the exposure in a large water phantom to the exposure in air, with a view to improving the accuracy of these basic data and, if possible, determining the causes of the discrepancies in the published data.

(b) To determine correction factors to be applied when the radium sources lie in the surface of a water phantom to provide data applicable to the dosimetry of radium moulds.

PART I

MEASUREMENTS OF THE APPARENT ABSORPTION OF THE GAMMA RAYS OF RADIUM IN A LARGE WATER PHANTOM

1. Outline of Project

To determine the apparent absorption of the gamma rays of radium in water it was necessary to measure the exposure in air due to radium sources in a fixed geometry relative to a suitable exposure meter. The whole set-up was then transferred to a large water phantom to measure exposure in water with the same geometry. After suitable corrections (to be discussed later) were made the ratio of the second measurement to the first gave the fractional transmission through water. By repeating these measurements with the radium sources at different distances from the detector it was possible to determine the dependence of the fractional transmission on the path in water.

2. Experimental Set-up

All measurements of exposure were made with small cylindrical air-filled ionization chambers with graphite-lined plexiglas walls and with thin aluminum wires as central electrode. On the basis of other work done with these and similar ionization chambers, they are known to be energy-independent* over the energy range involved in this work. This was an essential requirement for the exposure-measuring instrument used in this project since filtration and scattering in the water change the energy spectrum from that of the primary radiation in air.

Ionization chambers of two different volumes were used. The essential dimensions of the two chambers were as follows:

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* In general for ionization chambers, $I = kE$ where I is the ionization current and E is the exposure rate. For an ionization chamber constructed of materials having the same effective atomic number as air ($Z = 7.5$) the constant of proportionality k is independent of the energy of the x- or gamma radiation to which the ionization chamber is exposed.

Size	Length of cavity	Internal diameter of cavity	Wall thickness
Small	1.9 cm.	0.32 cm.	0.24 cm.
Large	1.9 "	0.95 "	0.16 "

The construction of the larger chamber is shown in figure 1. The possible effect of the finite size of the sensitive volume of the detector will be considered in the discussion of the results.

The ionization chamber was connected directly to a preamplifier which, in turn, was cable-connected to the main amplifier. The amplifier circuit used was essentially that described by Fedoruk, Johns and Watson (20). It was not necessary to have an absolute calibration of the instrument since only ratios of ionization currents were required in this work.

The experimental arrangement used for the measurements is shown in figure 2. The ionization chamber and the preamplifier were supported from a horizontal circular plexiglas plate and cable-connected to the amplifier which measured the ionization current. Radium tubes or needles were supported by fine nylon threads (shrinkage negligible when wet) in a circle with the ionization chamber at the center of the circle. Holes were drilled in the plexiglas plate so the radium could be placed on circles of radii 3, 4, 5, etc., up to 10 cm. The diameter of the circle in which the radium was placed in any particular experiment was accurately known and exact centering of the ionization chamber was obviously not critical The center of the radium sources and the center of the sensitive volume of the ionization chamber were adjusted to the same horizontal plane.

Some measurements were made with radium tubes and some with radium needles. The dimensions of the sources were as follows:

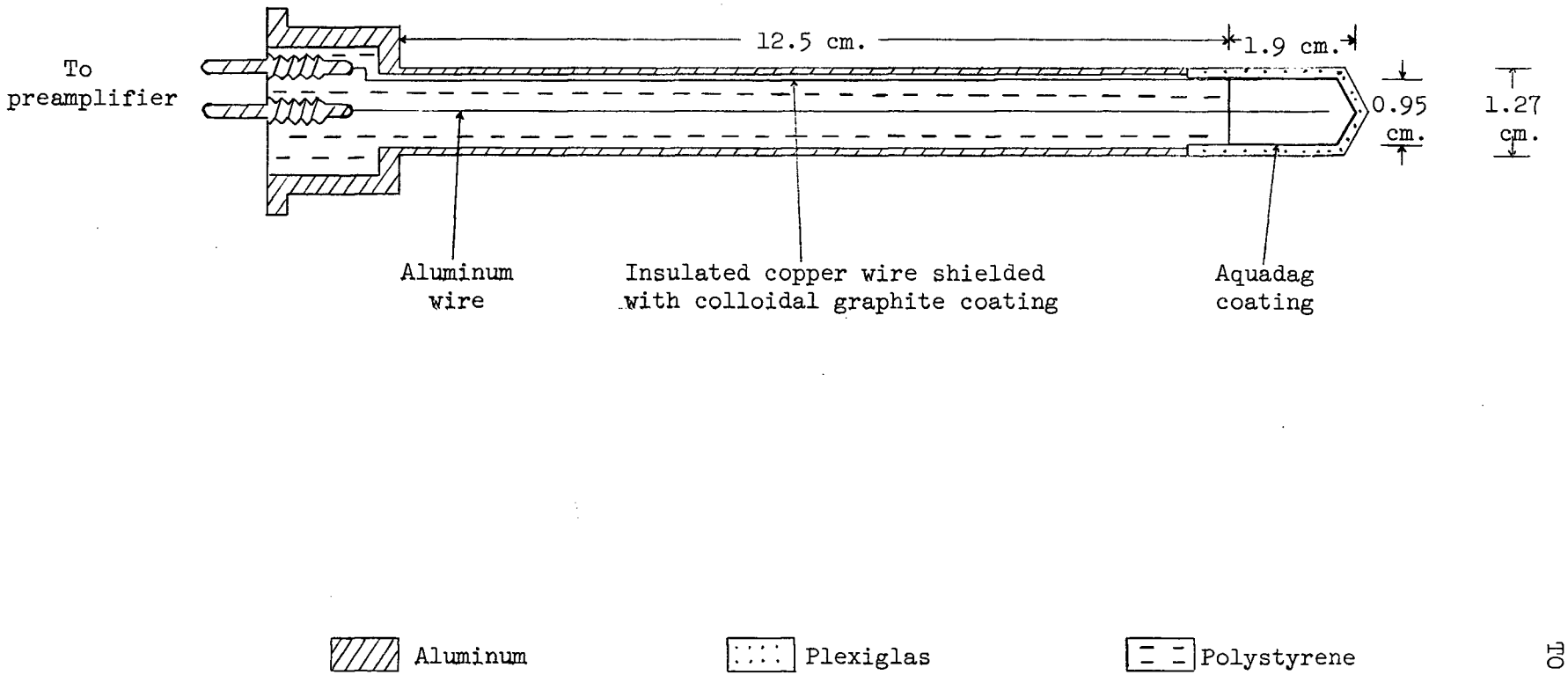

FIGURE 1. CROSS-SECTION OF THE LARGE IONIZATION CHAMBER (Full scale).

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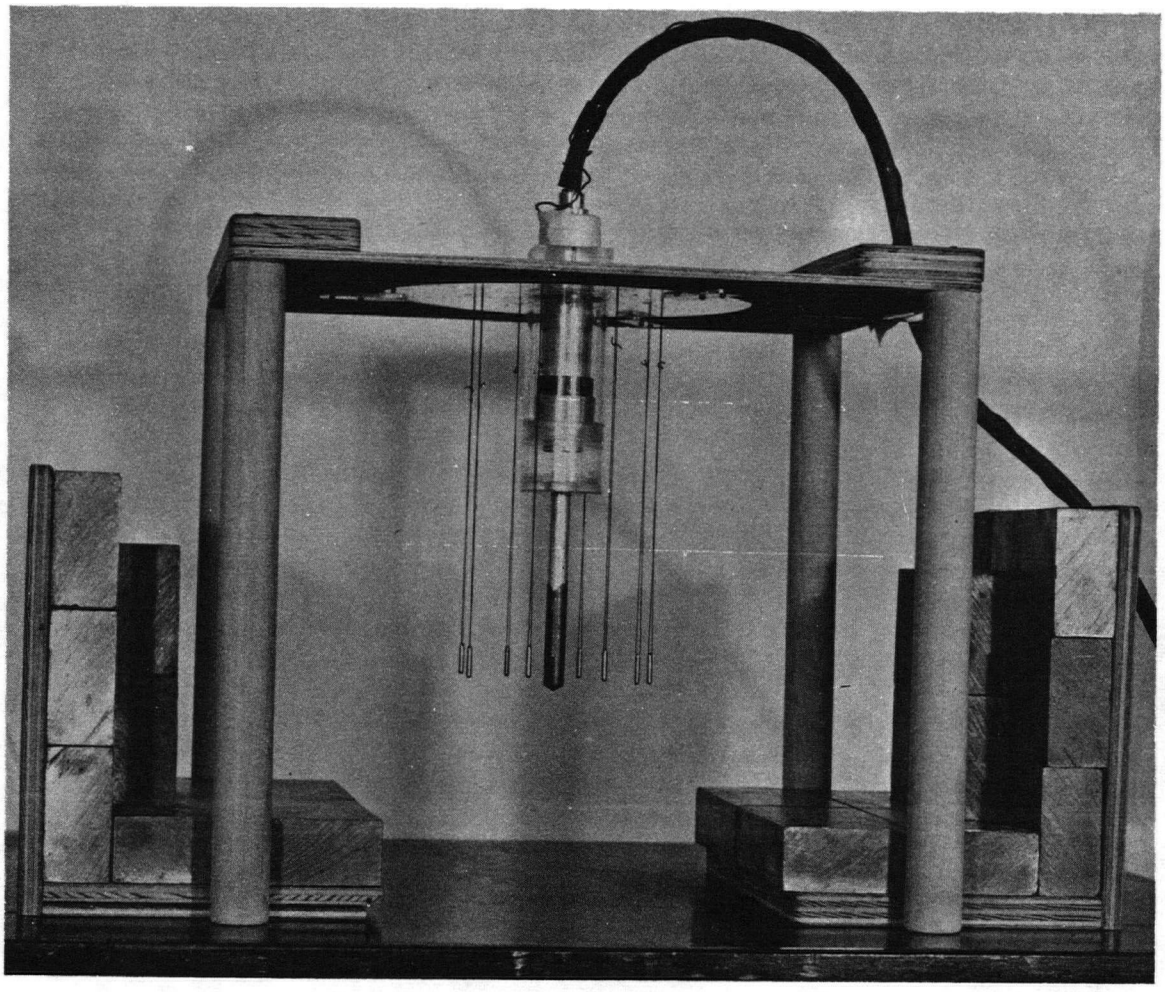

FIGURE 2. EXPERIMENTAL ARRANGEMENT OF IONIZATION CHAMBER AND RADIUM SOURCES

Type	Quantity of radium	Outer diameter	Platinum filtration	Active length	Total length
Tube	20 mg.	0.32 cm.	1.0 mm.	1.2 cm.	2.2 cm.
Needle	10 "	0.19 "	0.5 "	1.0 "	1.9 "

For exposure measurements in air, the apparatus was used as shown in figure 2. The lead bricks which can be seen in the photograph provided protection from excessive radiation exposure when placing and manipulating the radium. Exposure measurements in air with and without the bricks showed that they did not contribute measurable scatter to the total exposure. For exposure measurements in water, the whole equipment was placed over the water phantom shown in figure 3 so the ionization chamber and the radium were in water. The phantom used was a plexiglas tank of elliptical cross-section (which was available from previous work) having minor and major diameters 34 and 39 cm., respectively, and a depth of 29 cm. This phantom was large enough, even with the radium at 10 cm. from the ionization chamber, to be considered as an infinite phantom.

3. Preliminary Experiments

Three preliminary experiments were necessary before attempting the measurements of the main experiment.

First, it was necessary to test the stem of the ionization chamber and the preamplifier for leakage ionization current since any air spaces in the stem of the chamber or in the preamplifier were exposed to radiation in the experiment and would, if in the field of the collecting voltage, contribute to the measured ionization current. The stem of the ionization chamber was designed so that there was no collecting field since the lead carrying the collector voltage was placed in a grounded shield. Further, it had been proved that exposure of the stem in a cobalt 60 radiation field did not give

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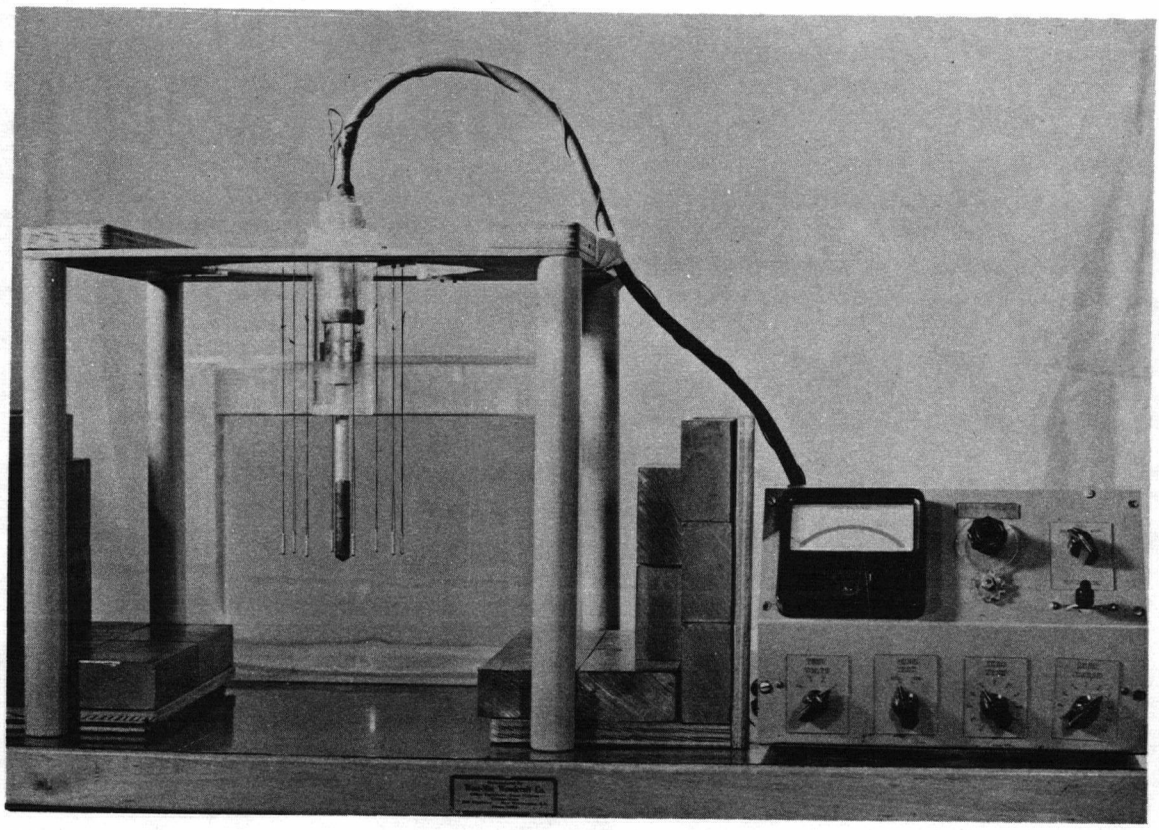

FIGURE 3. EXPERIMENTAL SET-UP INCLUDING WATER PHANTOM AND AMPLIFIER

a detectable reading. The preamplifier design, however, did not preclude the possibility of having a measurable leakage current and direct tests for leakage current had not been made. It was, therefore, necessary to make a direct test under the conditions of the present experiment. This was done by setting up the radium and preamplifier as required for the experiment but without an ionization chamber connected to the preamplifier. Under these conditions, there was no measurable ionization current. Hence, any ionization current measured in the experiment was due entirely to exposure of the ionization chamber proper.

The second preliminary experiment was necessary to determine that the conditions under which an ionization chamber measures exposure were satisfied. These conditions are as follows:

(a) The effective atomic number of the chamber must be the same as that of air.

(b) The thickness of the wall surrounding the air cavity must be greater than the maximum range of the secondary electrons liberated by the primary photons since, if an air-cavity ionization chamber is to measure exposure, all the electrons which produce ionization in the cavity must originate in air-equivalent material and, also, the mass of irradiated "air" must be such that any further increase in mass will not produce any greater ionization in the cavity.*

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* In a "free-air ionization chamber" exposures are measured directly from the definition of exposure, i.e., a mass of air Δm is irradiated and the charge Δq of all the ions produced by the secondary electrons liberated in the irradiated air is measured wherever the ions are produced. In other words, a defined air mass is irradiated and the resulting ions are collected wherever formed. In a cavity chamber the process is the inverse, i.e., an essentially infinite mass of air is irradiated and ions are collected in a defined mass Δm. If a cavity chamber satisfies the conditions stated in the text, it can be shown that the measured ionization in the cavity chamber is the same as in the free air chamber, if the defined mass Δm is the same in each case.

Further, if the wall of the ionization chamber attenuates the primary radiation appreciably, correction must be made for this attenuation.

Requirement (a) is the condition that the measurements be independent of the energy of the radiation. As already pointed out, for gamma rays from radium for which Compton effect is the predominant absorption process in low atomic number materials, ionization chambers of the construction used are known to satisfy condition (a) adequately.

Condition (b) required investigation since the maximum range of secondary electrons liberated in an air-equivalent material by the gamma rays of radium is of the order of a few millimeters and the attenuation of the gamma rays in this wall thickness is appreciable. For this purpose, ionization chambers with relatively thin walls were used and close-fitting plexiglas "caps" of different thicknesses were placed over the chamber to increase the wall thickness. For the small ionization chamber, measurements were made with total wall thicknesses ranging from 0.24 to 0.90 cm. and for the large chamber from 0.16 to 1.20 cm. These measurements provided the data (a) to determine the wall thickness required for maximum ionization and (b) to determine the correction for the attenuation of the gamma radiation in this wall.

The third preliminary experiment was necessary to determine whether or not secondary electrons or other soft radiation originating in the platinum containers of the radium sources, were contributing to the exposure in air. This contribution, if any, must be eliminated since it is not included in the specific gamma ray constant 8.25 roentgen-cm^2 per mg-hour of equation 1 which is used to calculate exposure in air and would not contribute to the measured exposure in water. For this purpose, ionization in air was measured with and without close-fitting plexiglas "sleeves" placed over the radium sources.

Sleeves of wall thickness 0.25, 0.50, 0.75 and 1.0 cm. were used. It was, of course, necessary to correct for the gamma ray attenuation in the sleeves but the ionization measurements provided the necessary data.

Figure 4 is a photograph of the experimental set-up with an "added cap" on the ionization chamber and "sleeves" over the radium sources.

To investigate the wall thickness required for the ionization chamber and to obtain data to correct for gamma ray attenuation in the wall, measurements of ionization in air were made with different added caps on the ionization chamber, all other factors being kept constant in any one experiment. Since the change in the ionization produced by the addition of any cap was at most a few per cent and since the sensitivity of the amplifier drifted slightly, the reading with any added cap was "bracketed" with two "no-cap readings" and the difference produced by the cap was expressed as a fraction of the no-cap reading. For each experiment the logarithm of the relative ionization was plotted against the total wall thickness of the ionization chamber, the ionization with no added cap being taken as unity. These measurements were made with both large and small ionization chambers, with the radium at different distances from the ionization chamber, with and without plexiglas sleeves over the radium sources, with radium needles and with radium tubes.

The dependence of the relative ionization on the wall thickness of the ionization chamber, as measured with the large ionization chamber with radium tubes at 4 cm. from the chamber and without any sleeves over the radium sources, is shown by the circles in figure 5. Results obtained with the small ionization chamber under the same conditions are shown by the + symbols in figure 5, the latter having been adjusted to allow for the fact

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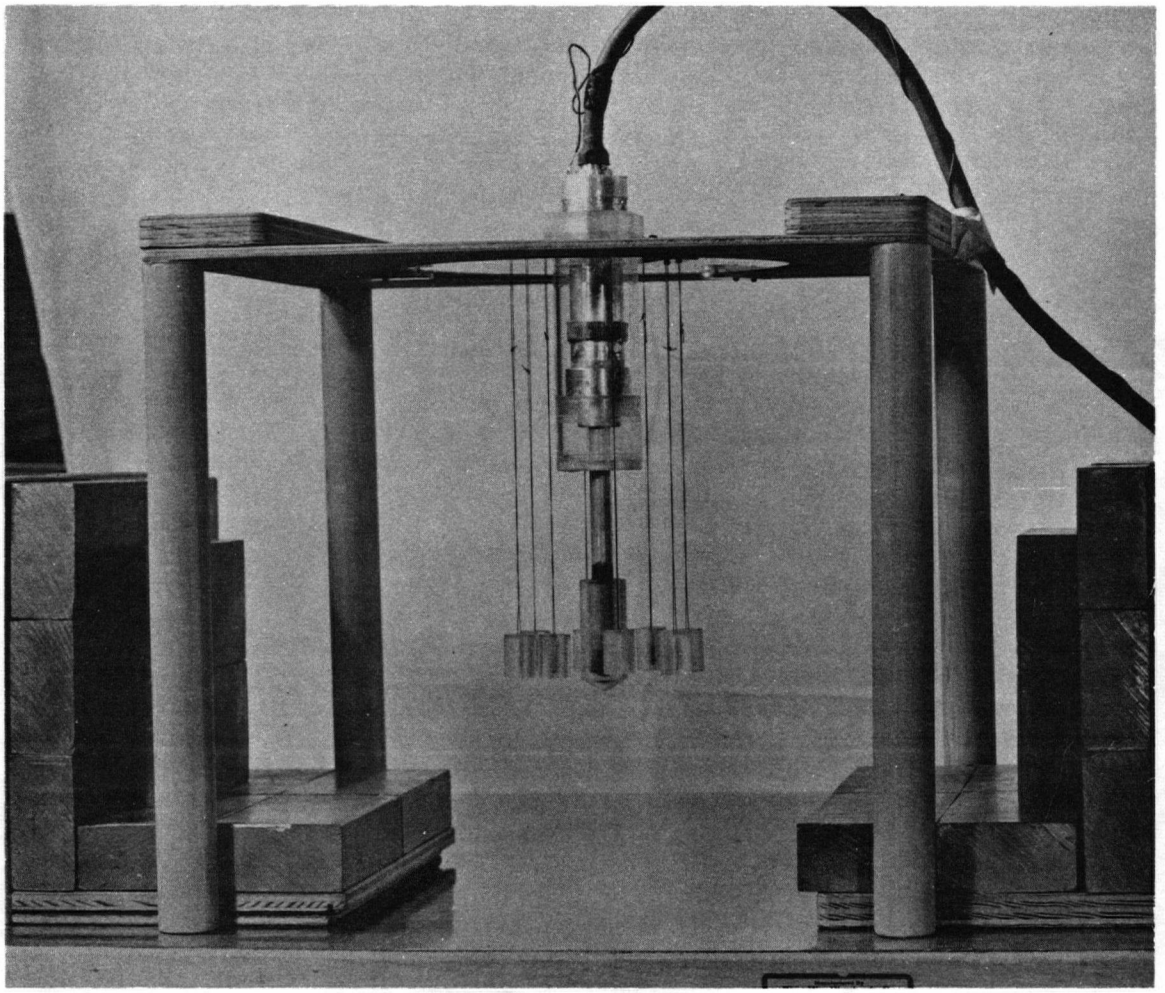

FIGURE 4. IONIZATION CHAMBER WITH ADDED CAP AND RADIUM SOURCES WITH PLEXIGLAS SLEEVES

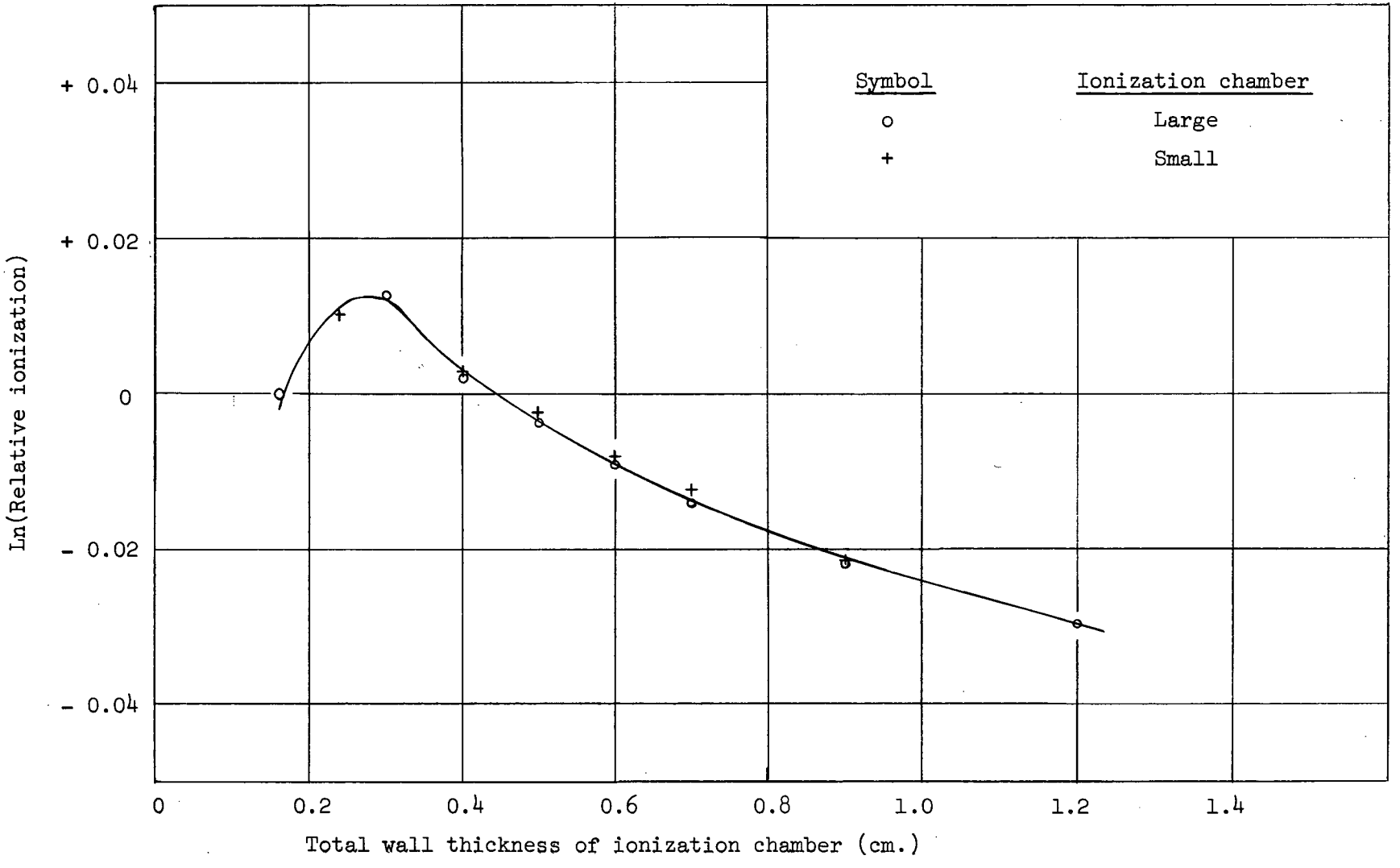

FIGURE 5. LN(RELATIVE IONIZATION) VERSUS TOTAL WALL OF IONIZATION CHAMBER WITHOUT SLEEVES ON RADIUM SOURCES.

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that, since the two ionization chambers had different wall thicknesses, the reference points in the two cases were different. With this adjustment, all the points can be fitted by a single curve. The increase in relative ionization with increase in wall thickness for small total wall is due to the increased yield of secondary electrons originating in the wall and contributing to the ionization in the cavity. The rapid decrease beyond the maximum is interpreted by Wootton (10) and by the present investigator as decrease due to absorption of photoelectrons (or, perhaps, some other very soft component of radiation) from the platinum container. In fact, in the region of the maximum, two processes, i.e., build-up of ionization with increasing number of secondary electrons and decrease of ionization due to absorption of a soft component, are in competition resulting in maximum ionization current with somewhat smaller wall thickness than would be required for maximum ionization with the uncontaminated primary gamma radiation. Beyond the region of the rapid decrease the ionization current decreases exponentially due to the attenuation of the primary gamma radiation in the wall of the chamber. It was the region of rapid decrease in the central portion of the curve which suggested the desirability of making measurements with plexiglas sleeves fitted over the radium sources.

The measurements to determine the effect of sleeves over the radium on the ionization produced were similar to the measurements with different caps on the ionization chamber, i.e., the relative ionization was determined with different radium sleeves, all other factors constant in any one experiment. As in the previous experiment, any reading with radium sleeves was bracketed with two "no-sleeve" readings. The following parameters were varied in different experiments: added cap on the ionization chamber, size of ionization chamber, distance from radium to ionization chamber and the platinum filtration of the radium sources.

The results obtained with radium tubes at a distance of 4 cm. from the large ionization chamber are shown in figure 6. In this figure the logarithm of relative ionization has been plotted against the total wall thickness of the ionization chamber for different sleeves on the radium, all readings relative to the reading with no added cap and no sleeves. (It is to be noted that to avoid confusing the points, the scale has been shifted for each curve on the graph).

Curves were obtained similar to those of figure 6 for each combination of the parameters shown in table I. The curves obtained for the different conditions were similar in shape and spacing but differed in absolute

TABLE I

COMBINATIONS OF PARAMETERS FOR WHICH THE ATTENUATION DATA WERE MEASURED

Ionization chamber	Radium used	Distance from radium to chamber
Large	4 x 20 mg. tubes	4.0 cm. *
"	8 x 20 " "	6.0 "
"	8 x 20 " "	8.0 "
Small	8 x 20 " "	4.0 " *
"	8 x 20 " "	6.0 "
Large	8 x 10 " needles	4.0 "

* Complete curves like those of figure 6 were obtained for the two conditions marked by asterisks. To avoid excessive radiation exposure of personnel, less complete data were taken for the other cases.

values due to different reference points for each set of conditions. The absolute values were, therefore, adjusted to bring the curves into coincidence for a total ionization chamber wall of 0.5 cm. and radium sleeves of 0.5 cm. The adjusted values for all conditions of measurements are shown in figure 7. (The shift of scale for each curve is the same as in figure 6).

The straight lines shown in figure 7 were plotted from the following

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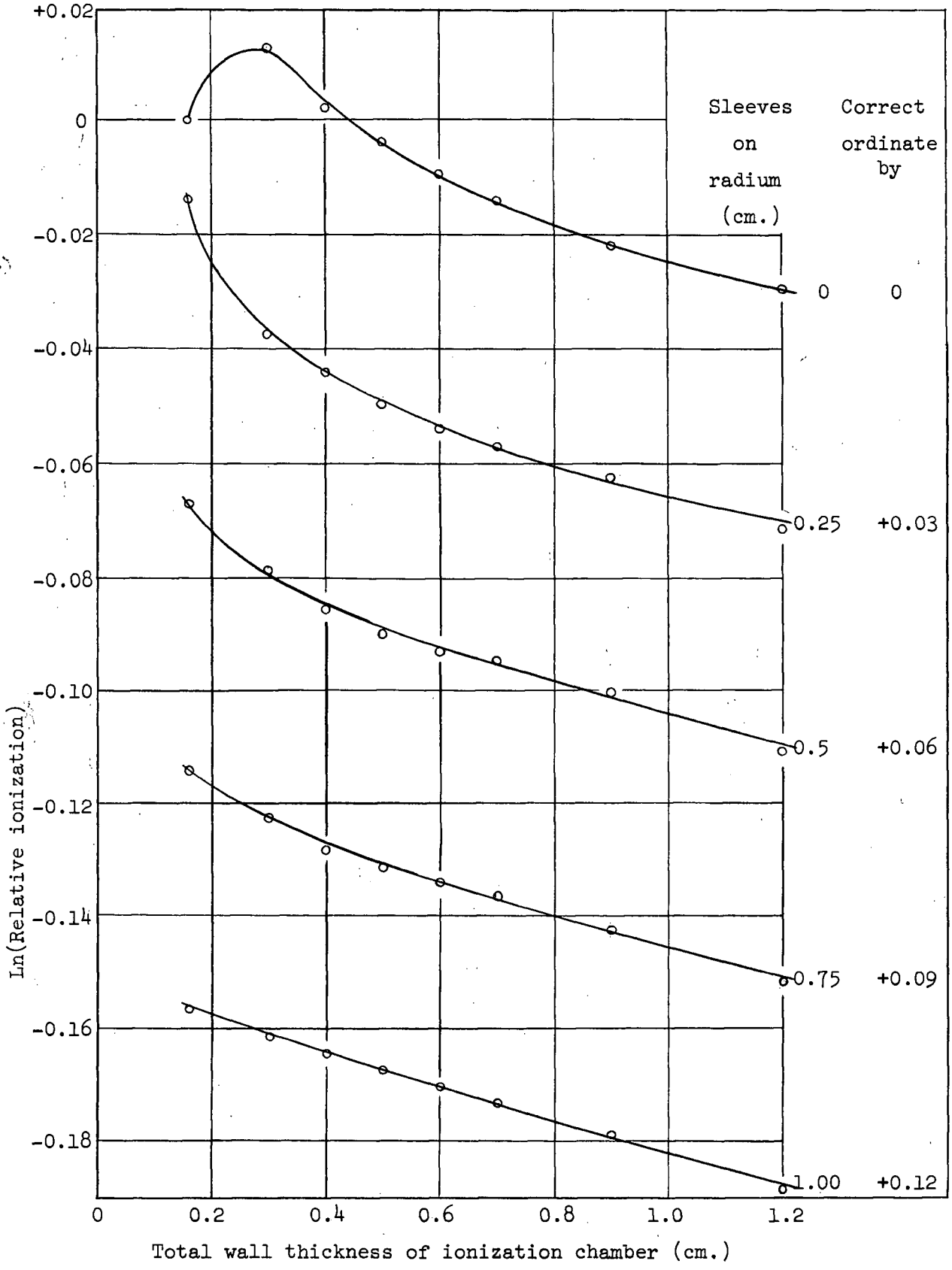

FIGURE 6. LN(RELATIVE IONIZATION) VERSUS TOTAL WALL OF IONIZATION CHAMBER WITH DIFFERENT SLEEVES ON RADIUM SOURCES FOR ONE CONDITION OF MEASUREMENT.

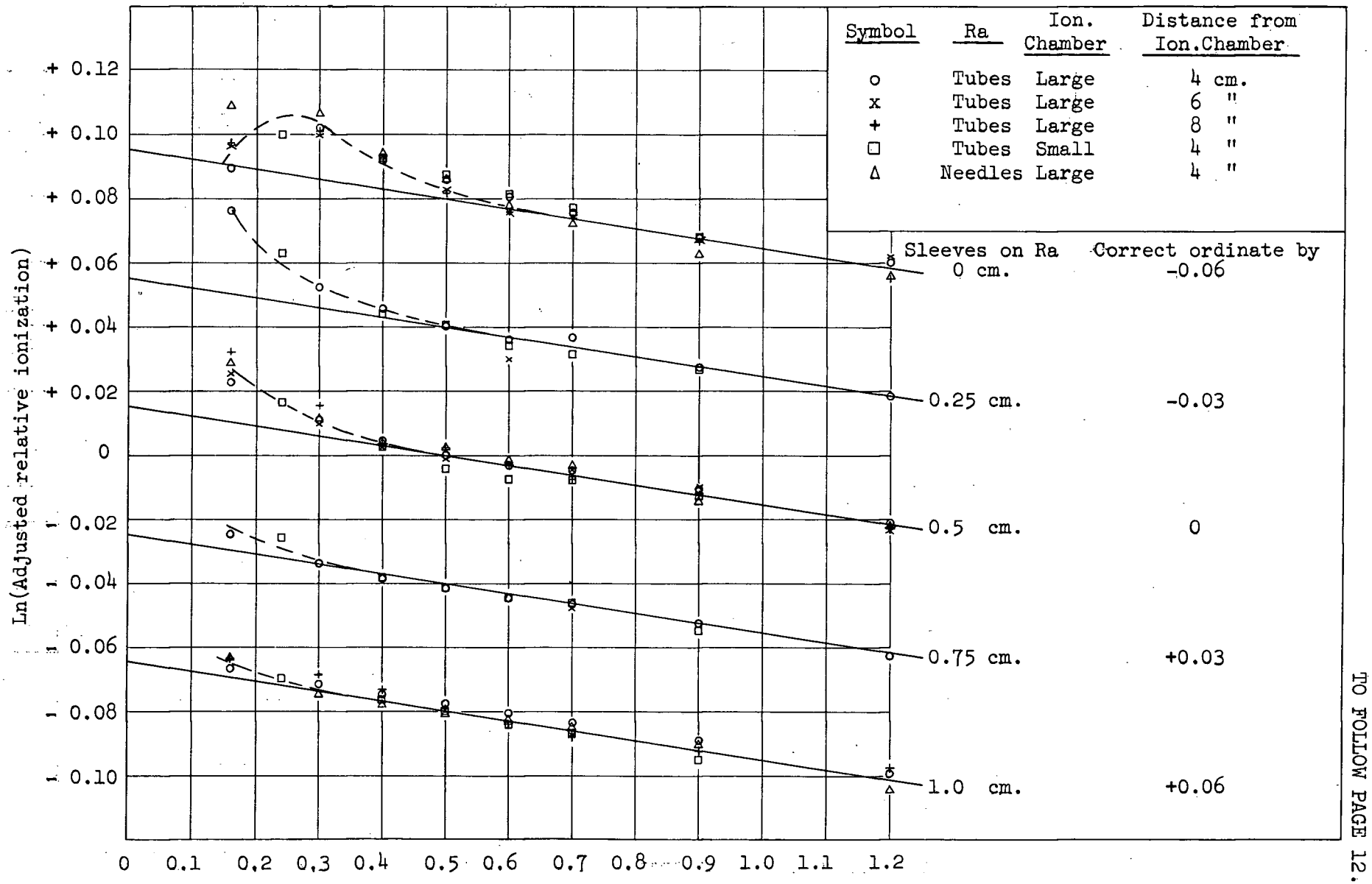

FIGURE 7. LN(ADJUSTED RELATIVE IONIZATION) VERSUS TOTAL WALL THICKNESS OF IONIZATION CHAMBER FOR ALL CONDITIONS OF MEASUREMENT

TO FOLLOW PAGE 12.

empirical equation

$$\text{Ln(Adjusted relative ionization)} = 0.0352 - 0.0306W - 0.0398S \qquad (2)$$

where W = total wall thickness of ionization chamber in cm. and S = thickness of sleeves over radium sources in cm. It can be seen that beyond the region of build-up and the region of absorption of the soft component, all points are fitted very well by this empirical equation.

Equation 2 can be rewritten in the following form:

$$\text{Ln(Adjusted relative ionization)} = 0.0352 - 0.0306(W + 1.3S) \qquad (3)$$

Therefore, the logarithm of the adjusted relative ionization can be plotted against total effective thickness of plexiglas (= W + 1.3S) for all conditions of measurement on a single graph. This has been done in figure 8 where the straight line was plotted from equation 3. Again it is evident that for large values of total effective plexiglas the attenuation is exponential and is described by the empirical equation 3.

On the basis of the above results, for the measurements of the main experiment a total ionization chamber wall of 0.6 cm. or greater was used in all cases to ensure full build-up. Further, to ensure complete absorption of any soft component of radiation originating in the radium sources, a total thickness of plexiglas of at least 0.9 cm. was placed somewhere in the path of the radiation, either in the ionization chamber wall or in the sleeves over the radium sources. To correct for gamma-ray attenuation in the plexiglas in the radiation path, all ionization readings in air were multiplied by the correction factor obtained from figure 8 and equation 3, namely,

$$\text{Correction factor} = e^{0.0306(W + 1.3S)} \qquad (4)$$

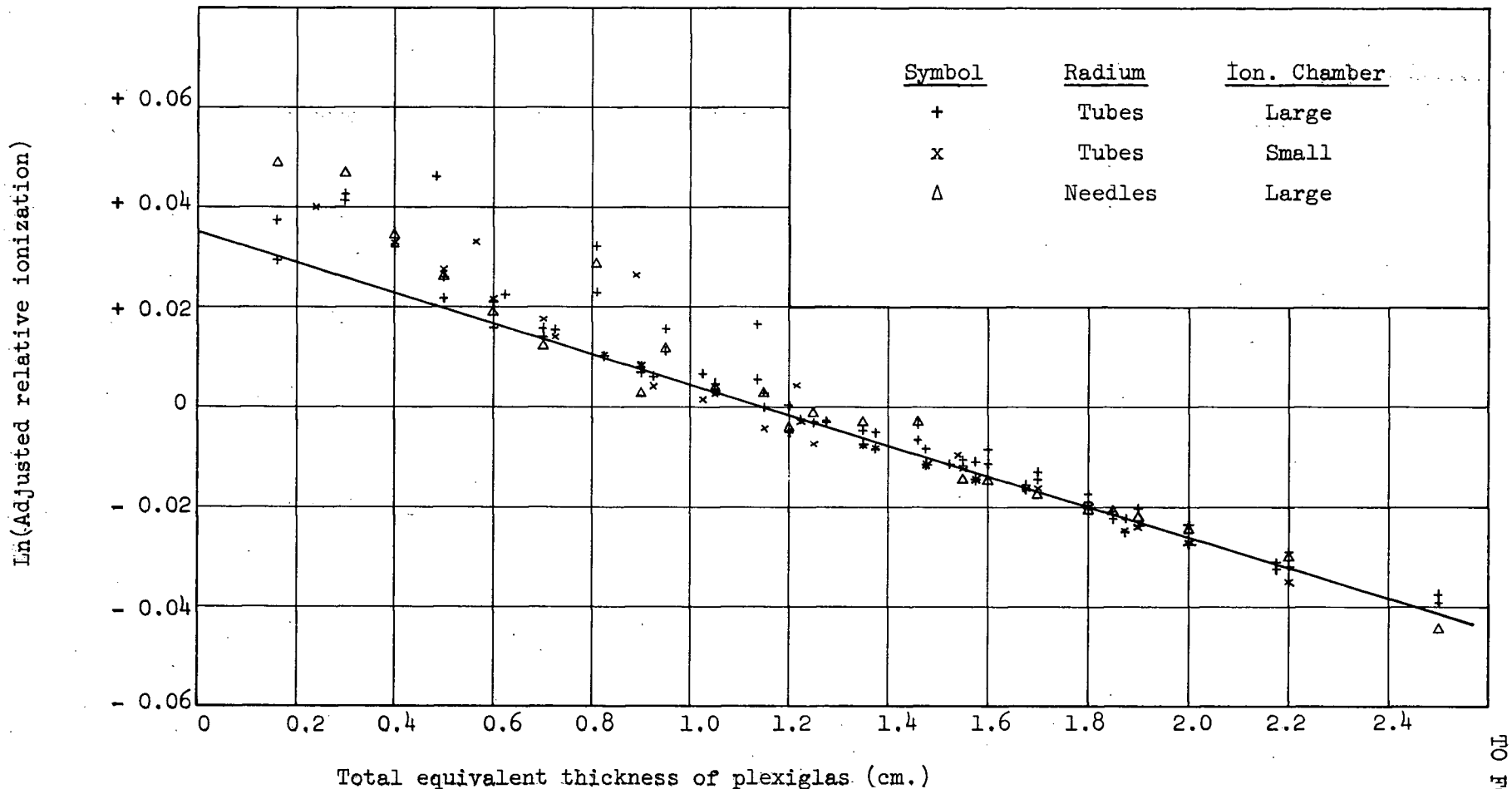

FIGURE 8. LN(ADJUSTED RELATIVE IONIZATION) VERSUS TOTAL EQUIVALENT THICKNESS OF PLEXIGLAS FOR ALL CONDITIONS OF MEASUREMENT

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4. Measurements of the Ratio of the Exposure in Water to the Exposure in Air

The ratio of the exposure in water to the exposure in air was measured as already described for different combinations of the following parameters: type of radium sources, size of ionization chamber, total wall thickness of ionization chamber, thickness of sleeves, if any, over the radium sources and distance from radium sources to ionization chamber (center to center). These results are shown in table II.

Column 1 of table II shows the number of sources, quantity of radium per source and type of radium which were used for each measurement. The size of ionization chamber used is shown in column 2. The dimensions of the radium sources and the ionization chambers have already been given. Column 3 gives the wall thickness of the ionization chamber, including the added cap, for each measurement. The thickness of the sleeves, if any, used over the radium sources is shown in column 4.

R of column 5 is the radius of the circle on which the radium sources were placed, i.e., the distance from the center of the radium sources to the center of the ionization chamber. The equivalent path P in water as shown in column 6 is taken as the actual path in water plus the water equivalent of the path in plexiglas. For radium gamma rays in low atomic number materials, absorption is almost entirely due to modified scattering (i.e., Compton effect) for which electron density is the only significant factor. Therefore,

$$\text{Water equivalent of plexiglas} = \text{Thickness of plexiglas} \times \frac{\text{Electron density of plexiglas}}{\text{Electron density of water}} \times \frac{\text{Density of plexiglas}}{\text{Density of water}}$$

$$= \text{Thickness of plexiglas} \times \frac{3.25 \times 10^{23} \text{ electrons per g}}{3.34 \times 10^{23} \text{ electrons per g}} \times \frac{1.185 \text{ g per cm}^3}{1.0 \text{ g per cm}^3}$$

$$= 1.153 \times \text{Thickness of plexiglas}$$

TABLE II

RATIO OF EXPOSURE IN WATER TO EXPOSURE IN AIR

Radium used	Ion. chamber	Total ion. chamber wall W	Sleeve over radium S	R	Equiv. path in water P	Readings				Ratio	Symbol
						Air			Water		
						Reading	Correc-tion	Corr. reading			
1	2	3	4	5	6	7	8	9	10	11	12
		(cm.)	(cm.)	(cm.)	(cm.)						
3 x 20 mg. tubes	Large	0.6	0.5	3.0	2.53	39.98	1.039	41.54	40.00	0.963	+
2 x 20 " "	"	"	"	"	"	40.03	"	41.59	40.13	0.965	
" " "	"	"	"	"	"	39.96	"	41.52	40.03	0.964	
4 x 20 " "	"	"	"	4.0	3.53	40.02	"	41.58	39.45	0.949	
" " "	"	"	"	"	"	39.98	"	41.54	39.18	0.943	
" " "	"	"	"	"	"	39.92	"	41.48	39.34	0.948	
" " "	"	"	"	5.0	4.53	40.03	"	41.59	38.34	0.934	
" " "	"	"	"	6.0	5.53	40.05	"	41.61	38.12	0.916	
8 x 20 " "	"	"	"	7.0	6.53	39.96	"	41.52	37.22	0.896	
" " "	"	"	"	8.0	7.53	39.94	"	41.50	36.12	0.870	
" " "	"	"	"	9.0	8.53	39.99	"	41.55	35.57	0.856	
" " "	"	"	"	10.0	9.53	39.94	"	41.50	34.52	0.832	
2 x 20 mg. tubes	Large	0.6	1.0	3.0	2.60	39.94	1.060	42.34	40.99	0.968	x
4 x 20 " "	"	"	"	4.0	3.60	40.08	"	42.48	40.30	0.949	
" " "	"	"	"	"	"	39.98	"	42.38	40.09	0.946	
8 x 20 " "	"	"	"	7.0	6.60	40.13	"	42.54	38.08	0.895	
3 x 20 mg. tubes	Large	0.9	0	3.0	2.50	40.12	1.028	41.24	40.02	0.970	o
4 x 20 " "	"	"	"	5.0	4.50	39.99	"	41.11	38.45	0.935	
8 x 20 " "	"	"	"	8.0	7.50	39.92	"	41.04	36.02	0.878	
" " "	"	"	"	10.0	9.50	39.89	"	41.01	33.98	0.829	

(Continued on next page)

TO FOLLOW PAGE 14.

TABLE II (Continued)

Radium used	Ion. chamber	Total ion. chamber wall W	Sleeve over radium S	R	Equiv. path in water P	Readings				Ratio	Symbol
						Air			Water		
						Reading	Correction	Corr. reading			
1	2	3	4	5	6	7	8	9	10	11	12
		(cm.)	(cm.)	(cm.)	(cm.)						
8 x 20 mg tubes	Small	0.9	0	3.0	2.82	40.64	1.028	41.78	40.19	0.962	●
" " "	"	"	"	"	"	40.13	"	41.25	39.84	0.966	
" " "	"	"	"	4.0	3.82	40.64	"	41.78	39.61	0.948	
" " "	"	"	"	"	"	40.08	"	41.20	39.15	0.950	
" " "	"	"	"	5.0	4.82	40.01	"	41.13	38.23	0.929	
8 x 20 mg tubes	Small	0.9	0.5	3.0	2.89	39.98	1.049	41.94	40.14	0.957	□
" " "	"	"	"	4.0	3.89	40.54	"	42.53	40.48	0.952	
" " "	"	"	"	5.0	4.89	40.08	"	42.03	39.20	0.933	
4 x 10 mg needles	Large	0.9	0	3.0	2.56	39.90	1.028	41.02	39.87	0.972	Δ
8 x 10 " "	"	"	"	4.0	3.56	40.01	"	41.13	39.26	0.955	
" " "	"	"	"	5.0	4.56	39.97	"	41.09	38.76	0.943	
" " "	"	"	"	6.0	5.56	39.91	"	41.03	37.81	0.922	
" " "	"	"	"	7.0	6.56	40.18	"	41.31	37.36	0.904	
" " "	"	"	"	9.0	8.56	40.00	"	41.12	35.40	0.861	
4 x 10 mg needles	Large	0.9	0.5	3.0	2.63	40.04	1.049	42.00	40.31	0.960	▽
8 x 10 " "	"	"	"	5.0	4.63	40.21	"	42.18	39.28	0.931	
" " "	"	"	"	7.0	6.63	39.54	"	41.48	37.10	0.894	

TO FOLLOW PAGE 14.

Hence,

Total equivalent path in water

= P = Actual path in water + 1.153 x Path in plexiglas

= (R - Radius of air cavity of ion. ch. - Radius of Ra sources

- thickness of plexiglas) + 1.153 x Thickness of plexiglas

= R - Radius of air cavity - Radius of Ra sources

+ 0.153 x Thickness of plexiglas (5)

Net correction = - Radius of air cavity - Radius of Ra sources

+ 0.153 x Thickness of plexiglas

The net corrections to R for all the combination of parameters which were used in the experiments are shown in table III.

Columns 7 and 10 of table II are the ionization readings obtained in air and water, respectively, as already described. Each ionization reading in air was multiplied by a correction factor calculated from equation 4 to correct for gamma-ray attenuation in the total effective plexiglas in the radiation path. This correction for the particular values of W and S shown in each line of columns 3 and 4, respectively, is given in column 8 and the corresponding value in column 9 is the corrected ionization in air.

The value given in each line of column 11 is the ratio of the value in column 10 to the value in column 9, i.e., it is the ratio of the exposure in water to the exposure in air under the conditions of the measurement. This ratio is, in fact, the fractional transmission through the corresponding equivalent path in water as given in column 6.

The results given in table II are plotted in figure 9 where the symbol used for each combination of parameters is as shown in the last column

TABLE III

NET CORRECTION TO R TO OBTAIN EQUIVALENT PATH P IN WATER

Radium sources	Correction for radium source	Ionization chamber	Correction for air cavity	Wall of ionization chamber	Sleeves over radium	Total correction for plexiglas	Net correction
Tubes	-0.16 cm.	Large	-0.48 cm.	0.6 cm.	0.5 cm.	+0.17 cm.	-0.47 cm.
"	"	"	"	"	1.0 cm.	+0.24 cm.	-0.40 cm.
"	"	"	"	0.9 cm.	0	+0.14 cm.	-0.50 cm.
"	"	Small	-0.16 cm.	"	0	+0.14 cm.	-0.18 cm.
"	"	"	"	"	0.5 cm.	+0.21 cm.	-0.11 cm.
Needles	-0.095 cm.	Large	-0.48 cm.	"	0	+0.14 cm.	-0.44 cm.
"	"	"	"	"	0.5 cm.	+0.21 cm.	-0.37 cm.

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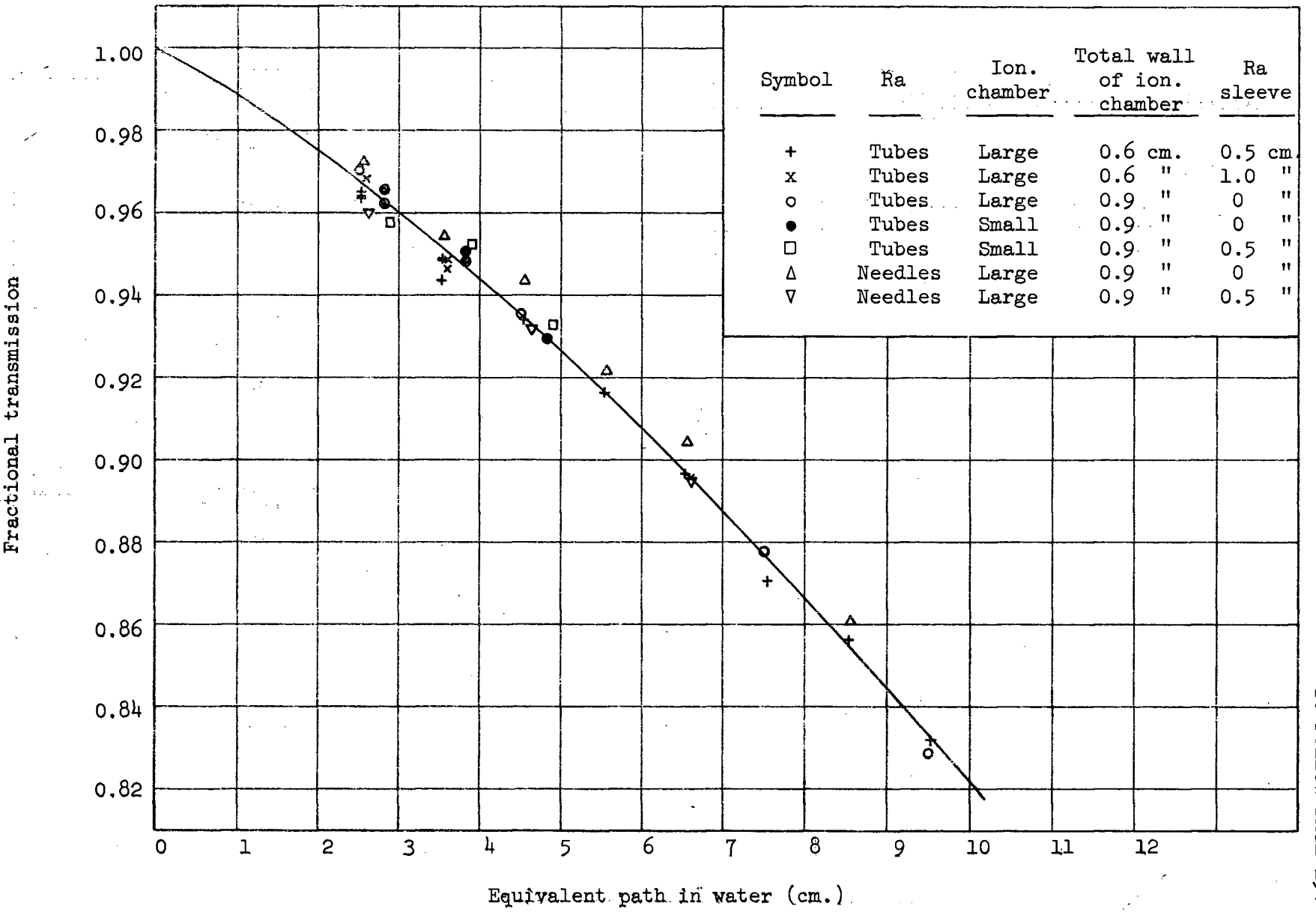

FIGURE 9. FRACTIONAL TRANSMISSION THROUGH WATER MEASURED IN A LARGE WATER PHANTOM.

TO FOLLOW PAGE 15.

of table II. In this graph, fractional transmission has been plotted against equivalent path in water, i.e., the values in column 11 of table II have been plotted against the corresponding values in column 6.

The ionization readings in air and in water as given in columns 7 and 10, respectively, are in each case the averages of several readings taken on the same day. Where more than one reading has been given in the table for the same combination of variables, the readings were taken on different days and have been plotted as separate points in figure 9.

The curve shown in figure 9 is plotted from the following empirical equation:

$$\text{Fractional transmission} = e^{-(0.0110 + 0.00086P)P} \qquad (6)$$

where P is the equivalent path in water. The fit of this equation is at least as good as the data being fitted.

5. Discussion of Results

Most of the measurements were made with the large ionization chamber. Since the volume of the air cavity of the large chamber was about nine times that of the small one, the required sensitivity of the amplifier was smaller and the stability was better. Some measurements, however, were made with the small chamber to determine whether there was any systematic difference in results which depended on the diameter of the air cavity. Due to the reduced sensitivity of the detector all these measurements were made with the radium sources on circles of radii 5 cm. or less. In figure 9 the difference between the results with the small chamber (symbols used □, ●) and with the large one (symbols used +, x, o) does not appear to be greater than the general scatter of the experimental points, i.e., for chambers of the size used, the diameter of the air cavity did not appear to affect the results.

No measurements were made to determine whether the length of the air cavity and the active length of radium sources influenced the results. The effect, if any, would be to change the effective distance R between the radium sources and the detector and would be most important for small values of R. Calculations were made to estimate the magnitude of this effect. The geometry of the arrangement is shown in figure 10.

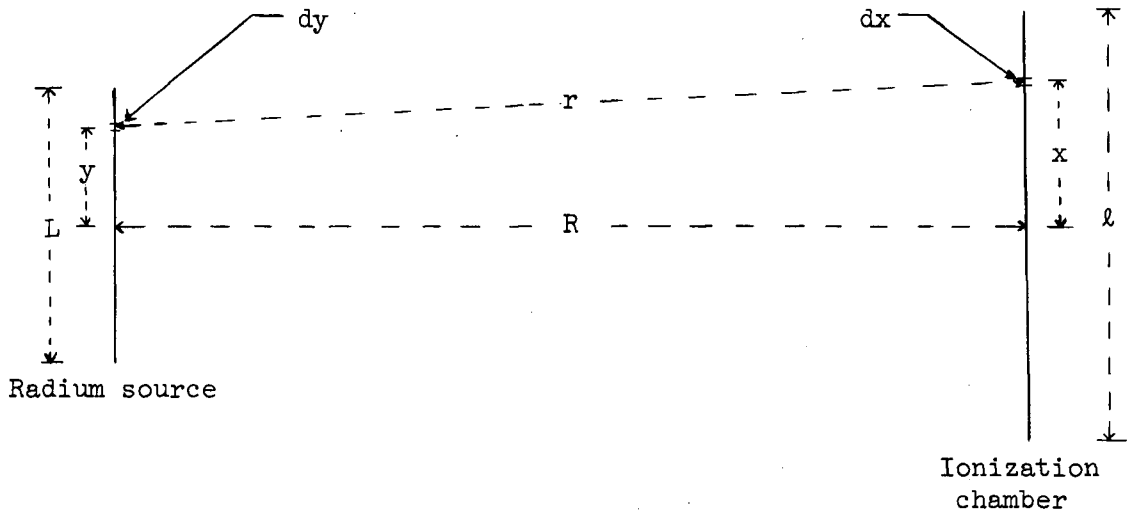

FIGURE 10. GEOMETRY OF THE EXPERIMENTAL ARRANGEMENT (3 x full scale)

In this diagram, L is the active length of the radium source, ℓ is the effective length of the air cavity of the ionization chamber, R is the perpendicular distance from center to center, x is the distance of an element of the air cavity from its center, y is the corresponding variable for the radium source and r is the oblique distance between an element of the detector and an element of the source. If S is the response of the detector, then

$$dS = K \frac{dx}{\ell} \cdot \frac{C}{r^2} M \frac{dy}{L}$$

where M is the quantity of radium, C is the specific gamma-ray constant of radium and K is a constant of proportionality which depends on the sensit-

ivity of the detector. (In this differential equation, oblique filtration in the platinum container has been omitted since it would have negligible effect on the results). Integrating

$$S = \frac{KCM}{\ell L}\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} \frac{1}{r^2}\,dx\,dy = \frac{KCM}{\ell L}\int_{-\frac{L}{2}}^{\frac{L}{2}}\int_{-\frac{\ell}{2}}^{\frac{\ell}{2}} \frac{1}{R^2 + (y - x)^2}\,dx\,dy$$

$$= \frac{KCM}{\ell LR}\left[(L + \ell)\tan^{-1}\left(\frac{L + \ell}{2R}\right) - (L - \ell)\tan^{-1}\left(\frac{L - \ell}{2R}\right) - R \ln\left\{1 + \left(\frac{L + \ell}{2R}\right)^2\right\} + R \ln\left\{1 - \left(\frac{L - \ell}{2R}\right)^2\right\}\right] \qquad (7)$$

For the values of L, ℓ and R used in the experiment, an acceptable approximation to the exact solution given in equation 7 can be obtained by using

$$\tan Z = Z - \frac{1}{3}Z^3 \qquad \text{and} \qquad \ln(1 + Z) = Z - \frac{1}{2}Z^2 \qquad \text{for } Z^2 < 1.$$

With these approximations, equation 7 reduces to

$$S = \frac{KCM}{R^2}\left\{1 - \frac{1}{12}\left(\frac{L^2 + \ell^2}{R^2}\right)\right\} = \frac{KCM}{R_e^2} \qquad (8)$$

where R_e is the effective distance between source and detector. For the worst case where L = 1.2 cm., ℓ = 1.9 cm. and R = 3.0 cm., R_e = 3.07 cm. A change of 0.07 cm. in the abscissae of the points in figure 9 would not be detectable in view of the scatter of the points.

Most of the measurements were made with 20 mg. radium tubes since these were the largest sources available and it was desirable to obtain the required activity for any given measurement with the minimum number of sources. By this means the amount of manipulation and, hence, the radiation

exposure of personnel was reduced. Some measurements were made, however, with 10 mg. needles to determine whether the difference in the gamma-ray spectrum resulting from the smaller filtration affected the results. These points are shown as triangles in figure 9. There may be some suggestion that the transmission through water is greater for the more lightly filtered radiation but it would not be justified to conclude from this experiment that there is a real difference. If, in fact, the radiation from the more lightly filtered source is less rapidly attenuated in water than the radiation from the heavily filtered source, as suggested by figure 9, it must be argued that the degradation by scattering in the additional platinum is more important than the additional filtration.

Apart from a possible small dependence on the filtration of the radium, there do not appear to be any systematic differences between results obtained under different conditions of measurement, i.e., the differences appear to be random. All experimental points lie within 1% of the empirical curve fitted to the data. This is about the scatter which might be expected from the sensitivity of the measuring equipment. The smallest ionization currents measured were about 0.6×10^{-12}A. Therefore, for 1% accuracy it was necessary to read a change in the ionization current of 0.6×10^{-14}A. This was about the limit of sensitivity of the equipment used.* It appears that if the curve drawn is in error more than 0.5 to 1%, it must be due to systematic errors common to all the measurements.

The equation of the curve drawn in figure 9 has already been given, namely,

$$\text{Fractional transmission} = e^{-(0.0110 + 0.00086P)P} \qquad (6)$$

---

* The limit of accuracy of the measuring equipment used appears to be determined by a small erratic surface leakage of the polystyrene insulation used in the ionization chamber when the insulation is exposed to radiation.

The bracket of the exponent of this equation is of the nature of an attenuation coefficient which increases with increasing P. The experimental data can be fitted equally well by the following empirical equation:

$$\text{Fractional transmission} = 1 - 0.01\ P^{1.25} \qquad (9)$$

This equation differs from equation 6 by less than 0.2% for any value of P up to 10 cm. For some purposes (16), equation 9 is more convenient to use than equation 6. Either equation must be considered as simply an empirical fit of the experimental data for the range of the measurements. Neither should be extrapolated to larger values of P since neither has a form to be expected for large P. From equation 9 the fractional transmission becomes negative for very large values of P, which is impossible. In equation 6 the bracket representing an attenuation coefficient increases indefinitely with increasing P instead of approaching a constant value as would be expected.

It is to be noted that, from either equation 6 or 9, the apparent absorption in water depends not only on the path in the water but also on the distance of the water from the source. For example, 1 cm. path in water between 9 and 10 cm. from the radium reduces the fractional transmission more than 1 cm. path between 3 and 4 cm. from the radium. It was for this reason that the ionization readings in air had to be corrected for gamma-ray attenuation in plexiglas and the plexiglas included as part of the equivalent path in water. In other words, the fractional transmission as plotted in figure 9 is the transmission through water from the surface of the radium source to the air cavity of the ionization chamber. This is the closest possible experimental approach to the usual situation in interstitial and intracavity radium therapy in which the radium sources are surrounded by tissue and the point of measurement lies in tissue.

The results of the present work are compared with those obtained by previous workers in table IV and in figure 11. Van Dilla and Hine's results (9) have been omitted from this comparison since, due to the scale used, it was not possible to read values in the range of 0 to 10 cm. with reasonable accuracy from their published curve. In table IV the first column, the distance from the source, is for the present work the equivalent path in water. It is not clear from the papers of the other investigators whether they used the geometrical distance or corrected this to an equivalent path in water. The values of fractional transmission in column 2 were read from the empirical curve of figure 9 and those in columns 3 and 4 were read from the curves published by the respective authors. The results of Kenney's group in column 5 are as tabulated in their paper. In figure 11 the best curves have

TABLE IV

A COMPARISON OF THE EXPERIMENTAL VALUES OF THE RATIO OF EXPOSURE IN WATER TO EXPOSURE IN AIR OBTAINED BY DIFFERENT INVESTIGATORS

Distance from source	Present work	Ter-Pogossian et al (8)	Wootton et al (10)	Kartha, Kenney and Cameron (11)
1	2	3	4	5
2 cm.	0.975	0.966	0.979	0.98
4 "	0.944	0.944	0.946	0.95
6 "	0.908	0.920	0.888	0.90
8 "	0.866	0.890	0.822	0.88
10 "	0.822	0.858	0.762	0.84

been plotted for Ter-Pogossian's, Wootton's and the present work (i.e., the curves from which the data of columns 2, 3 and 4 were taken) but the individual points only have been plotted for Kenney's group. The scatter of Wootton's points about his best curve is similar to the scatter in the present experiment, i.e., about 0.5% on either side of the curve. In Ter-Pogossian's work the points scatter 1.5 to 2% on either side of the curve. The results of the present work appear to differ from those of Ter-Pogossian et al and from

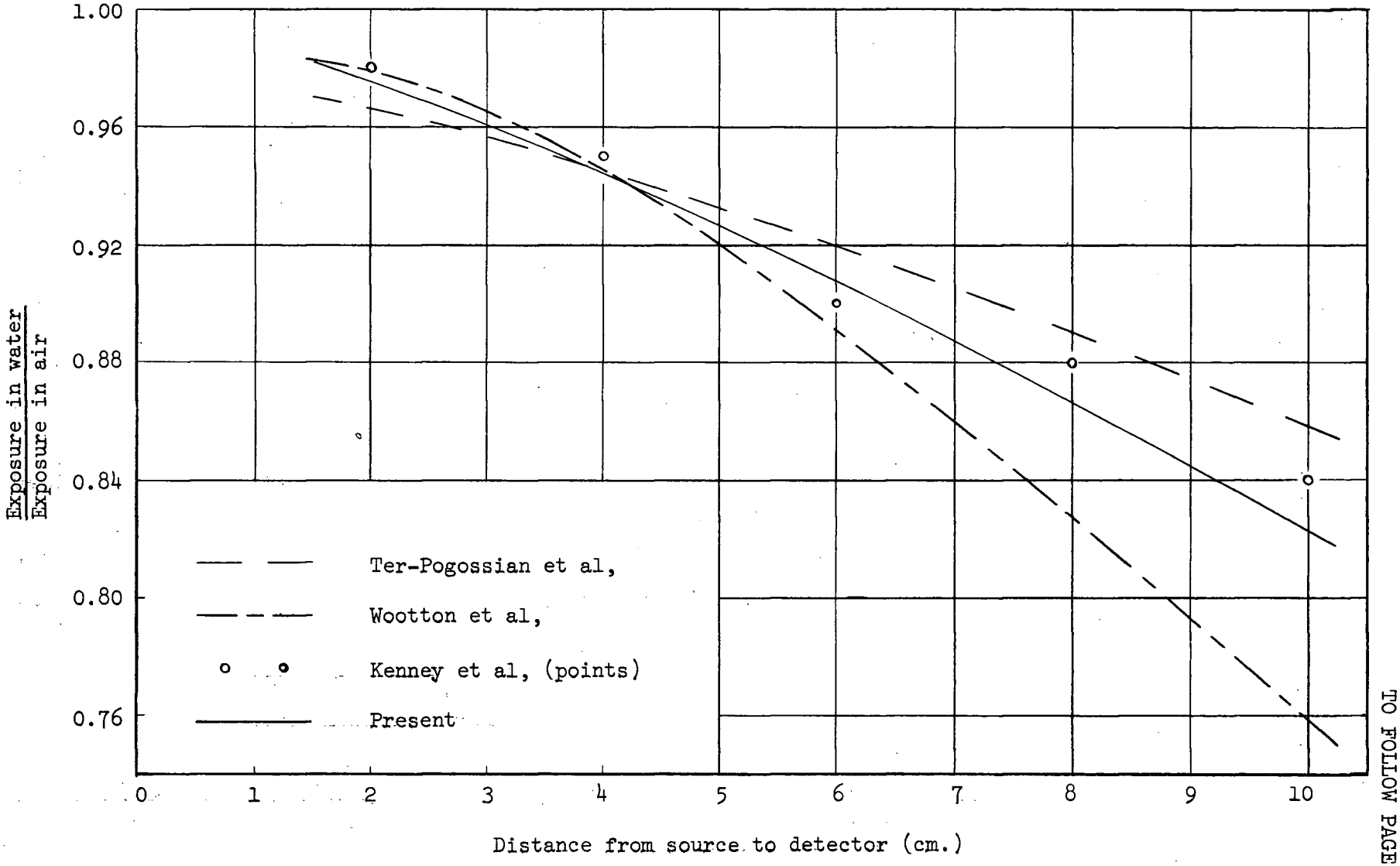

FIGURE 11. COMPARISON OF THE PRESENT RESULTS WITH THOSE OF PREVIOUS WORKERS.

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Wootton and co-workers by more than the random experimental error of any one of the experiments. On the other hand, the results of Kenney's group are scattered about the line of equation 6.

It is difficult to find reasons for the discrepancies between the results of different investigators. Possible causes of disagreement include differences in the following factors:

(a) Type of detector used.

(b) "Build-up" cap on detector and correction for gamma-ray attenuation in this cap.

(c) Size and filtration of radium sources used.

(d) Presence of secondary electrons (or other soft component of radiation) originating in the platinum containers of the sources.

(e) Method of supporting the radium sources.

(f) Size of water phantom used.

(g) Meaning of "distance from source to detector".

There is no suggestion that the results of the different groups differ due to the size of water phantom used since the phantoms in all cases were of adequate dimensions. Neither is it possible that the differences depend on the radium sources used since all (with the exception of Van Dilla and Hine) used typical medical radium sources with 0.5 or 1.0 mm. platinum filtration. There were differences in the methods of supporting the radium sources which might result in small differences in the scatter contribution to the readings in air but it is hard to believe that this factor is sufficient to explain the discrepancies in the final results. (It is to be noted that an added scatter contribution to the air reading results in a lower apparent transmission through water). As already pointed out, it is not clear from the published papers that "distance from source to detector" has the same meaning

in each case but, at most, this factor would produce only a small lateral shift in a curve whereas the curves obtained by different investigators differ appreciably in slope.

Wootton's group made some measurements with a small ionization chamber very similar to that used in the present work and some measurements with a small anthracene crystal. In each case a total wall thickness of 0.57 cm. was used around the sensitive volume to provide build-up and correction was made for gamma-ray attenuation in this wall. The results obtained with the two detectors were in fair agreement. The results with the anthracene scintillation detector were, at small distances, lower and, at large distances, higher than those measured with the ionization chamber but for large distances were still appreciably lower than values obtained by Ter-Pogossian et al with a similar anthracene crystal or obtained with an ionization chamber in the present work. It appears from figure 5 that the wall thickness of 0.57 cm. used by Wootton was just adequate to provide full build-up and to absorb any soft component of radiation originating in the platinum wall of the source. The factor of 1.017 which was used to correct for gamma-ray attenuation in the wall agrees almost exactly with the correction factor calculated from equation 4. In view of the similarity of the experimental conditions used it is very difficult to account for the differences between the results obtained by Wootton and co-workers and those reported in this thesis.

It is more difficult to compare the results of Ter-Pogossian's group with those of the present work since they used a small anthracene crystal (3.5 mm. diameter and 4 mm. long) instead of an ionization chamber as the detector. The crystal was surrounded by slightly more than 1 cm. of plexiglas which was certainly sufficient to ensure full electron build-up and to remove any soft component of radiation originating in the platinum container

of the radium source. Correction was made for gamma-ray attenuation in this plexiglas but the correction used is not stated. As in all experiments of this type, there is uncertainty about the values of "distance from source to detector" but, as already noted, this factor could not explain the difference in results. It is to be noted that the differences between Ter-Pogossian's results with an anthracene crystal and the present results with an ionization chamber are similar in both direction and magnitude to the differences observed by Wootton's group with the two types of detectors. This suggests that the response of the anthracene crystal is energy-dependent and for this reason gives results different from those obtained with the ionization chamber. Some other factor or factors must be found, however, to explain the fact that Wootton's results with either detector are lower at large distances than the corresponding results obtained by Ter-Pogossian's group or by the present investigator.

Kartha, Kenney and Cameron used an experimental set-up very similar to that used by other workers except they used lithium fluoride thermoluminescent dosimeters which after irradiation were read on a commercial reader. The dosimeter capsules were surrounded by plastic of unstated thickness. The average standard deviation of several readings of the same exposure was found to be 1.6%. Within this limit their experimental points are in agreement as shown in figure 11 with the best curve obtained in the present work.

While the differences in the results of the different investigators are still unexplained, in view of the general agreement with Ter-Pogossian and Kenney it is unlikely that equations 6 and 9 are in error by more than 1 or 2% for distances of 10 cm. or less. It should be emphasized, however, that neither equation (particularly equation 9) can be extrapolated appreciably.

PART II

MEASUREMENTS OF THE APPARENT ABSORPTION IN A WATER PHANTOM WITH RADIUM SOURCES IN THE SURFACE OF THE PHANTOM

1. Outline of Project

In the first part of this experiment, exposures in a large water phantom were compared with exposures in air to determine the apparent fractional transmission through water when radium sources and measuring instrument were surrounded on all sides by several centimetres of water, i.e., were immersed in an essentially infinite water phantom. The purpose of this part of the experiment was to measure correction factors to be applied to the above results to correct for the reduced exposure in water resulting from reduced scatter when the radium sources were in the surface of the water instead of immersed in the phantom. These measurements are of interest in radium dosimetry because they provide useful data for the estimation of tissue doses due to radium moulds in which, in general, the radium lies in the surface of tissue-equivalent material and has absorbing and scattering material on one side of the radium but no scattering material behind the radium.

In fact, the scope of this part of the experiment was broadened to obtain more data than merely that required for the dosimetry of radium moulds. The radium sources were placed in a plane with the detector on a normal to this plane through the center of the radium and at a fixed distance from the plane. This whole arrangement could be moved relative to the surface of a water phantom so that the radium sources and the detector could be completely immersed in water, could be in air well above the water or in any intermediate position including the one of particular interest in this experiment, namely, the radium in the surface of the phantom.

2. Experimental Set-up

The geometry of the experimental arrangement is shown in figure 12. The radium sources were supported on a 1/8th-inch thick plexiglas plate grooved so that the centers of the radium sources were at the level of the upper surface of the plate. The 20 mg. radium tubes described in the first part of this work were used for all measurements in this part.

All measurements were made with the large ionization chamber already described using an added plexiglas cap to bring the total wall thickness to 0.9 cm. A plexiglas post cemented to the cap as shown in figure 12 supported the plexiglas plate carrying the radium sources at a fixed distance vertically above the center of the ionization chamber. This distance could be changed by 1 cm. intervals from 3 to 10 cm. by means of plexiglas spacers inserted between the plate and the post.

Ionization currents were measured with the same preamplifier and amplifier as in Part I of this work.

The ionization chamber with the supporting platform for the radium sources was used in a plexiglas water phantom of surface area 50 cm. x 60 cm. and 50 cm. deep which was already available. This phantom was provided with a remotely controlled motor drive* which could be used to raise and lower the ionization chamber and the radium in the tank. The arrangement is shown in the photograph of figure 13. With the tank about half full of water and with the ionization chamber and its associated preamplifier completely waterproofed, the whole measuring assembly could be lowered so it was completely immersed in water or raised so it was entirely in air above the water or could be placed in any intermediate position.

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* The tank with its motor drive was designed for measurements of isodose curves for a Cobalt 60 teletherapy unit. Its construction and use has been described previously (21).

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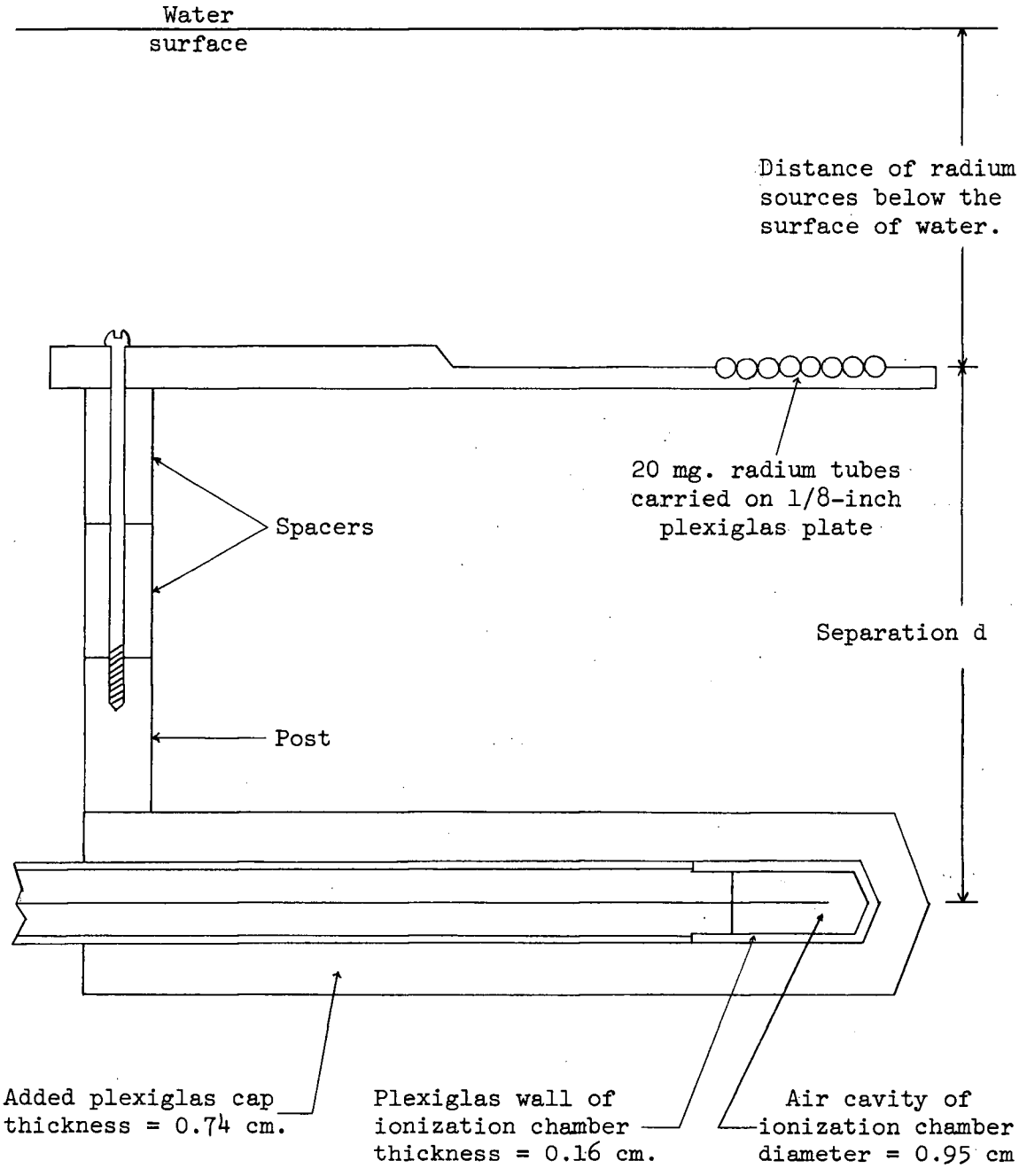

FIGURE 12. GEOMETRY OF THE EXPERIMENTAL ARRANGEMENT OF PART II (Full scale).

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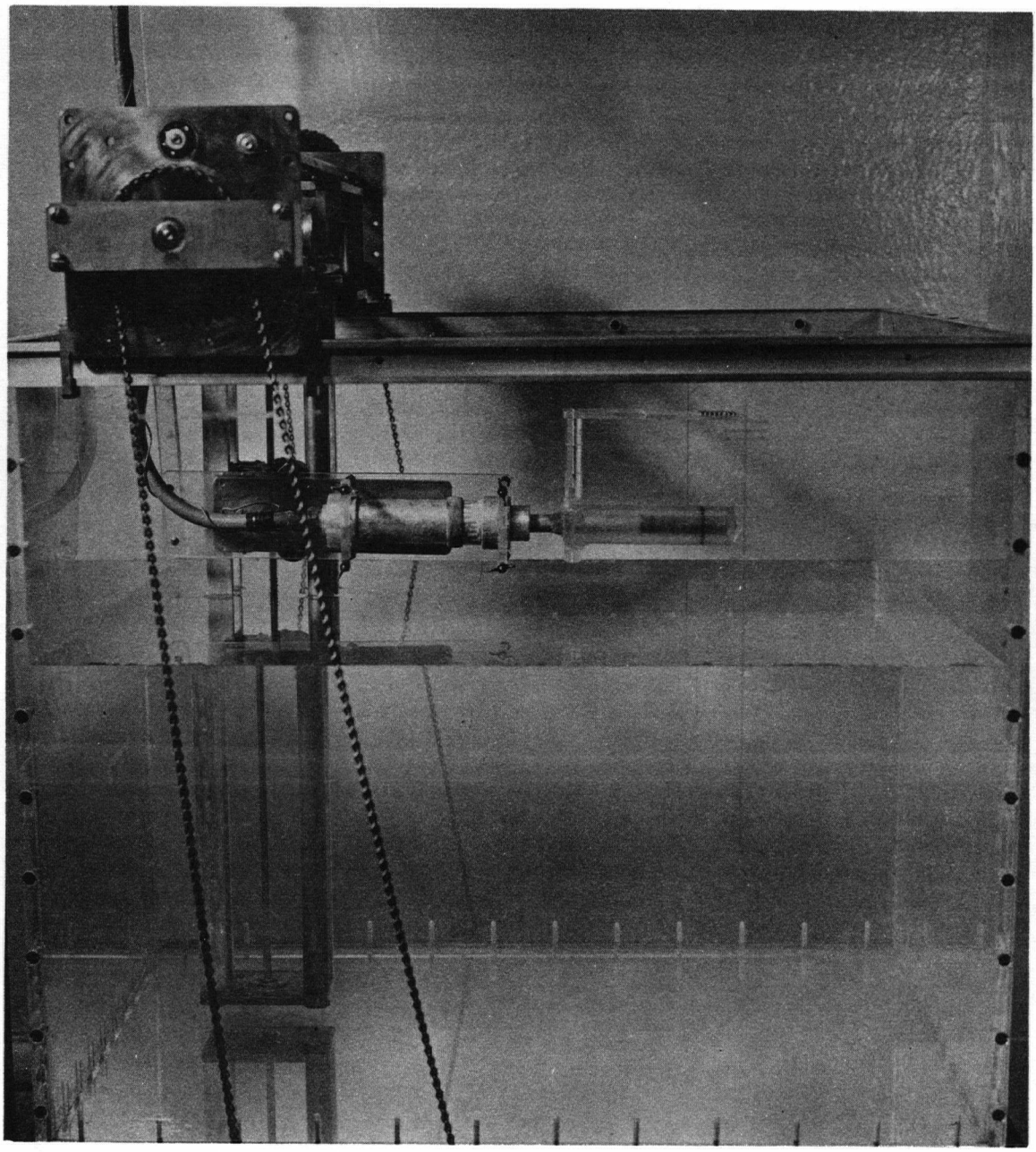

FIGURE 13. EXPERIMENTAL ARRANGEMENT FOR MOVING IONIZATION CHAMBER AND RADIUM SOURCES RELATIVE TO THE SURFACE OF THE WATER

3. Measurement and Results

Ionization current measurements were made starting with the ionization chamber at least 10 cm. above the surface of the water and the relative ionization was determined as the assembly was lowered into and below the water. Measurements were continued until the radium was at least 15 cm. below the surface of the water (but the ionization chamber at least 10 cm. from the bottom of the tank). These measurements were made for distances of 3, 4, 6, 8 and 10 cm. between the center of the ionization chamber and the plane of the centers of the radium sources.

The results of the above measurements are shown in figure 14 where the ordinate is the ionization in any position relative to the ionization with the assembly well above the water and the abscissa is the actual distance of the plane of the centers of the radium below the surface of the water. One curve has been plotted for each separation of detector and radium as indicated by the legend on the figure. The points plotted are, in general, averages of two or more readings taken on different days. Particular emphasis was placed on determining the maxima and minima of the curves accurately. The individual readings scattered up to 0.5% on either side of the average. It is to be noted that the ordinates are uncorrected ratios of ionization currents, i.e., no corrections have been made for gamma-ray attenuation in the wall of the ionization chamber or in the platform supporting the radium.

To improve the accuracy of measurement a bracketing procedure was used as in Part I of the project, i.e., each reading was bracketed with readings at a reference point so the differences could be determined with maximum accuracy. For convenience, two reference points were used, one on the flat part of the curve with the assembly well above the water and one on the flat part of the curve with the assembly completely immersed. This reduced con-

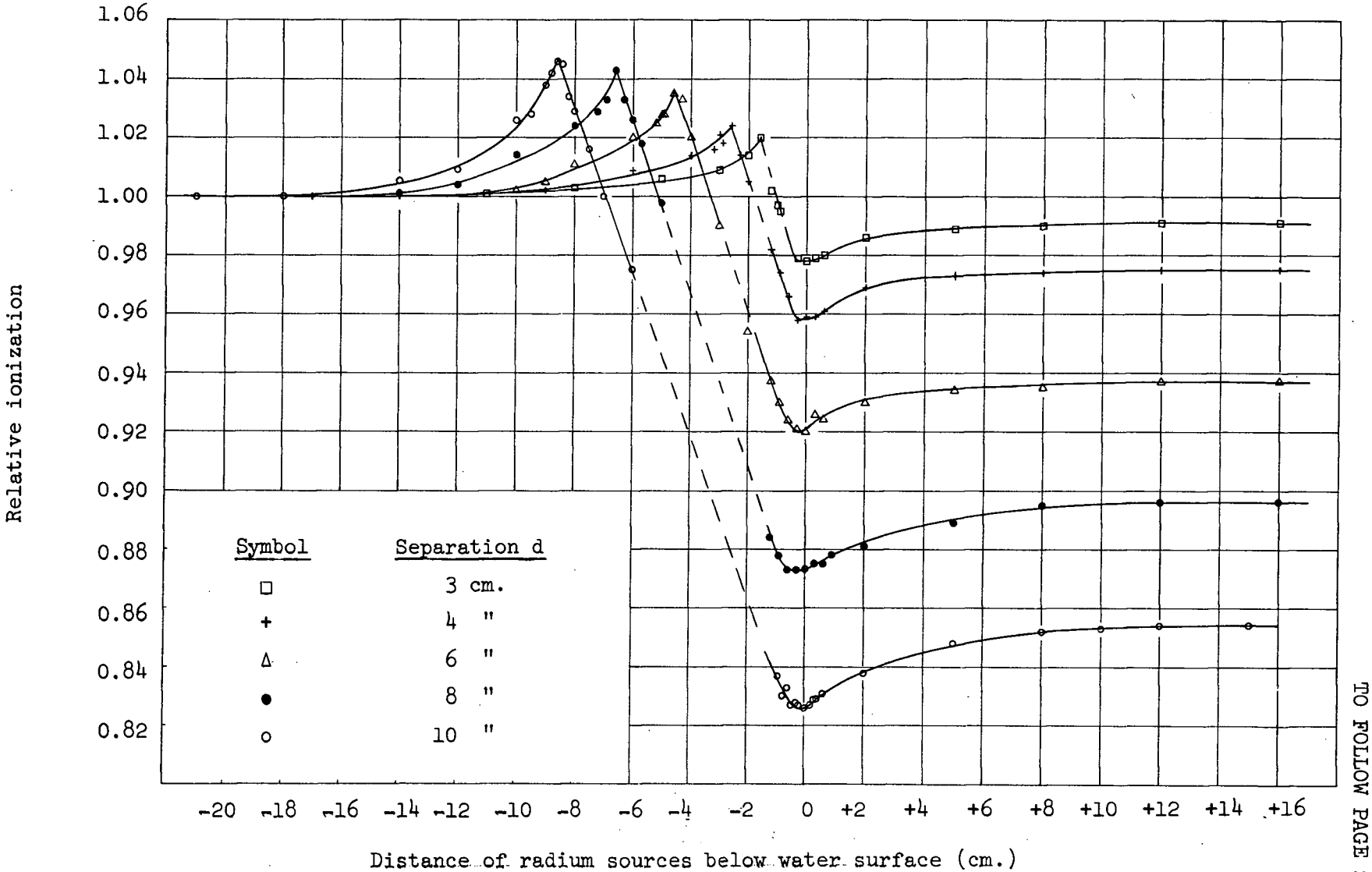

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FIGURE 14. RELATIVE IONIZATION VERSUS POSITION OF RADIUM SOURCES RELATIVE TO SURFACE OF WATER FOR DIFFERENT SEPARATIONS OF RADIUM SOURCES AND DETECTOR.

siderably the time spent in moving from the point of measurement to the reference point. To relate the two parts of the curve accurately, a careful comparison was made between the two reference points.

4. Discussion of Results

The explanation of the curves of figure 14 is as follows. All ionization currents were referred to the ionization current with the ionization chamber at least 10 cm. above the water as already stated. As the assembly was lowered so the ionization chamber approached the water, the ionization current increased due to backscatter from the water. The maximum was reached when the ionization chamber was just immersed in water, i.e., for a chamber of the dimensions used, when the center of the air cavity was 1.4 cm. below the surface of the water or the radium was (d - 1.4) cm. above the water. As the assembly was lowered still further, the ionization current fell rapidly due to the increasing absorption in water which much more than compensated for the increasing scatter. The minimum ionization current occurred when the plexiglas plate carrying the radium touched the water, i.e., when the center of the radium was 0.3 cm. above the water, since in this position the absorption was a maximum. Beyond this position the absorption was constant but the scatter contribution increased resulting in an increased ionization current. The ionization current reached a constant value when the assembly was immersed ~~in an essentially infinite~~ phantom. For a separation d = 10 cm., this required about 10 cm. of water above the radium. If the ionization chamber had been brought too close to the bottom of the tank the ionization current would have decreased again due to decreased scatter. It was for this reason that the ionization chamber was kept at least 10 cm. from the bottom.

It is evident that, for any curve of figure 14, the ratio of the reading with the assembly well immersed in water to the reading in air well

above the water can be compared with the results of the previous part of the experiment if the distance d is converted to the equivalent path in water and the air reading is corrected for gamma-ray attenuation in the plexiglas. By comparison with equation 5 it is seen that the equivalent path in water for the present case is given by the following:

Equivalent path in water

= d - Radius of air cavity - Radius of Ra sources

+ 0.153 x Thickness of plexiglas

= d - 0.48 - 0.16 + 0.153 (0.90 + 0.16) = (d - 0.48) cm.

Equation 4 was used to determine the correction for gamma-ray attenuation in the plexiglas. From this equation

$$\text{Correction factor} = e^{0.0306(W + 1.3S)} = e^{0.0306(0.90 + 1.3 \times 0.16)} = 1.034$$

The values of the fractional transmission through water as determined from the corrected readings for each value of d used in this part of the experiment are compared in Table V with the corresponding values from Part I. Column 3 gives the uncorrected ratios of the ionization current in water to that in air as read from figure 14 and column 4 gives the ratios obtained after correction of the air reading for gamma-ray attenuation in the plexiglas.

TABLE V

A COMPARISON OF THE EXPERIMENTAL VALUES OF FRACTIONAL TRANSMISSION OBTAINED IN PART I AND PART II

Distance d	Equivalent path in water	Uncorrected ratio	Corrected ratio	Fractional transmission from fig. 9
3 cm.	2.52 cm.	0.991	0.957	0.967
4 "	3.52 "	0.975	0.942	0.951
6 "	5.52 "	0.937	0.905	0.917
8 "	7.52 "	0.896	0.866	0.876
10 "	9.52 "	0.854	0.825	0.833

The last column of the table is the value of the fractional transmission for each equivalent path as read from the curve of figure 9. These values are seen in all cases to be intermediate between the uncorrected and the corrected ratios of the present experiment, being about 1% higher than the corrected ratios with which they should agree. The consistency of the differences in the values in the last two columns of the table suggests a systematic error in one or the other experiment. There are two possible sources of error in the ratios determined from this part of the experiment. First, the distance d which has been tabulated was the perpendicular distance between the centre of the ionization chamber and the plane of the radium. The average distance between the centre of the chamber and the centres of the radium sources would, in fact, be a little greater than d. The difference, however, would be scarcely significant. The more important source of error in the second part of the experiment is the correction used for gamma-ray attenuation in the plexiglas. Equation 4 should still give a valid correction for the wall of the ionization chamber since the geometry is unchanged. It may, however, give an over-correction for the plexiglas plate carrying the radium since the absorption was due to 0.16 cm. thickness of plexiglas but the scatter from the plate would be greater than from a 0.16 cm. thick cylindrical sleeve, i.e., the overall attenuation would be less than that due to the corresponding sleeve. In view of these uncertainties, the agreement between the values in the last two columns of table V may be accepted as reasonable verification of the results of the second part of the experiment. The values of the fractional transmission in water as determined in part I should, however, be considered much the more reliable since they were measured in an experiment designed for the purpose.

The particular purpose of this part of the experiment, as stated in the outline of the project, was to determine correction factors to be applied

when the radium sources, instead of being completely immersed in a water phantom, were located in the surface of the phantom. The correction can be obtained directly from figure 14 for each value of d used in the experiment by taking the ratio of the ionization current when the radium was in the surface of the water (i.e., abscissa = 0) to the constant ionization current with the assembly well immersed in water (i.e., large positive abscissa). These ratios are given in table VI.

TABLE VI

CORRECTION FACTORS FOR THE RADIUM IN THE SURFACE OF THE PHANTOM

Separation, d	$\frac{\text{Ionization with radium in surface}}{\text{Ionization with radium well immersed}}$
3 cm.	0.987
4 "	0.983
5 "	0.982*
6 "	0.983
8 "	0.974
10 "	0.967

* For d = 5 cm., this ratio only was measured, not the complete curve.

The correction factors shown in table VI have been plotted in figure 15 against the separation d. The data are not accurate enough to determine the exact quantitative relationship between the correction factor and the separation. However, the correction factor must have a value of unity for zero separation. The straight line drawn in figure 15 satisfies this condition and fits all the points within experimental error. The equation of the line is

$$\text{Correction factor} = 1 - 0.0034d \qquad (10)$$

To use the results of this part of the experiment to determine the exposure at a depth d in water (or tissue) when the radium sources are in the surface of the water, the exposure at the point in air is determined and this

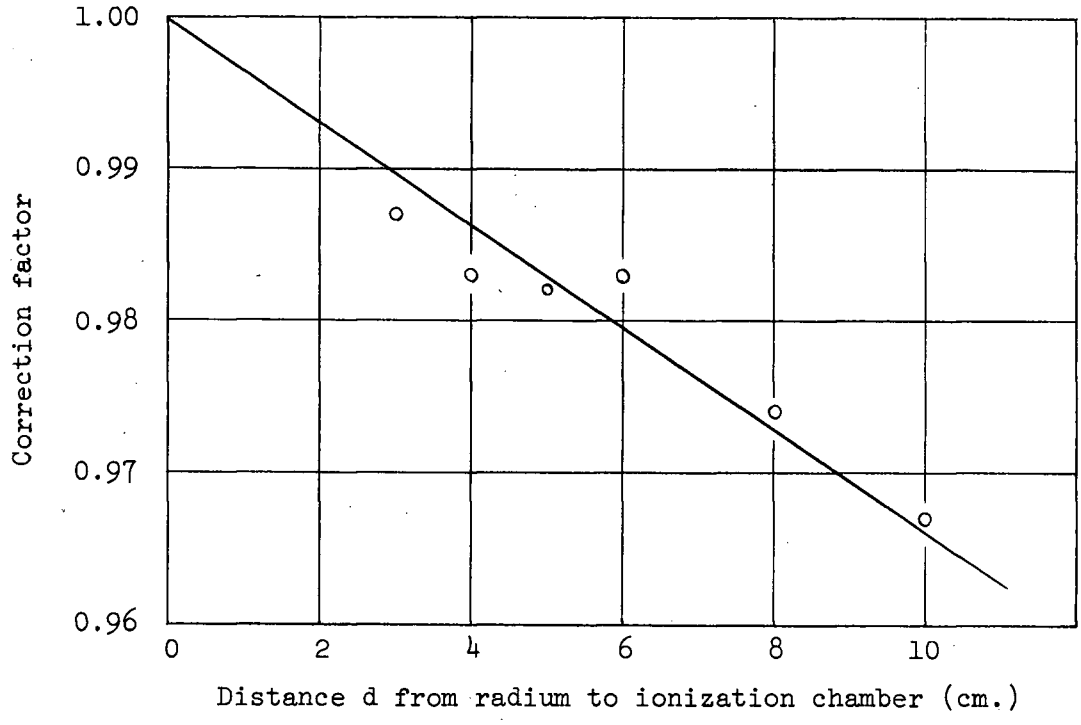

FIGURE 15. CORRECTION FACTORS FOR DIFFERENT VALUES OF d.

is multiplied by a factor from figure 9 or from equation 6 or 9 (using P = d) to find the exposure at the point when the sources are well immersed in water. Then this product is multiplied by a second factor read from figure 15 or equation 10 to correct for the reduced scatter when the sources are in the surface of the phantom.

The work of Roberts and Honeyburne (17) was not exhaustive and was intended to determine semi-quantitatively to what degree scattering compensated for absorption for different geometries in a water phantom. Their data are not directly comparable with the present results.

Cook's measurements (18,19) were more extensive than those of this part of the present emperiment in that he used extended sources of various areas in the surface of the water phantom whereas compact sources only (maximum overall area of radium sources = 2.2 cm. x 2.6 cm.) were used in the

present work. On the other hand, Cook did not make measurements at distances greater than 2 cm. from the plane of the radium. At a distance of 2 cm. from a small radium distribution he found a much larger apparent absorption in water than would be obtained from the results of the present experiment.

The present experiment does not supply complete data for the dosimetry of radium moulds since measurements have been made only along a normal through the centre of a compact radium source. It would be useful to make similar measurements along parallel lines at various distances from the normal through the centre of the source since this would make it possible to determine the exposure due to any array of radium sources in the surface of the phantom.

It should be possible by further work to get a more quantitative explanation of the curves of figure 14. The absorption in the medium between the radium source or sources and the point of measurement can be calculated from the total absorption coefficients of the phantom material, i.e., the exposure at the point due to the primary gamma radiation can be calculated. However, there are not data available which make it possible to estimate the exposure at a point due to scattered radiation except for one or two particular geometries in which measurements have been made. An analysis of the curves of figure 14 which gave further information on the scatter contributions from different parts of the irradiated medium would be useful in practical radium dosimetry.

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