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A SMALL WRIST DOSIMETER FOR BETA AND GAMMA RADIATION

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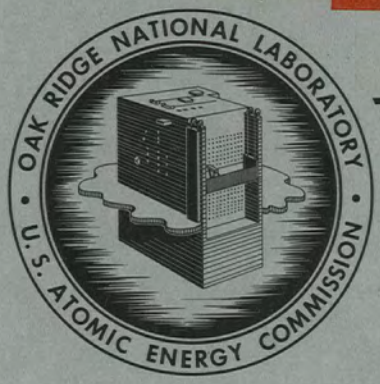

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HEALTH PHYSICS DIVISION

A SMALL WRIST DOSIMETER FOR BETA AND GAMMA RADIATION

H. H. Hubbell, Jr.
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Submitted as a thesis to the Faculty of the Graduate School of Vanderbilt University in partial fulfillment of the requirements for the degree of Master of Science in Physics.

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ABSTRACT

An ion chamber for personnel dosimetry of both beta and gamma radiations must satisfy several requirements. From the standpoint of dosimetry, the walls should be air equivalent and preferably thick enough to produce electronic equilibrium for gamma rays, yet have a superficial density of only 7 mg/cm^2 over at least part of the surface in order to admit any beta rays which are energetic enough to reach the basal layer of the epidermis. The electric field must always be large enough to collect all the ions formed at any reasonable dose rate. For economic reasons, the volume and capacitance should be chosen to yield correct dose readings with an existing electrometer system, and the dimensions should be minimized for the wearer's convenience. The principles of ion chamber design are discussed, and a dosimeter embodying them is described. The device is basically a parallel-plate ionization chamber with closely spaced circular electrodes and may be worn conveniently anywhere on the body. The sensitive volume and capacitance of the chamber are chosen to permit it to be charged and read on a Victoreen Minometer, and it has an X- and gamma-ray response which is independent of energy above 100 Kev. The maximum departure from energy independence is about 30% and occurs at 50 Kev. The outer, ribbed structure is made of nylon and forms a short cylinder about an inch and a half in diameter and about three quarters of an inch high. Filling the space between the ribs is a conducting

plastic film approximating the human epidermis in thickness and forming one plate of the chamber. The electrical capacitance is not only in the air gap between the plates, but also in the insulating plastic base between the lower plate and the metal cap which holds the dosimeter to the wrist or elsewhere. Calibrations for beta rays were made with 2π geometry obtained by inserting the dosimeter in a paraboloidal cavity formed in a rotating solution of one of several beta-emitting isotopes. The response varies from 38% to 63% of the dose to the basal layer of the epidermis for isotopes emitting beta rays with average energies in water from 52 Kev for S^{35} to 694 Kev for Y^{90} respectively.

The problem of measuring beta-ray exposures to personnel has become increasingly acute with the growing use of beta-ray emitting isotopes and because of the variable beta-to-gamma dose ratio from fall-out from weapons tests. A number of satisfactory survey instruments are available, but there is currently on the US market no dosimeter sensitive to low or medium energy beta rays yet small and rugged enough to be worn on the person. The dimensional requirements are even more stringent for such a device if it is to measure dose to the hands.

Small ionization chambers, usually about the size of a fountain pen, are widely used to monitor low-level exposures of personnel to X and gamma rays. However, if such a device is to be sensitive to any beta rays which can damage the skin, it must have walls only a few mils thick. It must also be rugged enough to withstand reasonably rough service and yet be cheap to manufacture and service. In the work described here a dosimeter suitable for wrist wear which measures X-ray, gamma-ray, and beta-ray exposures has been developed and calibrated.

A satisfactory design for such a device must be consistent with a number of different factors. Among these are that the device must measure dose in accordance with the usual definition thereof; it must possess certain electrical characteristics such as a high enough electric field to collect all the ions formed by the radiation; it

must have the appropriate capacitance and volume needed to produce correct readings on a given electrometer; it must be of minimum size and of low cost; it must be readily calibrated for response to X and gamma rays as well as beta rays. The final design described herein apparently satisfies all the above requirements.

The final instrument is an ionization chamber in the shape of a small pillbox about 1.5 inches in diameter and about 0.75 inch high, or a little larger than a wrist watch. The cylindrical cap and top are made of nylon 0.080" thick and have openings to admit beta rays through 50% of the surface area. The cap is lined with a graphite-coated plastic film 7 mg/cm^2 in superficial density whose absorption is approximately the same as that of the dead layer of the human epidermis. Thus any radiation which can reach the basal layer of the epidermis will penetrate the chamber wall over 50% of its area and be recorded. The response to non-penetrating radiation is thus 50% of that for penetrating radiation in accordance with permissible levels of exposure as recommended by Handbook 59[1].

The dose is measured by the amount of discharge of the ionization chamber when read on a fiber electroscope (the Victoreen "Minometer").

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[1] "Permissible Dose from External Sources of Ionizing Radiation", National Bureau of Standards Handbook 59 (1954), p. 42.

The volume and capacitance of the chamber were adjusted to give the same readings for a given X-ray or gamma-ray exposure as the Victoreen pencil-type pocket chamber.

The chambers were calibrated with heavily-filtered X rays of effective energies from 20 to 200 Kev and with radium gamma rays. The relative response per milliroentgen of exposure dose varied only 30% over this range.

The chambers were also calibrated with a series of thick, dilute water solutions of beta-ray emitting isotopes. These beta irradiations were made in a paraboloidal cavity in a rotating cup of solution so that the chambers received beta rays from 2π solid angle yet did not touch the solution. The response was found to vary from 38% to 63% of that observed with the chamber modified by removal of the nylon structure. The measurements covered a range of average electron energies from the solutions from 52 Kev for S^{35} to 694 Kev for Y^{90}. The reading of the new chamber after beta-ray exposure is practically 50% of its reading for the same air dose of X or gamma rays.

Several other personnel monitoring devices may be compared with this particular instrument. Film badges are widely used for the purpose and have a number of distinct advantages. They are simple, relatively cheap, and rugged, and the record is permanent once the film is processed. Identification marks can easily be put on the film so the chance of error in identification is slight. Film can integrate

the dose received over long periods of time so that the dose rate sensitivity may be very high except insofar as it is reduced somewhat by failure of the reciprocity law between exposure dose rate and exposure time. On the other hand, film in a film badge holder must always have a relatively thick layer of light-tight paper over it by which low-energy beta rays are strongly attenuated. Also, film response varies by as much as a factor of 20 or 30 for different X- and gamma-ray energies. Most of this energy dependence can be removed by suitable filters over the film, but the interpretation is still complex and subject to error. In addition, the photographic processing requires rather close control of temperature and other variables, and calibration films must be exposed and handled with each batch processed, so that dose measurements are slow and complicated. Films are also used in finger rings to measure dose to the hands, but again the necessary thick covers over the film and the need for processing reduce their usefulness.

Pocket pencil-type ionization chambers are convenient for quick measurements of small exposures but they must be read daily in practice. Furthermore, the chambers usually employed have such thick walls as to be nearly insensitive to beta rays. A pocket chamber was designed several years ago in the Dosimetry Section of the Health Physics Division at ORNL to measure beta-ray dosage. While it has performed very satisfactorily, it seemed to be too fragile, too expensive for routine commercial production, and it was not suitable for wear on the hands.

Some pocket chambers contain fiber electroscopes so that they can be read at once in the field, but for most purposes the added cost prohibits their extensive use.

As a result of these considerations this project was undertaken, and the resulting chamber seems to answer all the needs for a rugged, sensitive, inexpensive dosimeter for pocket and wrist wear. The principles developed in the study are applicable to many ion chamber dosimeters.

II. DESIGN REQUIREMENTS

The requirements for a satisfactory device to measure the dose of beta, X, and gamma radiation to the hands may be divided into four categories: dosimetric; electrical; mechanical; and those of a practical engineering nature.

For satisfactory dosimetry, the following needs must be met:

1. The device should record correctly any beta dose which can penetrate the dead layer of the epidermis, 7 mg/cm^2.[2]
2. Its response to beta rays at this depth should be a true measure of dose independent of the energy of the beta rays.
3. Its response to beta rays at a depth of 7 mg/cm^2 should be 50% of that to gamma rays since NBS Handbook 59 allows maximum permissible beta dose to be approximately twice the maximum permissible gamma dose at this depth.
4. Its response to X and gamma rays should be a true measure of exposure dose in roentgens independent of radiation energy.
5. Its response should be the same for radiation incident from any angle, at least over a hemisphere.

The electrical characteristics needed were principally determined by these additional considerations:

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[2] Op. cit., page 39.

6. Since fiber electroscopes such as the Victoreen "Minometer" are widely available and satisfactory, it seemed very desirable to have a chamber which could be charged and read on such an instrument. Therefore the capacitance and volume of the chamber should be such as to give a correct reading on the existing Minometer scale.

7. The electrical field throughout the chamber should be sufficient even at the lowest voltage used after full scale discharge to collect all the ions produced at any reasonable dose rate.

8. The chamber is basically a condenser which is discharged by radiation. Therefore, to avoid false readings, its electrica leakage must be negligible over at least 24 hours under all reasonable conditions of temperature, humidity, shock, etc.

In mechanical design, several further requirements had to be met:

9. The device should be convenient for wrist or pocket wear.

10. It should be as small as possible and of convenient shape.

11. It must be rugged enough to withstand reasonably rough treatment without damage or discharge, yet have thin walls over at least part of its surface.

Finally, practical considerations dictated that:

12. The device should be reasonably inexpensive to manufacture.

13. It should be cheap and easy to repair and to calibrate.

III. HISTORICAL DEVELOPMENT

Ionization methods have been used for the measurement of X rays since Roentgen's original discovery and for the measurement of radioactivity since the Curies' work. A definition of quantity of X rays in terms of air ionization was suggested by Villard in 1908, in a form quite similar to the presently accepted definition of the roentgen[3]. The thimble chamber for making such measurements was developed over a period of years from that time up to 1928 by Sievert, Glasser, Portmann, Seitz, Behnken, and many others. In 1927 Victoreen introduced such a device with a carbon chamber and aluminum central electrode. It was understood by that time that air dose could be measured correctly in such a chamber only if the average atomic number of its electrodes was the same as that of air. In 1928 the Condenser R-Meter was developed by Glasser, Portmann and Seitz[4] and marketed by Victoreen shortly thereafter. The principles of this instrument have been the basis for most dosimeters developed since then[5].

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[3] Villard, P., Arch. d' electric. med., Bordeaux, 14, 692 (1908).

[4] Glasser, O., Portmann, U. V., and Seitz, V. B., Am. Jour. Roentgenol. 20, 505 (1928).

[5] This work is summarized by Victoreen, J. A., Article "Roentgen Rays: Measurement of Quantity by Thimble Chambers" in MEDICAL PHYSICS Otto Glasser, editor (Year Book Publishers, Inc., Chicago, 1944, reprinted 1947).

For measuring small doses of stray radiation to personnel, Victoreen in 1940 introduced the "Minometer" and pocket chamber[6]. The "Minometer" is a string electrometer of low capacitance containing a 110 volt AC operated charging circuit and is designed to work with a pencil-size ionization chamber. Only the chamber is worn on the person, and its volume and capacitance are small enough to give full scale reading on the Minometer for 200 milliroentgens (mr) exposure. The usual pocket chambers have a thick wall for mechanical strength and to insure electronic equilibrium between the X rays and secondary electrons. This thick wall strongly attenuates both soft X rays and beta rays and stops any beta rays of energy below several hundred kilo-electron volts (Kev) from being recorded.

Parker in 1943[7] made chambers to measure beta radiation with the aid of the Minometer either by turning down an aluminum cylinder to a very thin wall or by using aluminum foil walls. In both cases beta rays which could reach the basal layer of the epidermis at a depth of 7 mg/cm^2 were admitted to the sensitive volumes of the dosimeters. Apparently Parker did not intend to use his chambers for measuring X and gamma rays since no attempt was made to match the average atomic number to air so that the chambers would read the latter radiations in

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[6] Rinaker, R. E., Nucleonics 2, No. 1, 78 (1948).

[7] Parker, H. M., AECD-2859 (Sept. 10, 1943) p. 8.

roentgens. Unless this precaution is taken, the dosimeter may overestimate the X-ray dosage by factors from 1.5 to 4 or more[8]. This effect is referred to as dependence of the response on radiation energy, or more simply as "energy dependence".

In 1950 Hubbell[9] began a project of developing a dosimeter for personnel monitoring of beta radiation. The method used was to have a relatively thick outer wall for mechanical strength and for electronic equilibrium for at least some of the incident gamma rays. The wall was perforated to admit beta rays over part of its surface. The inner sensitive volume was defined by a layer of conducting paper having the necessary 7 mg/cm^2 superficial density. Victoreen chambers with holes drilled in the sides were tried, but such chambers had too small a beta sensitivity, and were too insensitive to rays incident at more than a small angle to the normal to the chamber axis. Screen walls of stainless steel and aluminum were also tried. The former was unsatisfactory because of a large energy dependence for X rays, and the latter was too flimsy for practical use. No satisfactory method for calibration with beta rays was available at that time. Flat sheets of natural uranium gave about the expected response using extrapolation chamber data for the beta dose rate from uranium[10], but exposures inside hollow cylinders

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[8] Day, F. H., National Bureau of Standards Circular 507 (July 25, 1951).

[9] Hubbell, H. H. Jr., Health Physics Division Progress Reports, ORNL-968 (1/20/51), p. 22; ORNL-1353 (7/20/52), p. 11.

[10] Bortner, T. E., ORNL-740 (Sept. 26, 1950).

of uranium seemed to indicate a large and unexplained error in the observed dose. The effect of backscattering of electrons under these conditions seemed impossible to calculate.

The calibration problem was solved by the appearance of the Spencer-Fano theory of electron slowing down[11] coupled with the Rossi and Ellis[12] method of using water solutions of radioactive isotopes. Using these results, Hubbell, Johnson, and Birkhoff in 1956[13-18] designed a pocket chamber with a perforated thin aluminum shell surrounding an inner ionization chamber whose wall was made of 7 mg/cm^2 conducting paper, as shown in Figure 1. This chamber was charged and read on a Minometer, and its sensitivity was the same for gamma rays as the usual pocket chamber. The device showed no more energy dependence for X rays than the usual chamber. It was calibrated with water solu-

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[11] Spencer, L. V., and Fano, U., Phys. Rev. 93, 1172 (1954).

[12] Rossi, H. H., and Ellis, R. H., Am. Journ. Roentgenol. 67, 980 (1952).

[13] Health Physics Division Progress Report ORNL-2151 (7/31/59) p. 55.

[14] Birkhoff, R. D., Hubbell, H. H. Jr., and Johnson, R. M., Bull. Am. Phys. Soc. II, 1, 267-A (1956).

[15] Hubbell, H. H. Jr., Johnson, R. M., and Birkhoff, R. D., Radiology, 69, 268 (1957).

[16] Hubbell, H. H. Jr., Johnson, R. M., and Birkhoff, R. D., ORNL-2158, (April 1957).

[17] Birkhoff, R. D., Hubbell, H. H. Jr., and Johnson, R. M., U. S. Patent 2,875,343 (Feb. 24, 1959).

[18] Hubbell, H. H. Jr., Johnson, R. M., and Birkhoff, R. D., Nucleonics 15, No. 2, 85 (1957).

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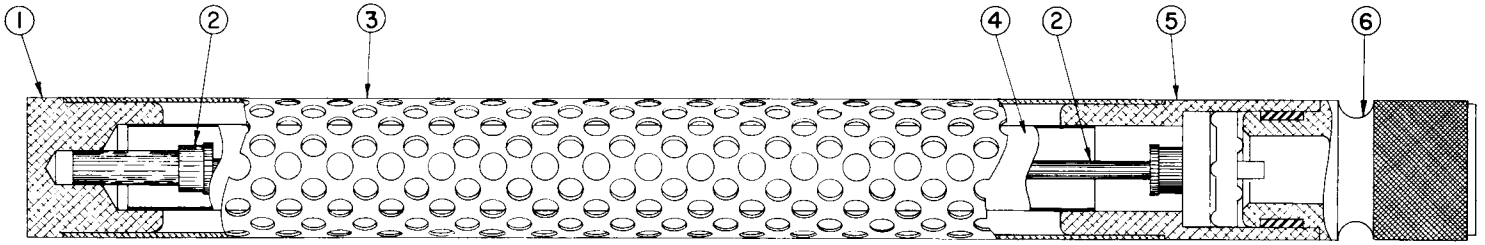

1. ALUMINUM END PIECE.
2. POLYSTYRENE OR POLYETHYLENE INSULATOR AND CENTER ELECTRODE.
3. PERFORATED ALUMINUM OR MAGNESIUM OUTER SHELL.
4. 7 mg/cm^2 CONDUCTING PAPER LINER.
5. ALUMINUM OUTER END PIECE.
6. ALUMINUM CAP.

Fig. 1. Aluminum or Magnesium Wall Pocket Chamber.

tions of beta-ray emitting isotopes over the range from S^{35} to Y^{90}, which covered practically the whole range of beta emitters which can damage tissue by external exposure.

Preliminary field tests seemed to indicate that this chamber would prove useful and satisfactory, though it was more fragile than would be desirable. While this type of chamber satisfied most of the design requirements listed above, the chambers were never made commercially, probably because the estimated cost seemed more than the market would absorb and because they were somewhat fragile and difficult to repair. Also the chamber was not of suitable geometry for use on the hands where the highest beta-ray exposures occur.

Pocket chambers modeled after these have been produced at Knolls Atomic Power Laboratory[19]. This laboratory also reports a double chamber, one half with a thick wall, sensitive only to hard X rays and gamma rays and the other half like that just described with a thin wall and a perforated protecting cylinder so that it is sensitive to beta and soft X rays as well as gamma rays. A similar double chamber was developed by J. C. Hart and others[20] at the Metallurgical Laboratory of the Manhattan Project about 1943. This early design was abandoned because the sensitivity of each half chamber was too low and because

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[19] Feinberg, R. J., KAPL-1964 (April 1959) p. 4.

[20] Hart, J. C., private communication.

leakage and discharges not caused by radiation gave too high a proportion of false exposure readings. The KAPL double chambers apparently were not been adjusted in dimensions to give the correct reading in mr on the usual Victoreen Minometer, nor is any statement made as to their energy dependence for X rays or for beta rays.

Davis, Gupton and Hart[21] designed a half-cylindrical chamber with a thin window on the cylindrical surface, as shown in Figure 2a. The center electrode was part of an electrode from a Victoreen pocket chamber, and the end fitted in the Minometer. This device was sensitive to low-energy beta and X rays and was cheap and reasonably satisfactory in the field, but it required special calibration to register dose correctly since its volume and capacitance were not correct to match the Minometer with which it was used. Also the electric field was probably too weak in much of the sensitive volume to collect all ions formed. This chamber was calibrated with radium, with unspecified radiation of low penetration, and with uranium beta rays, so its energy dependence for either X rays or beta rays was not known. Complete discharge of the chamber gave a reading of only 155 on a 200 mr Minometer scale.

In 1957, Davis, Gupton and Hart carried out some unpublished preliminary development of a beta-sensitive ionization chamber suitable

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[21] Davis, D. M., Gupton, E. D., and Hart, J. C., ORNL Health Physics Division, unpublished memo AI-127-53 (June 20, 1953).

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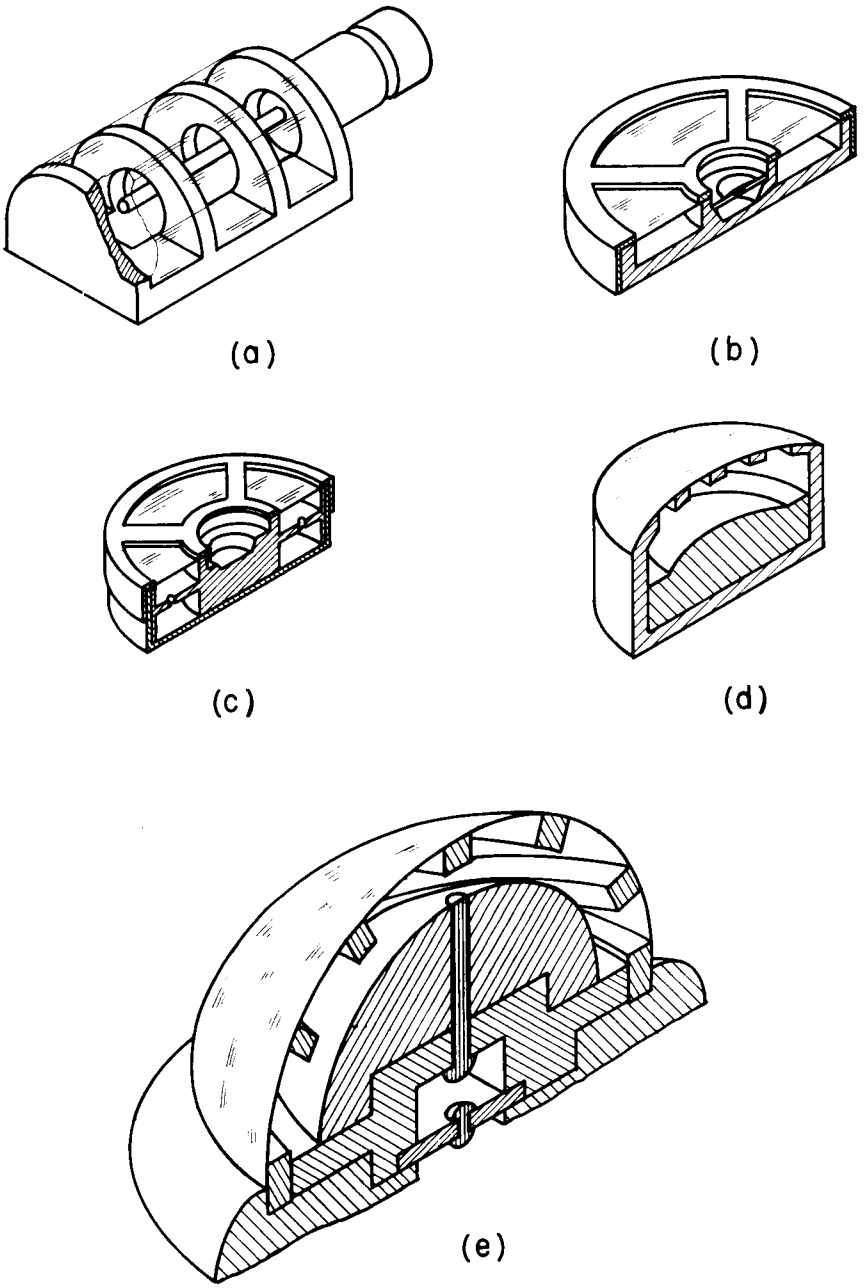

Fig. 2. Various Suggested Beta Dosimeter Chamber Designs.
(a) Half-Cylinder Chamber (b) Pillbox Chamber
(c) Sandwich Chamber (d) Watch-Crystal Chamber
(e) Hemispherical Chamber

for wrist wear. The essential structure was that of a parallel-plate ionization chamber in the shape of a small pillbox as shown in Figure 2b. The bottom and sides were of plastic, and the inside surface of the bottom was coated with colloidal graphite to form the insulated electrode. The top was made of conducting paper 7 mg/cm^2 thick and acted as the grounded electrode. In test use it was found that perspiration from the wearer's wrist made the outside of the bottom another grounded electrode, thus increasing the total capacitance considerably and giving large, spurious and erratic discharge readings. Also, calculation indicates that the sensitivity would decrease rapidly as the angle of incidence of the beta rays on the top departed from the normal. The flat-surfaced top window was assumed to correspond to the essentially flat surface of the human skin. However, beta radiation incident on the chamber at 90° to the axis would produce no response, yet would damage tissue on, say, the side of the wrist if the chamber was worn on the back of the wrist. In order not to underestimate the "whole wrist" dose it seems desirable to have a uniform sensitivity for radiation incident over a hemisphere. Detailed calibrations of this chamber were not made.

To avoid the "perspiration effect", Davis, Gupton, and Hart altered the design to that shown in Figure 2c. The outside was aluminum except for a paper cover like that on the previous model. A plastic inner liner supported a wafer in the middle which was coated with graphite on

both sides to form the insulated electrode. The volume below the wafer would then be sensitive only to X and gamma rays, while that above would respond to beta rays also. In both designs, electrical contact was made to the insulated electrode for charging or reading by means of a flexible diaphragm in the top, with a metal button in the center. No beta-ray calibrations of either model were made. Again the lack of sensitivity for side irradiations seemed to be a serious drawback.

Work was begun on the present development with a careful consideration of these designs and others suggested in hopes of incorporating the desirable features of all in a final model satisfying all the requirements listed.

A simple modification of the pillbox design might reduce the directional variation of sensitivity. The electrodes could be made convex, like a watch crystal, and the upper one might consist of a screen supporting a 7 mg/cm^2 film on the inside. The design is sketched in Figure 2d. If the screen had a 50% open area, the third design requirement for 1:2 beta-to-gamma sensitivity would be satisfied. Two difficulties caused the rejection of this design: on the practical side, the only available meshes were expensive and of high Z materials such as stainless steel and copper, which would give the chamber a large energy dependence. Further, it was so difficult to calculate the capacitance and sensitive volume of the chamber that the selection of suitable dimensions was nearly impossible.

J. C. Hart of ORNL suggested that the use of concentric hemispheres as electrodes would give a better design since such a chamber would seem to have the same sensitivity to radiation incident from any direction in the hemisphere. The pieces could probably be easily molded of plastic. The essential design is shown in Figure 2e. Calculations to be given in the next section indicated that a chamber of reasonable dimensions could be designed with appropriate collecting field, volume and capacitance to work with the Victoreen Minometer. Two important problems, however, remained. The "perspiration effect" found with the first pillbox chamber indicated an essential condition which must be fulfilled to satisfy the electrostatic requirements of the chamber: the inner, insulated electrode must be completely surrounded by a grounded electrode. This meant that the base had to contain a metal plate connected to the outer hemispherical electrode and that an important part of the total capacitance of the device was then between the inner hemisphere and the base. Actually, this added capacitance furnished an extra adjustable parameter which proved quite useful in the design of the final model, as will be discussed below.

The second problem was again that of the variation in response of the chamber to beta rays incident from various angles. Three models were considered, each with a different angular response to soft radiation:

1 The outer hemisphere might have the 7 mg/cm^2 thickness, possibly supported by a ribbed structure for mechanical strength and transmitting 50% of the soft beta rays. The inner hemispherical electrode would be very thin, less than 1 mg/cm^2, so that any beta ray entering the chamber from the side would produce ions in both sides of the sensitive volume. The arrangement is indicated in Figure 3a. The response would obviously be uniform for radiation incident from any angle in a hemisphere, but there seemed to be no feasible method of supporting the inner electrode. Air pressure slightly above atmospheric could be used within the inner hemisphere, but a pressure leakage and resulting collapse of this electrode might give a false reading without indicating that the instrument was defective. Construction and service would also be difficult and probably expensive.

2. The inner electrode might be solid, so that it was opaque to beta rays and the outer one either the same as in (1) or perhaps supported by insulating posts from the inner hemisphere. However, the response would vary considerably with angle for this arrangement, since it was calculated that beta rays incident from the side would be able to enter at most only 67% of the sensitive volume. This result is suggested in Figure 3b.

3. The structure of suggestion (2) might be used if the central part of the outer hemisphere were covered by a large enough cap to shadow the same fraction of the sensitive volume that the inner

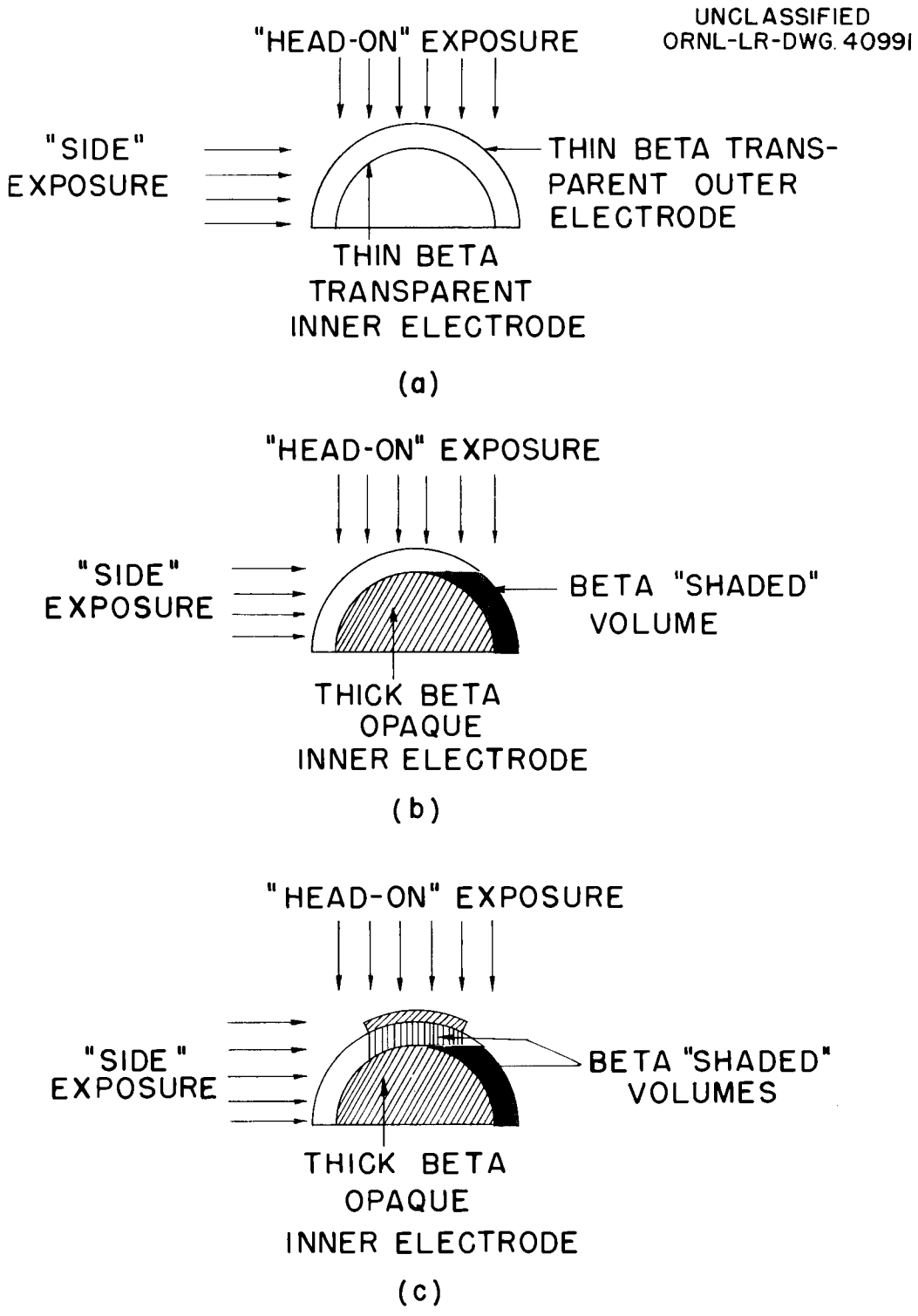

Fig. 3. Angular Dependence Considerations for Hemispherical Chamber.

electrode did for side exposure as indicated in Figure 3c. This turned out to be geometrically impossible, since such a cap would also shield too much of the volume for side exposures, at least for electrode radii suitable for operation with the Minometer.

The hemispherical designs were finally abandoned because there seemed to be no satisfactory solution of the problem of angular dependence of sensitivity, and because the chamber would project considerably further from the wearer's wrist than the pillbox design finally chosen. The minimum possible projection would certainly seem to increase the acceptability of the device to the wearer.

The principal problem in the pillbox model was the falling off in response for beta rays incident from the sides. The solution was to punch holes in the sides so that 50% of the beta rays striking the sides could get in. The perspiration effect was removed by making the base a conducting electrode, and by using this additional capacitance as an added parameter to permit making the chamber as small as possible. The detailed design of the chamber will be considered in a later section after a discussion of the basic theory of such ionization chamber-electrometer systems.

IV. THEORY OF THE DESIGN OF IONIZATION CHAMBER AND ELECTROMETER SYSTEMS

A. Dosimetry

1. Gamma and X Rays

The satisfactory design of any dosimeter requires a clear understanding of exactly what the dosimeter system is to measure. In Health Physics one usually wishes to determine the percentage of the maximum permissible dose which an individual has received. For X rays and gammas up to two or perhaps three Mev (million electron volts) the exposure dose is given in roentgens, where the roentgen is defined as "that quantity of X or gamma radiation such that the associated corpuscular emission per 0.001293 g of dry air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign."[22] The standard free air chamber measures this dose very accurately for laboratory purposes, but what is measured is the exposure dose at a point when the human body is absent[23]. Backscattering from the body may in extreme cases raise the surface dose by 50%, though the effect is usually less than 5%.

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[22] NBS Handbook 59, op. cit., p. 6.

[23] National Bureau of Standards Handbook 62, "Report of the International Commission on Radiological Units and Measurements", 1956.

The absorbed dose in a medium may be calculated from measurements with a cavity ionization chamber by the use of the Bragg-Gray principle[24-32]. The principle states that the absorbed dose in a medium may be measured by the ionization produced in a small gas-filled cavity in the medium by the use of the relation

$$E_m = J_m W \rho_m \qquad (1)$$

where E_m = energy absorbed in electron volts per gram of medium,

J_m = number of ion pairs per gram of gas,

ρ_m = ratio of the mass stopping power for electrons (ergs lost per gram per cm^2) of the medium to that of the gas,

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[24] Hine, G. J., and Brownell, G. L., RADIATION DOSIMETRY (Academic Press, New York, 1956) article by F. W. Spiers, pp. 23-39.

[25] Ibid, article by J. W. Boag, p. 154.

[26] Gray, L. H., Proc. Roy. Soc. A-122, 647 (1929); A-156, 578 (1936); Proc. Camb. Phil. Soc. 40, 72 (1944); Brit. J. Rad. 10, 600 (1937); 10, 721 (1937).

[27] Spencer, L. V., and Attix, F. H., Rad. Res. 3, 239 (1955).

[28] Attix, F. H., and De LaVergne, L., Radiology 63, 853 (1954).

[29] Fano, U., Rad. Res. 1, 237 (1954).

[30] Bragg, W., STUDIES IN RADIOACTIVITY (MacMillan and Co., London, 1912) p. 94 ff.

[31] Wang, T. J., Nucleonics 7, No. 2, p. 55 (1950).

[32] NBS Handbook 62, op. cit., p. 10.

W = average energy in electron volts expended by the radiation per ion pair formed in the gas. This is usually given as W = 34 e.v./i.p. for air for radiations in the X-ray region.

Three important restrictions must be placed on the use of this principle to determine the absorbed dose. First, (as nearly as possible) the stopping power for electrons must be the same in the dosimeter walls as in the dosimeter gas for all energies of radiation. Since ρ_m, the stopping power ratio, does in fact depend on the radiation energy to some extent, the walls of the cavity must be made of materials having as nearly as possible the same atomic number as the gas. Plastics containing no high Z elements represent a good match to many low Z gases. Even aluminum may produce a large energy dependence. Calibration at various energies is always necessary.

Second, the cavity must contain little enough material that essentially all secondary electrons leaving the walls are able to traverse the cavity.

The third restriction is that as many secondary electrons must be produced in each element of the walls as stop there, a condition which is referred to as "electronic equilibrium". This equilibrium is assured when the walls of the cavity have a thickness equal to the range of the most energetic secondary electrons produced by the radiation. On the other hand, the walls must not be thick enough to produce a significant attenuation of the radiation. For radiation of a wide range of energies,

these two requirements are mutually exclusive, since walls thick enough to produce equilibrium for 3 Mev gamma rays will significantly attenuate 20 Kev X rays. A compromise thickness is therefore used with some loss of accuracy. For example, a 3 Mev gamma ray can produce an electron of nearly 3 Mev energy, whose range in air is nearly 12 meters[33], or about 1.2 cm in plastic. This thickness of plastic will attenuate a 20 Kev monochromatic X-ray beam to about 35% of its original intensity. This is an extreme case since it is calculated for the limiting energies to be covered, but illustrates the dilemma and shows the maximum error which may appear. In practice approximate equilibrium can be attained for most radiations of interest with about 2 to 3 mm of plastic[34], with an intensity reduction to 88% of that incident at 30 Kev. This represents a practical thickness for dosimeter construction. The use of thick walls also reduces the error due to backscattering, since the backscattered radiation is always softer and thus attenuated more than the primary radiation.

If the dose absorbed in tissue is to be determined, the X-ray absorption coefficient of the walls of the dosimeter must be practically the same as that of tissue at all energies. This is a very stringent re-

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[33] Lapp, R. E., and Andrews, H. L., NUCLEAR RADIATION PHYSICS (Prentice-Hall, Inc., New York, 1948) p. 180.

[34] Ehrlich, M., and Fitch, S.H., Nucleonics 9, No. 3, 5 (1951).

quirement because the absorption coefficients in the X-ray region vary rapidly and over a wide range with changes in either radiation energy or atomic number.

2. Beta Rays

For the case of beta rays, it is less clear what should be measured. Handbook 59 specifies (p. 38) that the maximum permissible dose rate to the basal layer of the epidermis (defined as lying at a depth corresponding to 7 mg/cm^2) shall be 600 millirads per week. It is obviously not feasible to measure the dose directly in tissue. Since air and soft tissue have nearly the same effective atomic number, it is usually satisfactory to measure the absorbed dose in air, which can be done if the dosimeter walls have no more than 7 mg/cm^2 superficial density and are air equivalent. Any greater thickness will seriously attenuate soft beta rays. The dosimeter chamber must be very small to avoid attenuation of the beta rays in crossing the cavity. Since Handbook 59 allows only half the exposure to penetrating radiation which is permitted for non-penetrating, a compromise design with 50% of the wall area having a thickness of about 2 mm, and 50% having only 7 mg/cm^2 gives a dosimeter which reads in percentage of maximum permissible exposure to both types of radiation by being only half as sensitive to beta rays as to X rays.

3. Calibration with Beta Rays

Ideally one would like to calibrate a beta dosimeter with known beams of monoenergetic electrons incident on the dosimeter. Such beams can be produced in a vacuum, but if they emerge into air in order to expose a dosimeter, some electrons are lost, the energy is degraded, and the beam is broadened in energy by straggling in a manner difficult to compute. Alternatively one might try to expose the dosimeter to known nuclear beta spectra of varying end point energies. However, a source strong enough to produce reasonable dose rates would be thick, and the electrons would be degraded and straggled in energy as they traveled through the source material and through the air between source and dosimeter. Thus the spectrum actually striking the dosimeter would be known only approximately.

Therefore in order to irradiate the dosimeters with known spectra, very thick sources of beta rays were used, following the technique previously described[35]. The spectra of electrons emerging from thick water solutions of several isotopes were calculated in that work from the known nuclear beta spectra and the slowing down theory of Spencer and Fano[36]. A typical set of these spectra are shown in Figure 4 for

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[35] Hubbell, Johnson, and Birkhoff, op. cit.

[36] Spencer and Fano, op. cit.

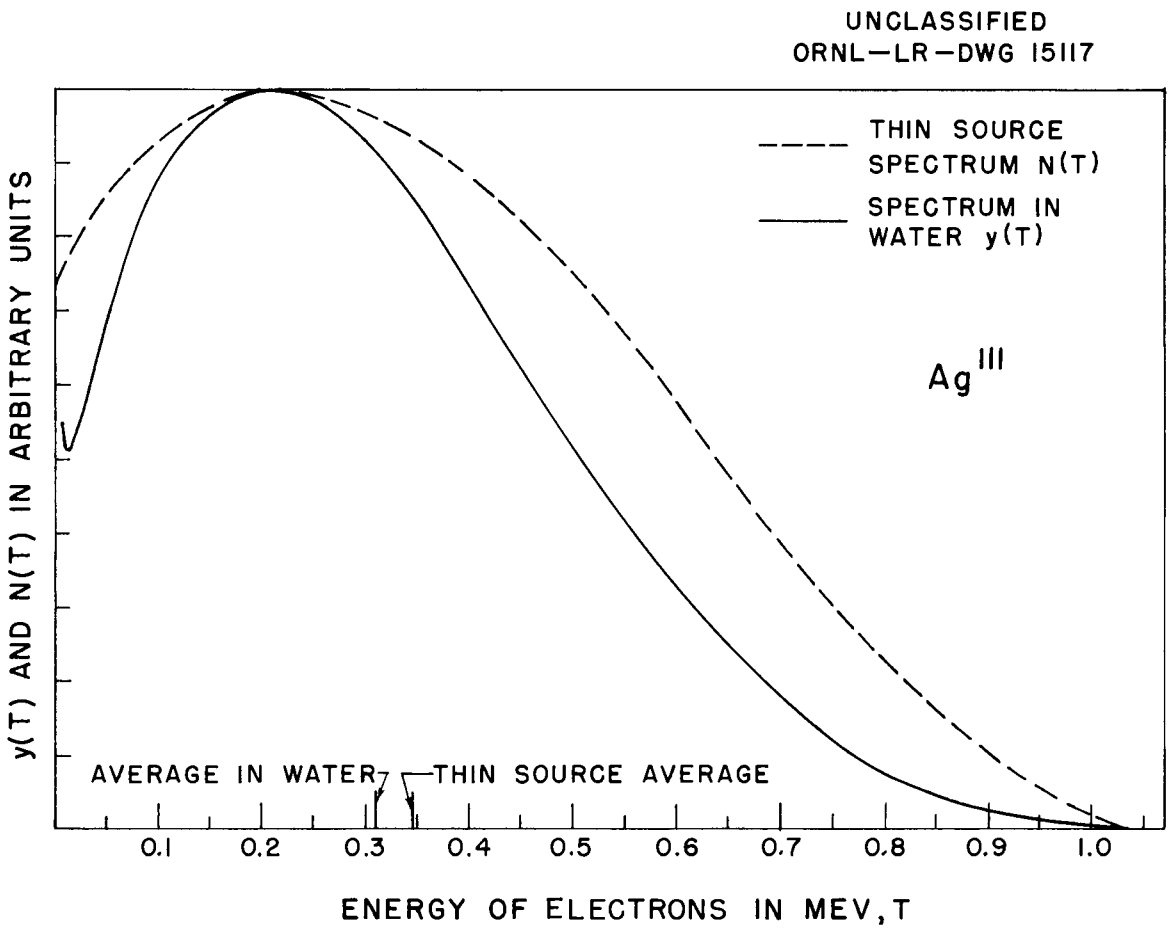

Fig. 4. Ag^{111} Spectra.

Ag^{111}. Two different average energies are of importance: first, the average energy of the nuclear beta ray spectrum, which is used with the Bragg-Gray principle in order to calculate the dose rate in the air at the surface of water; and second, the average energy of the electron flux incident on the dosimeter (assuming no energy loss in the air cavity surrounding the dosimeter). The latter average is used as an index of the energy of the beta rays striking the dosimeter and as an abscissa in the energy dependence curves of Figures 17 and 18.

The calculation of the dose rate which the dosimeter should record when exposed to such a solution proceeds as follows:

1. From the average energy of the nuclear beta-ray spectrum and the assay of the solution (in disintegrations per minute per milliliter for example), the number of ergs per gram of water per second (or rads in water per second) emitted by the source are calculated. Since the source is infinitely thick to a beta ray, the same number of ergs per gram per second is absorbed.
2. From the Bragg-Gray principle, the number of ergs per gram of air per second or rads in air per second in an air cavity in the solution is computed.
3. From this one may calculate the number of e.s.u. of charge per cubic centimeter of air per second, using the accepted value of W, the density of the air, and the electronic charge e. This is, of course, the electric current per unit volume from the dosimeter and may be expressed in air cavity roentgen equivalents per second.

4. The measured current per unit volume from the dosimeter placed in an air cavity in the solution may then be compared with that computed in step 3. The ratio of the measured current to that calculated is called the response of the dosimeter to beta rays having the average energy of the degraded electron flux in water.

For comparison with the maximum permissible exposure values it is desirable to know the response of the dosimeter as compared to the absorbed dose at a depth of 7 mg/cm^2 in tissue. Therefore as an alternative, the current from a similar cavity ion chamber having only this wall thickness may be used as a reference. Response curves based on both references are given in Figures 17 and 18.

It is to be noted that the dosimeter is not really calibrated against the same standards for beta rays as it is for X and gamma rays. In the beta-ray case the dosimeter response is taken as a per cent of the calculated absorbed dose in air, whereas for X and gamma rays, the calibration is in terms of exposure dose. For purposes of health physics monitoring, the difference can be neglected.

B. Electrical Characteristics

1. Derivation of the Relations Between Dose and the Parameters of the Chamber-Electrometer System

Since the string electrometer (like the Victoreen Minometer) is convenient and widely used, the dosimeter chamber was designed to be operated with such a device. The Minometer is basically an electro-

static voltmeter with a very low capacitance and a scale marked in milliroentgens. Although the scale is non-uniform, the calibration is linear in voltage as shown in Figure 5. The characteristics of the Minometer to be considered in designing a chamber to be used with it are the response in volts per division (or volts per mr on the scale), $\Delta v_m/D$, and the capacitance, c.

To charge an ion chamber (of capacitance C and volume V) it is first connected to the electrometer and the two are charged to a predetermined voltage v_m, marked "0 mr" on the scale. Then the chamber is removed, capped, and exposed to radiation. The exposure to D roentgens lowers the chamber charge in e.s.u. by an amount

$$\Delta Q = V \cdot D \qquad (2)$$

from the definition of the roentgen. The chamber voltage is lowered by

$$\Delta v_c = \frac{\Delta Q}{C} \quad . \qquad (3)$$

The chamber is then uncapped and reconnected to the electrometer and the resultant voltage of the two becomes v_D. The situation may be summarized in the following table:

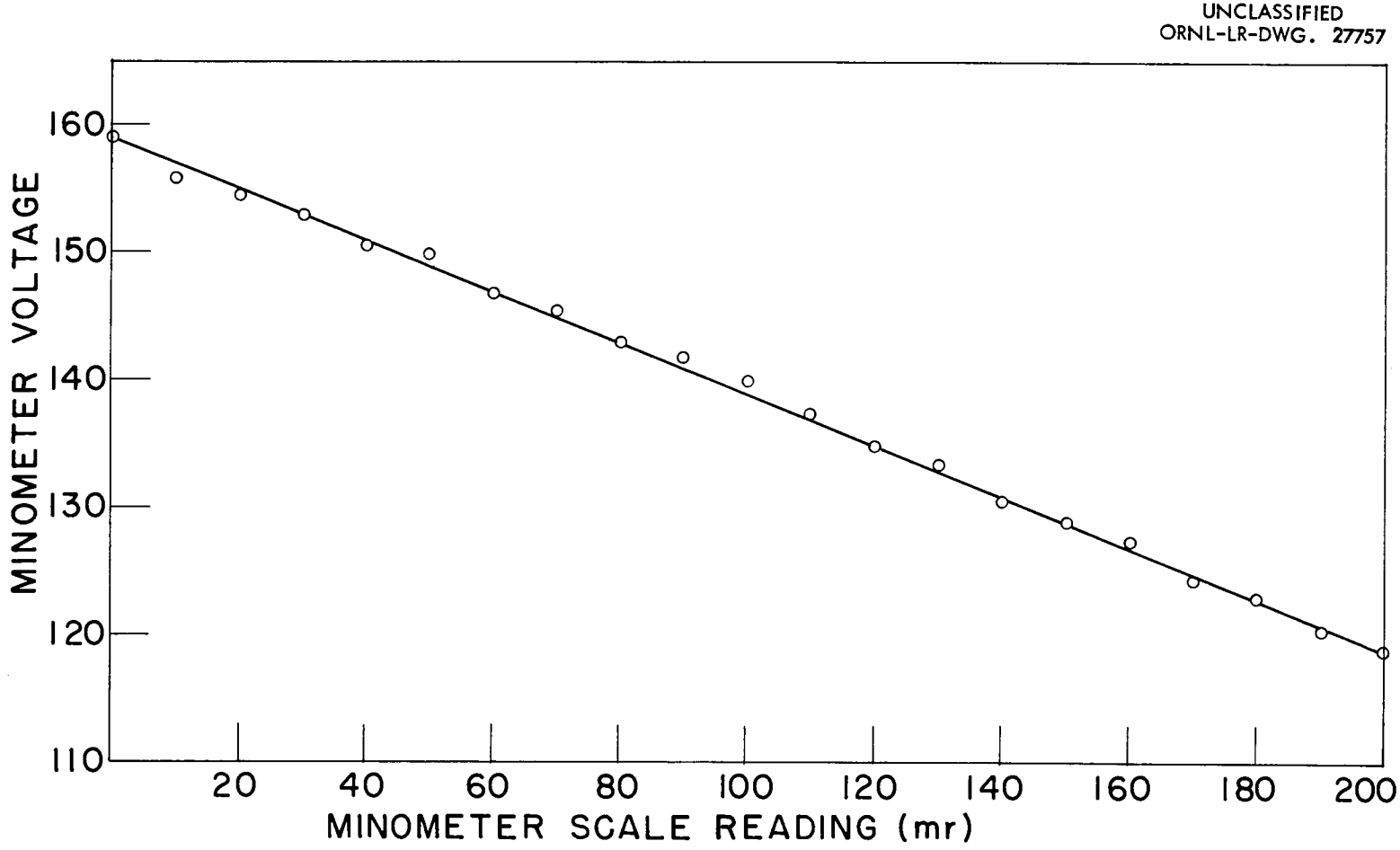

Fig. 5. Minometer Calibration.

	1. Before Exposure		2. After Exposure		3. After Reconnection	
	Chamber	Minometer	Chamber	Minometer	Chamber	Minometer
Voltage	v_m	v_m	v_c	v_m	v_D	v_D
Charge	Cv_m	cv_m	$Cv_c = Cv_m - \Delta Q$	cv_m	Cv_D	cv_D

From the conservation of charge from step (2) to step (3):

$$Cv_c + cv_m = Cv_m - \Delta Q + cv_m = Cv_D + cv_D \qquad (4)$$

or

$$\Delta Q = (C + c)(v_m - v_D) = (C + c)\,\Delta v_m \quad . \qquad (5)$$

Equation (2) may be combined with equation (5) to eliminate ΔQ and the voltage change of the Minometer is:

$$\Delta v_m = \frac{V \cdot D}{C + c} \quad . \qquad (6)$$

The sensitivity, S, of the system is then

$$S = \frac{\Delta v_m}{D} = \frac{V}{C + c} \quad . \qquad (7)$$

Two important conclusions can be drawn from this result: First, that the final reading of the electrometer after a radiation exposure to the chamber is independent of the charging voltage, as pointed out previously[37]. Second, that the same sensitivity and calibration may be obtained for different chambers either by making the new chambers have the same volume, V, and capacitance, C, as that for which the electrometer was designed, or by varying V and C but keeping the ratio $V/(C+c)$ constant.

It is to be noted also that the equations given are valid only in a consistent system of units. Since the dose, r, is defined in electrostatic units, the voltages and capacitances must also be in e.s.u. If the sensitivity S' is given in volts/mr, capacitances C' and c' are in $\mu\mu$f and V is in cm^3, then equation (7) becomes

$$S' \left[\frac{\text{volts}}{\text{milliroentgen}} \right] = \frac{V}{3(C'+c')} \quad . \tag{8}$$

A further conclusion can be drawn from an alternative form of equation (4):

$$\Delta v_m = \left(\frac{C}{C + c} \right) \Delta v_c \tag{9}$$

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[37] Hubbell, Johnson, and Birkhoff, op. cit. ORNL-2158, p. 34.

that is, the voltage change of the electrometer is only $C/(C+c)$ of that of the chamber.

2. Electric Field and Saturation

When the ionization chamber is at its lowest voltage, the electric field must still be large enough to bring about collection of all the ions formed at the highest dose rate to be measured. The desirability of having very low capacitance in the electrometer is obvious from equation (9) above, since during exposure the chamber voltage drops by $(C+c)/C$ of the electrometer drop at reconnection.

In a theoretical and experimental study, Boag[38] has given the ion collection efficiency for various electric fields and geometries. Experiments by Gupton[39] on Victoreen pocket chambers have indicated a somewhat lower efficiency than expected from Boag's work.

C. Basic Data for the Victoreen Pocket Chamber - Minometer

In this work it was planned to match (in range and sensitivity) the Victoreen Minometer -- pocket chamber combination. The electrical and dosimetric characteristics of these two devices are surprisingly difficult to measure or calculate with accuracy, since the geometry is complex and the capacitances are of the same order as stray lead

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[38] Boag, J. W., in Hine and Brownell's RADIATION DOSIMETRY (Academic Press, Inc., New York, 1956) p. 165 ff.

[39] Gupton, E. D., "Recombination Losses in Pocket Chambers", Thesis, Vanderbilt University (March 1955).

capacitances of any measuring system. For example it is very difficult to know how much of the volume of the chamber really delivers its ions to the electrodes and what effect the cap has on both volume and capacitance. In addition, the size and shape of the cap region are different when the cap is on during exposure from when it is off during charging and reading. Table I summarizes the average values found for a number of chambers and Minometers, but the accuracy is probably not better than $\pm$ 10%.

Figure 5 shows a typical calibration curve of a Minometer. For this instrument c' = 5.6 μμf and S' = 0.2 volts/mr, both slightly above the average.

The voltage drop in the chamber for an exposure of 200 mr was calculated to be about 87 volts, using equation (9) and the values of S', C'+c' from Table I. The minimum electric field is at the outer electrode of radius R after discharge and is given by

$$E_R = \frac{V_c}{R \ln(R/r)} \quad . \qquad (10)$$

Substituting the data of Table I, the minimum field after 200 mr discharge was found to be 96 volts/cm. Gupton[40] showed that this electric field was sufficient to collect 86% of the ions at discharge rates of

[40] Gupton, Ibid.

TABLE I. CHARACTERISTICS OF VICTOREEN DOSIMETER AND READER

Characteristics of Victoreen Minometer Model 287	
Charge Voltage (at "0 mr") v'_m	150-160 volts
Capacitance c'	5.4 ± 0.2 μμf
Sensitivity $S' = \Delta v'_m/D$	0.18_5 volts/mr
Full Scale Reading	200 mr
Full Scale Voltage (at "200 mr"), $v'_m - \Delta v'_m$	113-123 volts
Characteristics of Victoreen Pocket Chamber Model 362	
Air Volume -- minimum	4.5 cm^3
maximum, including cap	5.7 cm^3
probable effective	5.1 cm^3
Capacitance C', calculated maximum	4.2_0 μμf
measured average	4.0_2 μμf
Wall Thickness -- Tenite II	0.18 cm
Cardboard and Graphite	0.05 cm
Inside Radius	0.41 cm
Center Electrode Radius	0.08_3 cm
Minimum Chamber Voltage After 200 mr Discharge, about	63 volts
Minimum Electric Field at Outer Wall, E'_R, after 200 mr Discharge, about	96 volts/cm

200 r/hr. This would give full scale discharge of a 200 mr chamber in 3.6 seconds. The average collection efficiency would be much higher since the voltage would be falling throughout discharge.

Boag's work indicates that for the geometry and voltages of the Victoreen Minometer and chamber a much higher collection efficiency would be expected than that reported by Gupton. Therefore, a minimum electric field of the same order as that calculated for the Victoreen chamber would seem to be a reasonable design value.

D. Pressure and Temperature Corrections

Since personnel dosimeters with thin walls must operate at ambient air pressure and ambient or higher temperatures, corrections are needed to get true dose measurements from the chambers. The ionization produced by radiation is proportional to the mass of gas in the ion chamber, which varies according to the general gas law. Since the roentgen is defined for air at 0° C and 760 mm of mercury pressure (NTP), the true dose D_{NTP} is related to the observed dose D_o at pressure p mm and temperature T degrees Centigrade by the equation:

$$D_{NTP} = D_o\,(760/p)(T + 273)/273\ . \qquad (11)$$

To compensate for this correction, the Victoreen Condenser R-Meter scale is adjusted to read D_{NTP} correctly when the chambers are at 22°C,

760 mm. The manufacturer's literature does not state whether the same is true for the pocket chamber-Minometer combination, but if we assume this to be true, the correction equation becomes for observed dose D_o':

$$D_{NTP} = D_o' (760/p)(T+273)/295 \qquad (12)$$

In personnel monitoring it is not feasible to make this correction, but in calibration it is usually worthwhile. In use the errors made in neglecting the correction are less than the unavoidable errors due to possible shielding of the chamber by the wearer's body, backscattered radiation from the body and from other objects, etc.

E. Procedure for Choosing the Optimum Chamber Dimensions, with Application to the Hemispherical Chamber

As an illustration of the problems of designing an ion chamber, the case of hemispherical electrodes will be considered. It will be assumed first that all the capacitance is between the hemispheres and that the volume and capacitance are to be the same as those of the Victoreen pocket chamber. The volume between the hemispheres is

$$V = \frac{2\pi}{3} (R^3-r^3) \qquad (13)$$

where R and r are the radii of the outer and inner hemispheres respectively. The capacitance is given by

$$C = 2\pi\epsilon \frac{Rr}{R-r} \qquad (14)$$

where ϵ is the dielectric constant of a vacuum and in convenient units is:

$$\epsilon = 8.85 \times 10^{-2} \ \mu\mu f/cm.$$

Since C and V are fixed there are only two independent variables, R and r, so a unique solution exists for the two equations. However, the solution involves a sixth-order equation, so a graphical solution is given in Figure 6, where curves are drawn of the outer radius as a function of the inner radius for each of the two equations. The values R = 1.72 cm, r = 1.39 cm are seen to give the solution for C = 4.0 $\mu\mu f$ and V = 5.1 cm^3.

A dosimeter with these dimensions is still rather bulky for wrist wear, so it is of interest to see whether a smaller one can be designed. The two restrictions that the volume and capacitance of the chamber must each equal those of the Victoreen chamber may be reduced to a single condition that the overall sensitivity of the chamber-electrometer

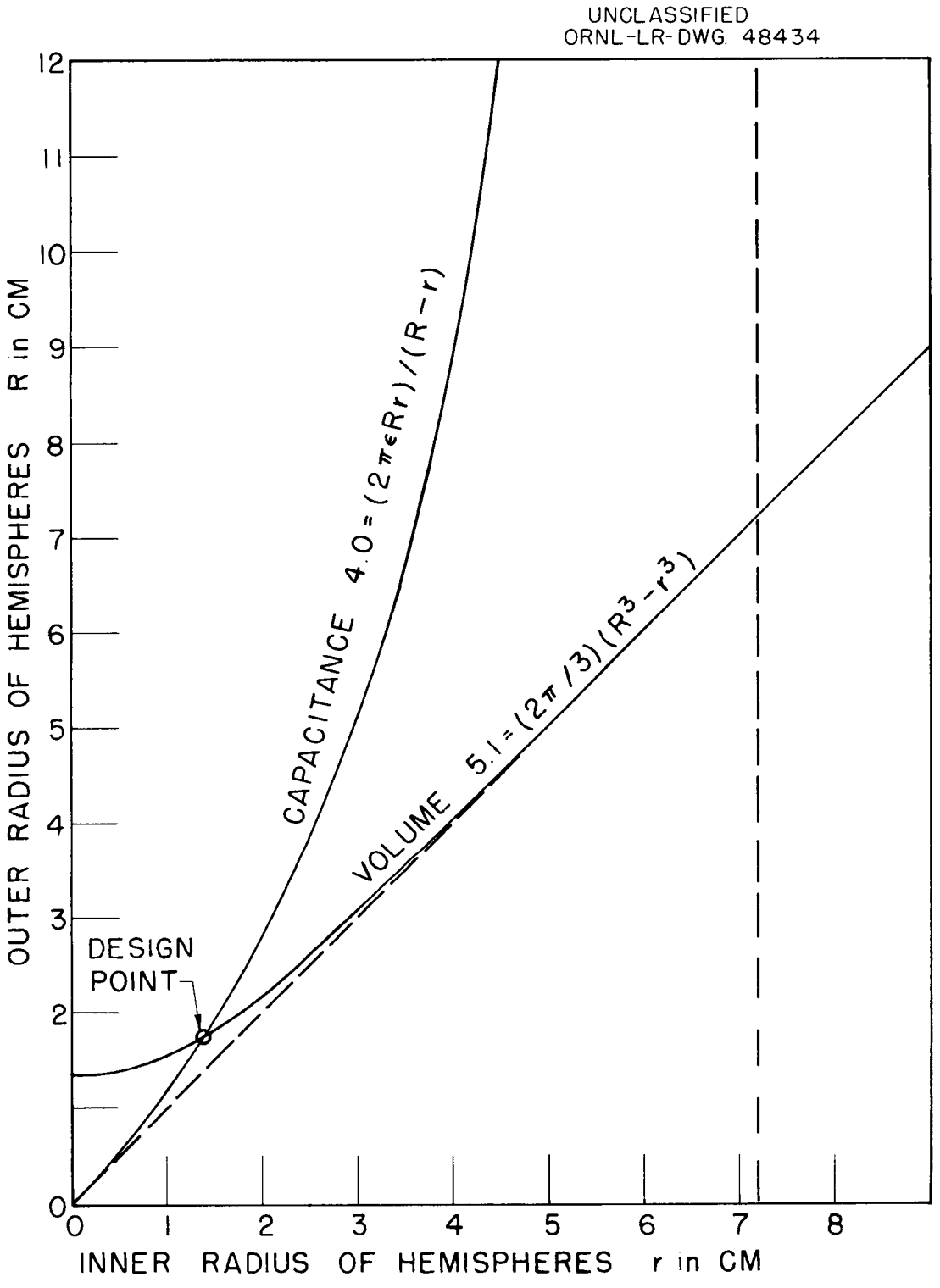

Fig. 6. Hemispherical Dosimeter Design.

system be the same. This condition is expressed by the sensitivity equation

$$S = \frac{V}{C + c} \tag{15}$$

where S is now the fixed quantity.

Equations (13), (14), and (15) may now be combined into a single equation $R = R(r,S,c)$ in two unknowns, the radii R and r, and the fixed quantities S and c. In order to minimize the size of the chamber, the derivative dR/dr may be set equal to zero and the resulting equation solved for r. This procedure should give the smallest chamber, and the method was used for the pillbox wrist dosimeter to be discussed below.

Another consideration was whether the minimum electric field after 200 mr discharge would still be adequate for saturation. For spheres the electric field at the outer hemisphere after 200 mr discharge is

$$E_R = \frac{r\, v_c}{R(R-r)} \quad . \tag{16}$$

For the case of fixed volume and capacitance, the radii given above were substituted, and the minimum field was found to be about 160 volts/cm. This value is larger than that in the Victoreen chamber, and would be satisfactory. A similar procedure for finding the minimum field after discharge could be followed for the case of fixed sensitivity.

Instead of minimizing the dimensions in the manner discussed, the electric field at the outer sphere after discharge may be required to exceed some design value. The minimum chamber voltage after discharge, v_c, is

$$v_c = v_m - \frac{C+c}{C} \Delta v_m \quad . \tag{17}$$

The equations for chamber sensitive volume (13), capacitance (14), system sensitivity (15), and an inequality condition for the electric field after discharge derived from (16) and (17) can be combined into a single inequality and the solution found for R and r.

The assumption was made in this discussion that there was no capacitance between the inner electrode and the base. But to prevent the "perspiration effect", the inner electrode must be completely surrounded by a grounded electrode, so that an appreciable capacitance to the base is unavoidable. This extra capacitance gives an added adjustable parameter, so that the dimensions based on fixed S and c are no longer unique.

The capacitance equation (14) is replaced by

$$C = 2\pi\epsilon \frac{Rr}{R-r} + C_1 \tag{18}$$

where C_1 is the added capacitance through a solid dielectric in the base. With this added parameter it is now possible to satisfy both

conditions discussed above, but again the algebraic complexities are rather formidable.

Since it was evident that no practical design with hemispherical electrodes would have a sufficiently small variation in sensitivity to beta rays with angle of incidence (as discussed above), the hemispherical design was abandoned. The design considerations have been treated here first to illustrate the methods of solution, and second because at first sight the shape seemed to lend itself to satisfactory construction and dosimetry.

F. The Choice of Dimensions for the Pillbox Wrist Dosimeter

1. Dimensions for Fixed Volume and Capacitance

The essential design procedure discussed for the hemispherical chamber was applied to the parallel-plate design. The whole device has the shape of a shallow pillbox, whose geometry is shown in Figure 7. The volume of the ionization chamber is

$$V = \pi r^2 x \quad . \tag{19}$$

The capacitance is the sum of that in the air chamber and that through the dielectric to the base:

$$C = \epsilon \pi r^2 (1/x + k/y) \quad . \tag{20}$$

Edge effects are neglected here, but will be considered later.

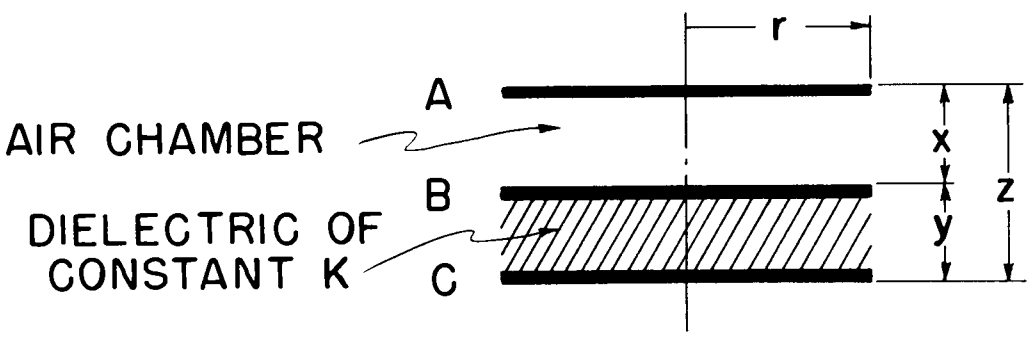

Fig. 7. Geometry of Pillbox Chamber.

Consider first the case of fixed volume and capacitance. There are now four independent parameters, r, x, y, and k. Two more conditions may therefore be imposed; for example, the minimum electric field must be more than some specified value, and the device may be designed to have minimum thickness. It is easier to consider (k) as a constant at first and to leave the minimum field condition to be satisfied later by choice of the dielectric. This is logical because the field condition only sets an upper limit to x but does not otherwise restrict it.

Define the total thickness as

$$Z = x + y \tag{21}$$

and let

$$\alpha = C/\epsilon V \quad . \tag{22}$$

Equations (19) through (22) may be combined to give

$$Z = \frac{kx}{\alpha x^2 - 1} + x \quad . \tag{23}$$

To find the air chamber thickness x for minimum total thickness Z, find dZ/dx

$$\frac{dZ}{dx} = \frac{3\alpha x^2 - 2\alpha xZ + (k-1)}{\alpha x^2 - 1} \quad . \tag{24}$$

The denominator must not vanish, so

$$x^2 > \frac{1}{\alpha} = \frac{\epsilon V}{C} \quad . \tag{25}$$

To find the minimum, set the numberator equal to zero and solve for x

$$x_m = \left[\frac{1}{2\alpha} \left(k + 2 \pm \sqrt{k^2 + 8k} \right) \right]^{1/2} \quad . \tag{26}$$

Since $k \geq 1$, the negative sign is impossible. It may be verified that this value of x_m gives a true minimum for Z by calculating $[d^2Z/dx^2]_{x_m}$

$$[d^2Z/dx^2]_{x_m} = \frac{2\alpha x \sqrt{k^2 + 8k}}{(\alpha x^2 - 1)^2} > 0 \quad . \tag{27}$$

Hence, the solution found for x gives a minimum. From x_m the other dimensions may be calculated to be:

$$y_m = \frac{kx_m}{\alpha x_m^2 - 1} = \frac{-k + \sqrt{k^2 + 8k}}{4} \cdot x_m \quad , \tag{28}$$

$$Z_m = \frac{4 - k + \sqrt{k^2 + 8k}}{4} \cdot x_m \quad , \tag{29}$$

$$r_m = \sqrt{V/\pi x_m} \quad . \tag{30}$$

It may be asked whether the minimum thickness found when x is considered as the independent variable is the same as the minimum thickness when r is the variable. The proof that the two are identical is quite simple. As before

$$Z = f(x) \tag{31}$$

but

$$x = g(r) \quad , \tag{32}$$

therefore

$$\frac{dZ}{dr} = \frac{dZ}{dx}\,\frac{dx}{dr} \quad . \tag{33}$$

If $dZ/dx = 0$, then $dZ/dr = 0$ unless $dx/dr = \infty$. In this chamber

$$x = \frac{V}{\pi r^2} \tag{34}$$

so

$$\frac{dx}{dr} = -\frac{2V}{\pi r^3} \quad . \tag{35}$$

Hence $dx/dr = \infty$ only if $r = 0$, and the values of x, y, and z determined from $(dZ/dx = 0)$ are the same as those obtained from $dZ/dr = 0$.

Figure 8 shows that the minimum thickness increases rather slowly with dielectric constant, so the choice of base material is not critical. Still, low values of k give somewhat thinner chambers. The most important considerations in the choice of the base dielectric material are that it must be an extremely good insulator to avoid leakage and resulting false exposure readings, and that the average atomic number of the constituents should be as close to that of air, 7.3, as possible for correct dosimetry.

Figure 9 shows the trend of the various parameters of the chamber for a fluorothene base as the diameter is varied. The broad minimum in the total thickness is evident.

The minimum electric field in the parallel-plate case is simply

$$E = \frac{V_c}{x} \quad . \tag{36}$$

Calculations from Boag's theory indicate that the collection efficiency for 63 volts minimum potential and a thickness x of 0.836 cm should be over 99% at 200 r/hr. Gupton's results indicate a somewhat lower efficiency. In personnel monitoring a dose rate as high as 200 r/hr would almost certainly give a dose of far more than 200 mr so the reading would be off scale. Therefore, the saturation in the pillbox would seem to be adequate for practical use.

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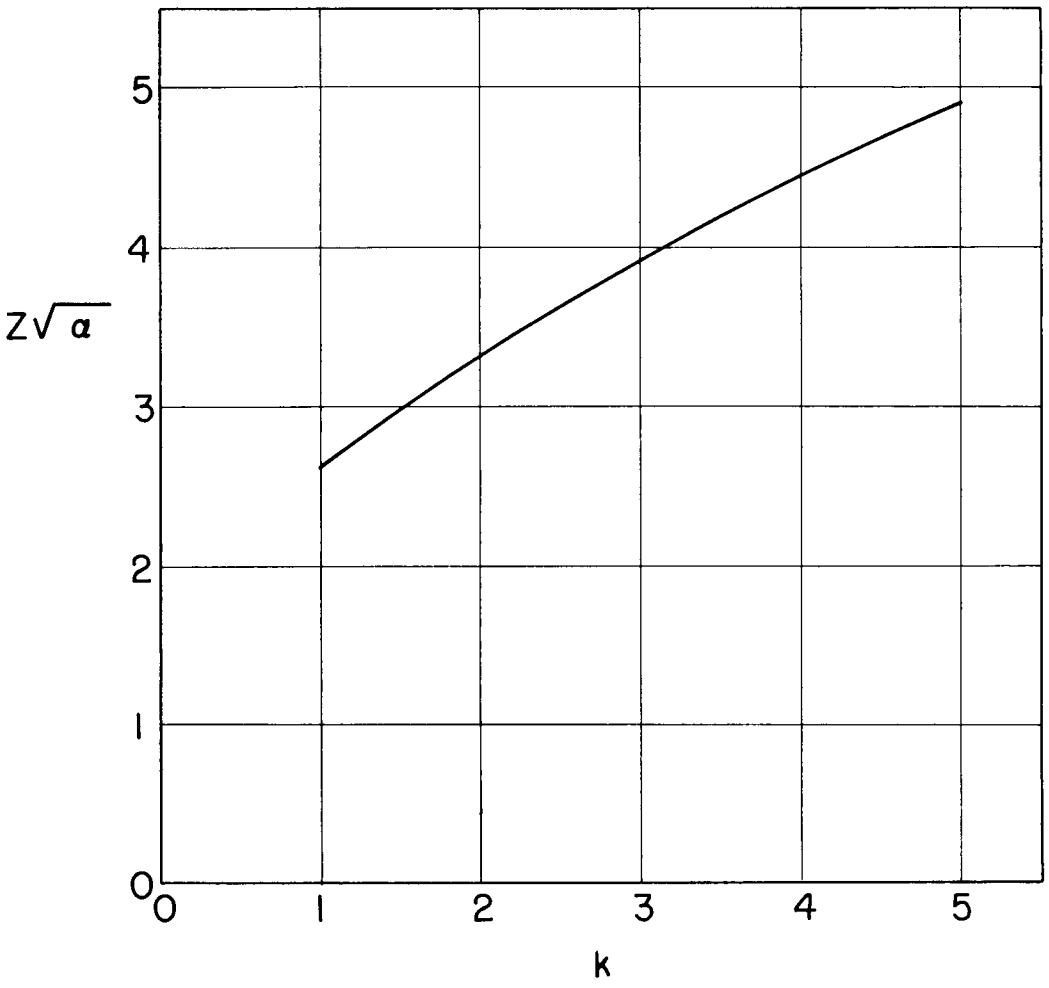

Fig. 8. Variation of Thickness Parameter with Dielectric Constant of Base for Pillbox Chamber.

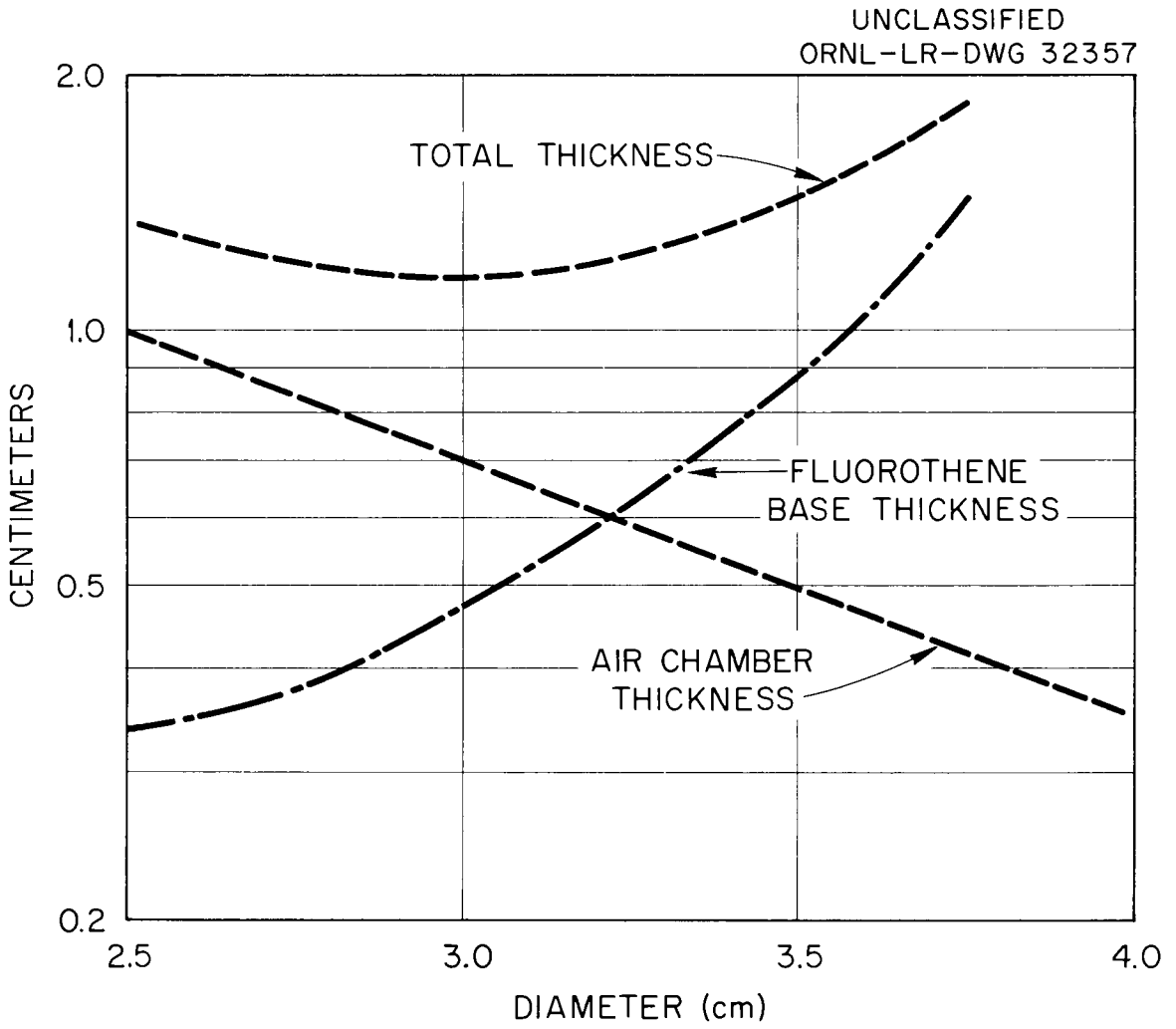

Fig. 9. Variation of Dosimeter Parameters as a Function of Chamber Diameter.

2. Dimensions for Constant Sensitivity

The restriction of the design to fixed volume and capacitance may be relaxed, as was discussed for the hemispherical dosimeter. Instead, the sensitivity of the over-all system of chamber plus electrometer may be fixed. In principle, this gives an added degree of freedom to the design, so that it would seem to be possible to minimize both dimensions, Z and r of the chamber. The governing equations are

$$V = \pi r^2 x \quad , \tag{19}$$

$$C = \epsilon \pi r^2 (1/x + k/y) \quad , \tag{20}$$

$$S = \frac{V}{C+c} \quad , \tag{7}$$

$$Z = x + y \quad . \tag{21}$$

These may be combined to eliminate V, C, and y to give an equation for Z as a function of r, x, k, and the fixed quantities c, S, ϵ, and π.

$$Z = \frac{S \epsilon k x}{x^2 - Sc/\pi r^2 x - S\epsilon} + x \quad . \tag{37}$$

The denominator of the fraction in equation (37) must be positive in order that $Z > x$. The thickness Z is seen by inspection to decrease monotonically as r increases. The value of air gap thickness x which

produces the minimum Z for any given r is found from the relation

$$\frac{\partial Z}{\partial x} = 0 \quad . \tag{38}$$

The differentiation of equation (37) yields:

$$\pi^2 r^4 x^4 + S^2 c^2 x^2 - S\epsilon(k+2)\,\pi^2 r^4 x^2 - 2Sc\pi r^2 x^3$$

$$+ 2S^2 c\epsilon\pi r^2 x - (k-1)\,S^2\epsilon^2\pi^2 r^4 = 0 \quad . \tag{39}$$

The equation is a quadratic in r^2, and may be solved to yield r as a function of x. The value of x which satisfies this equation for any given r may be substituted into equation (37) to yield the minimum dosimeter thickness Z for that given radius r.

In practice, the edge corrections to the dosimeter capacitance are so large as to make the above analysis useful only in making a rough determination of the dosimeter dimensions.

3. Corner Corrections to Chamber Capacitance

It was assumed in Sections 1 and 2 that the parallel-plate formula gave the capacitance correctly. Actually this is not strictly true in that an appreciable fraction of the total chamber capacitance is between the edge of the center electrode and the side cylindrical portion. The basic geometry is shown in Figure 10. The edge correction formula

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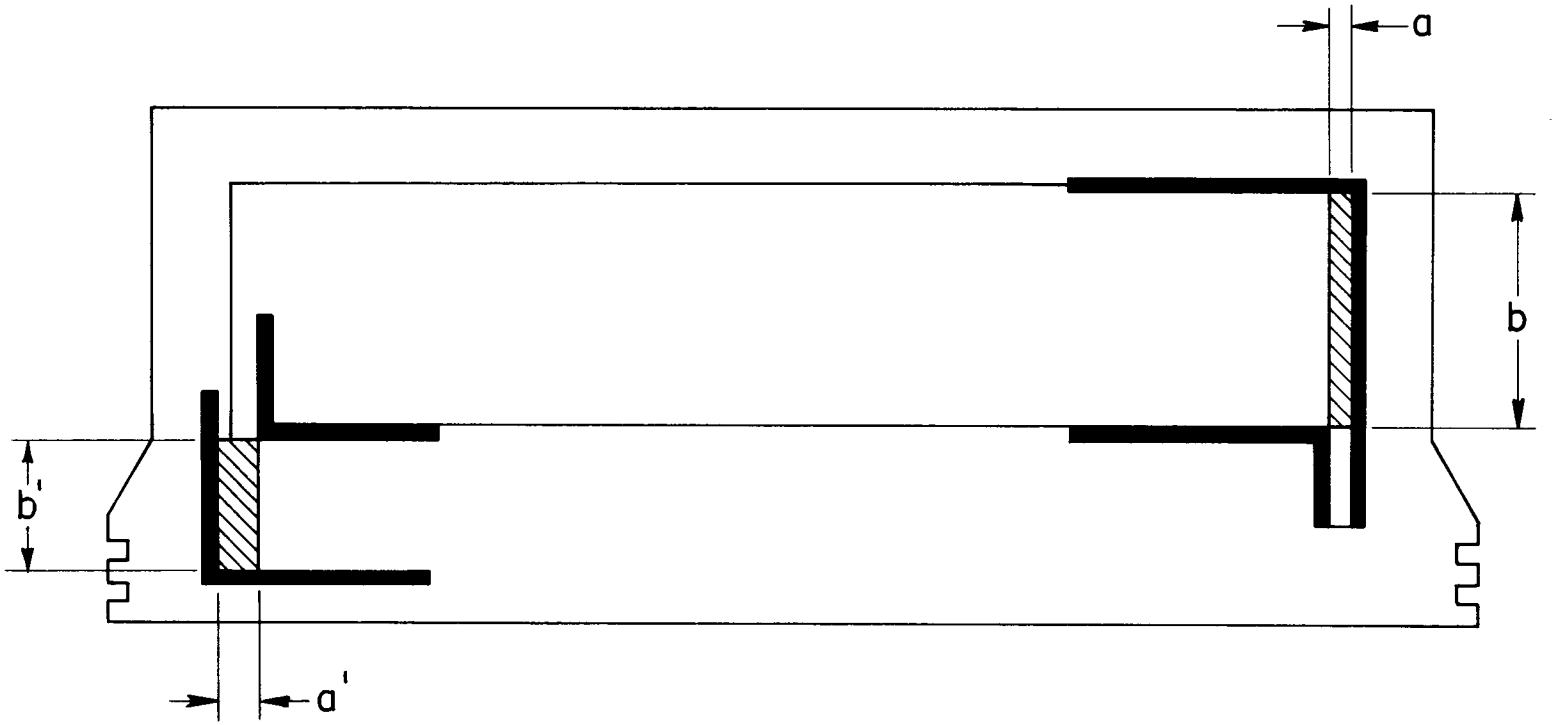

Fig. 10. Geometry of Pillbox Chamber for Corner Correction.

for a plane edge per unit length multiplied by the circumference $2\pi r$ may be used as a good approximation.

This correction is given as follows in the AIP Handbook[41]: "Two infinite sheets, each of which has one-half bent at right angles to the other, are placed with the edges of the bends parallel so that the distance between sheets on one side of the bend is (a) and on the other (b). The additional capacitance per unit length of bend over that given by the assumption of a uniform field over each half of the inner sheet and no field in the corner rectangle is

$$\frac{2\epsilon}{\pi}\left[\ln\left(\frac{a^2+b^2}{4ab}\right)+\frac{a}{b}\tan^{-1}\frac{b}{a}+\frac{b}{a}\tan^{-1}\frac{a}{b}\right]." \qquad (40)$$

Two corner corrections are involved, one in the air chamber (dimensions a and b) and the other in the dielectric (dimensions a' and b'). Calculations indicate that about 35% of the total capacitance is in these corners, so elaborate calculations of the minimum dimensions neglecting these corrections are not justified. To include the corrections in the capacitance equation (20) would hopelessly complicate the calculations.

G. The Angular Dependence of the Response

It was pointed out above that in an ideal device the sensitivity of the chamber to beta rays ought not to vary for any angle of incidence

[41] AMERICAN INSTITUTE OF PHYSICS HANDBOOK, (McGraw-Hill, New York, 1957), p. 5-17, third paragraph.

over a hemisphere. The argument for this goes as follows. Suppose the chamber is worn on the back of the wrist. Then it is true that beta rays incident on the skin at large angles to the normal to the chamber will not deliver much, if any, dose to living tissue at that point. However, such rays will be incident normally at a nearby point on the wrist or hand, so the dose they deliver should be recorded. Beta rays originating from sources on the under side of the wrist will, of course, not be able to reach the dosimeter.

Many dosimeters such as the "soft-shell Cutie Pie" are made in cylindrical shapes with strengthening ribs giving different transmissions through the ends from those through the sides. Happer and Birkhoff[42] have calculated how much of the observed ionization is due to incident radiation which enters through the end of a cylinder and how much to that which enters through the side. A resumé of their discussion is given in Appendix IV.

If A_{top} is the unshielded area of the top and A_{side} is the unshielded area of the side, then the fractional irradiated volume $V_{eff}(\theta)/\pi p^2 h$ at an angle of incidence θ is

$$\frac{V_{eff}(\theta)}{\pi p^2 h} = \frac{A_{top}}{\pi p^2}\left[\frac{V_{top}(\theta)}{\pi p^2 h}\right] + \frac{A_{side}}{2\pi p h}\left[\frac{V_{side}(\theta)}{\pi p^2 h}\right] \qquad (41)$$

[42] Happer, W., and Birkhoff, R. D., "Angular Response of a Partially Shielded Cylindrical Dosimeter", submitted as a Note to the Editor of the Health Physics Journal, Jan. 12, 1960.

where p and h are the radius and height of the dosimeter, and $V_{top}(\theta)$ and $V_{side}(\theta)$ are the portions of the dosimeter volume irradiated through the top and sides respectively. The functions $V_{top}(\theta)/\pi p^2 h$ and $V_{side}(\theta)/\pi p^2 h$ are calculated and graphed in Appendix IV. It is clear that the sum of these functions at any θ is always unity. This implies that if the $A_{top}/\pi p^2 = A_{side}/2\pi ph \equiv f$ (i.e., if the dosimeter is shielded equally on top and sides) then the response will be independent of the angle θ. For the wrist dosimeter the shielding was adjusted to this condition and with $f \simeq 1/2$.

For the above calculation to be valid, the windows in the shielding must be sufficiently numerous that the average transmission through the sides and top will be a meaningful quantity (i.e., will not vary with the azimuthal angle of the radiation for instance). At the same time, the ratio of shielding thickness-to-window dimension must be small enough to prevent attenuation of radiation incident in directions non-normal to the windows (eliminating the shadowing effect of the edges of the shielding). Last, the dosimeter must contain a small enough quantity of matter for the radiation to traverse it without change in direction (small scattering), and without significant attenuation.

V. DETAILED DESIGN

The final design of the dosimeter chamber represents a compromise among all the detailed requirements which have been discussed. The result is shown in Figure 11, and the details will be discussed with reference to the design requirements as set forth in Section II.

The inner liner is of vinyl plastic coated with colloidal graphite, the whole having a superficial density of about 7 mg/cm^2 in order to record any radiation which can penetrate the epidermis. The materials are nearly air equivalent to assure that the Bragg-Gray principle is satisfied.

The thin liner is protected by a thick cylindrical cap having eight pie-shaped holes in the top and eight rectangular holes in the sides. The dimensions of the holes are chosen to give about 50% open area on the top and the same on the sides. Of course, there is some shadowing by the finite thickness of the cap for radiation incident at angles non-normal to the holes.

The cap is made of nylon 0.080 inches (about 250 mg/cm^2) thick. This material is nearly air equivalent and is very strong, so the chamber will withstand a good deal of rough treatment. The air equivalence ensures a minimum energy dependence for x and gamma rays. The thickness is sufficient to give electronic equilibrium for gamma rays up to

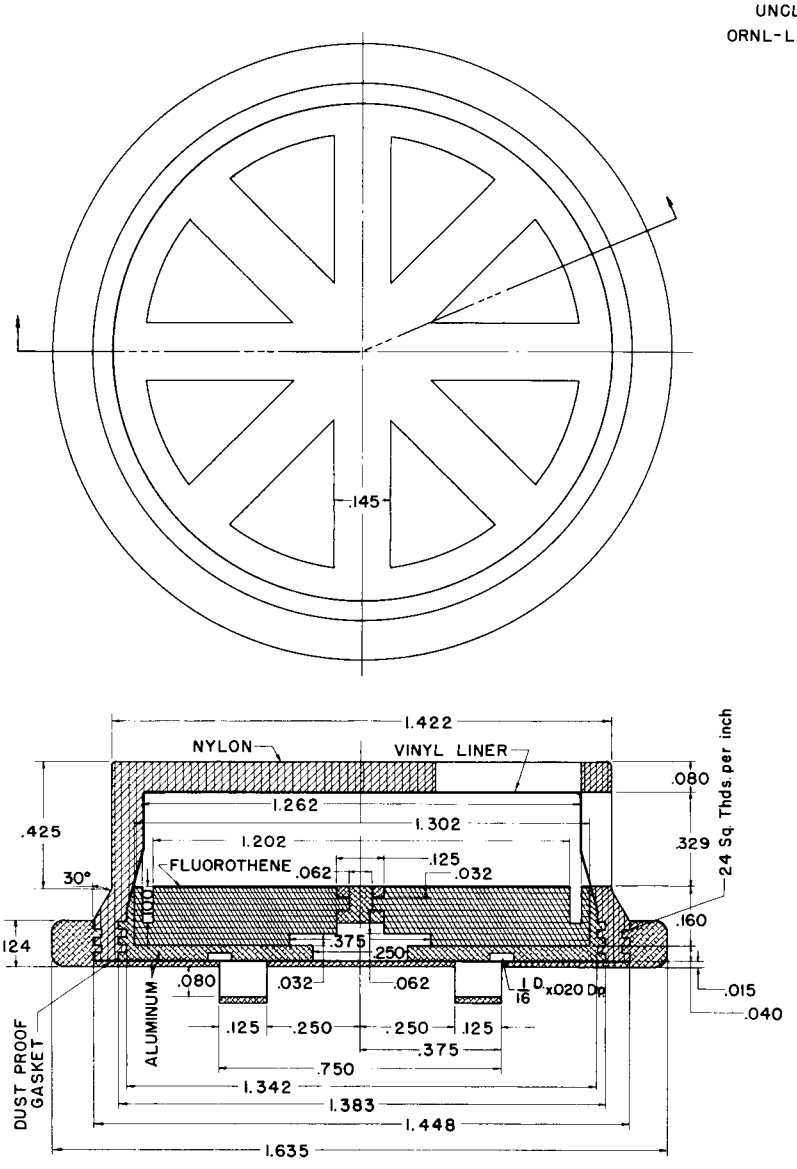

Fig. 11. Final Design of Wrist Dosimeter.

several Mev. Half the radiation, of course, enters through the holes where such equilibrium will not be obtained, but this compromise is inevitable in a device to be sensitive to both beta rays and gamma rays.

The angular dependence has been discussed. Again the design represents a compromise between a thin wall, which would give a device with no angular dependence, and a wall thick enough for mechanical strength and electronic equilibrium.

The base is made of fluorothene, which is polymerized C_2ClF_3. This material has extremely high volume and surface resistivity, so that even short paths over and through the insulation are sufficient to give a leakage corresponding to less than 5 mr in 24 hours. The dielectric constant of fluorothene is about 2.3. Polyethylene would be satisfactory as regards its resistivity, but it has a higher dielectric constant which would make the whole chamber somewhat thicker for the same capacitance. The main disadvantage of fluorothene is its high average atomic number, which causes the X-ray response to increase somewhat in the region of 20-100 Kev. Polyethylene would be preferable for this reason, if its surface leakage is small enough.

The capacitance of the parallel plates neglecting edge effects was calculated to be 4.45 μμf. The corner corrections increased this to a total of about 6.67 μμf. The volume of the air chamber is 6.74 cm^3. For a Minometer capacitance of 5.2 μμf, the sensitivity is S = 0.189 volts/mr. This compares favorably with S = 0.185 volts/mr for the Victoreen chamber.

The electric field after discharge by 200 mr is about 75 volts/cm. As mentioned above, Boag's theory indicates this should give nearly complete saturation at 200 r/hr.

A picture of the chamber as worn on the wrist is shown in Figure 12. Fifty chambers have been fabricated for field tests, and the cost and ease of manufacture both appear quite favorable. The most fragile part is the vinyl liner, which, however, is very cheap and easy to replace.

One major difficulty of such a chamber-electrometer system has always been the kick given the electrometer fiber when the electrical contact to the insulated electrode is made or broken. This seems to arise from contact potentials at the surfaces in contact and capacitance changes when the chamber is being inserted in the Minometer receptacle. It was successfully eliminated in this device by gold plating the contact points of the electrodes and by suitable design of the insertion well attached to the Minometer. To keep the insulation clean it was desirable to have a plastic plug which fitted into the base.

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Fig. 12. Photograph of Final Chamber.

VI. TESTING OF PILLBOX WRIST DOSIMETER

Testing of the pillbox design involved first a comparison of the dosimeter characteristics with the design requirements, and then a calibration with X ray, gamma, and beta sources in order to determine the response.

A. Experimental Evaluation of Capacitance, Energy Response, Collecting Field and Leakage

An initial testing model of dimensions calculated approximately as detailed in Sections IV and V was fabricated as shown in cross section in Figure 13. The sensitive volume was enclosed with a threaded .020" thick unperforated Al cap. The capacitance of the dosimeter as measured on an L,C Meter[43] was 5.6 μμf. This value was higher than anticipated for a parallel-plate condenser of these dimensions because of the conducting sides of the chamber and the base, as discussed in Section IV-F-3. In the version used for radiation calibrations, the capacitance was reduced to the desired 4.0 μμf (of the Victoreen pocket ionization chamber) by partially hollowing out the base and by increasing the thickness of the base from .160" to .260".

In order to assess the energy dependence for X rays, unperforated plastic caps were fabricated of fluorothene, nylon, and polyethylene,

[43] Type 130 L,C Meter, Tektronix, Inc., Portland, Oregon.

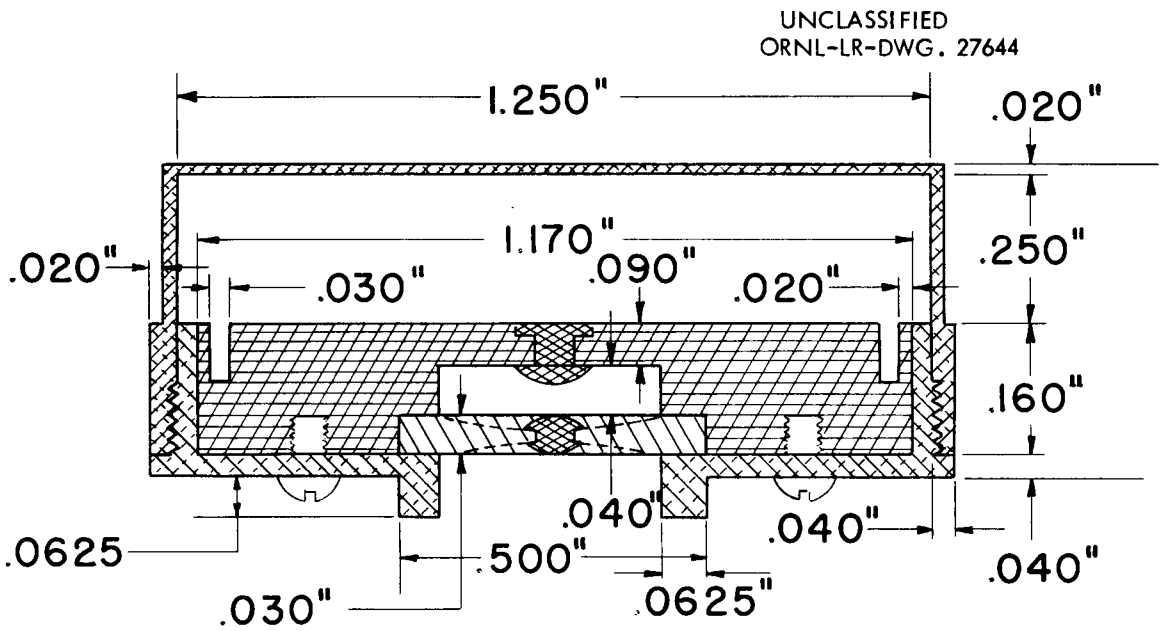

Fig. 13. Initial Test Model of Wrist Dosimeter.

to the inside of which a thin coating of colloidal graphite ("Aquadag") was applied. The wall thickness was .080". Chambers so equipped were irradiated with heavily filtered X rays from a standard 250 kilovolt Westinghouse Quadrocondex X-ray machine. Their readings were compared with that of a Standard Free Air Chamber which has been described[44] elsewhere. The response of these models relative to that of the standard air chamber is shown in Figure 14. Also shown is the relative response of Victoreen pocket ionization chambers as given by Day[45]. Nylon appeared to have the least energy dependent response and was chosen accordingly.

Collecting voltages on the dosimeter were varied in order to determine the minimum voltage at which the chamber was saturated. An increase of collecting voltage (and therefore collecting field strength) above this saturation voltage results in no increase in the rate of collection of ions and hence no increase in reading for a given exposure. Below this saturation voltage, readings fall off due to recombination of ions within the chamber before collection. The electrically "floating" Minometer used has been described by Gupton[46]. The average

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[44] Hubbell, Johnson, and Birkhoff, op. cit. ORNL-2158.

[45] Day, F. H., op. cit.

[46] Gupton, E. D., op. cit.

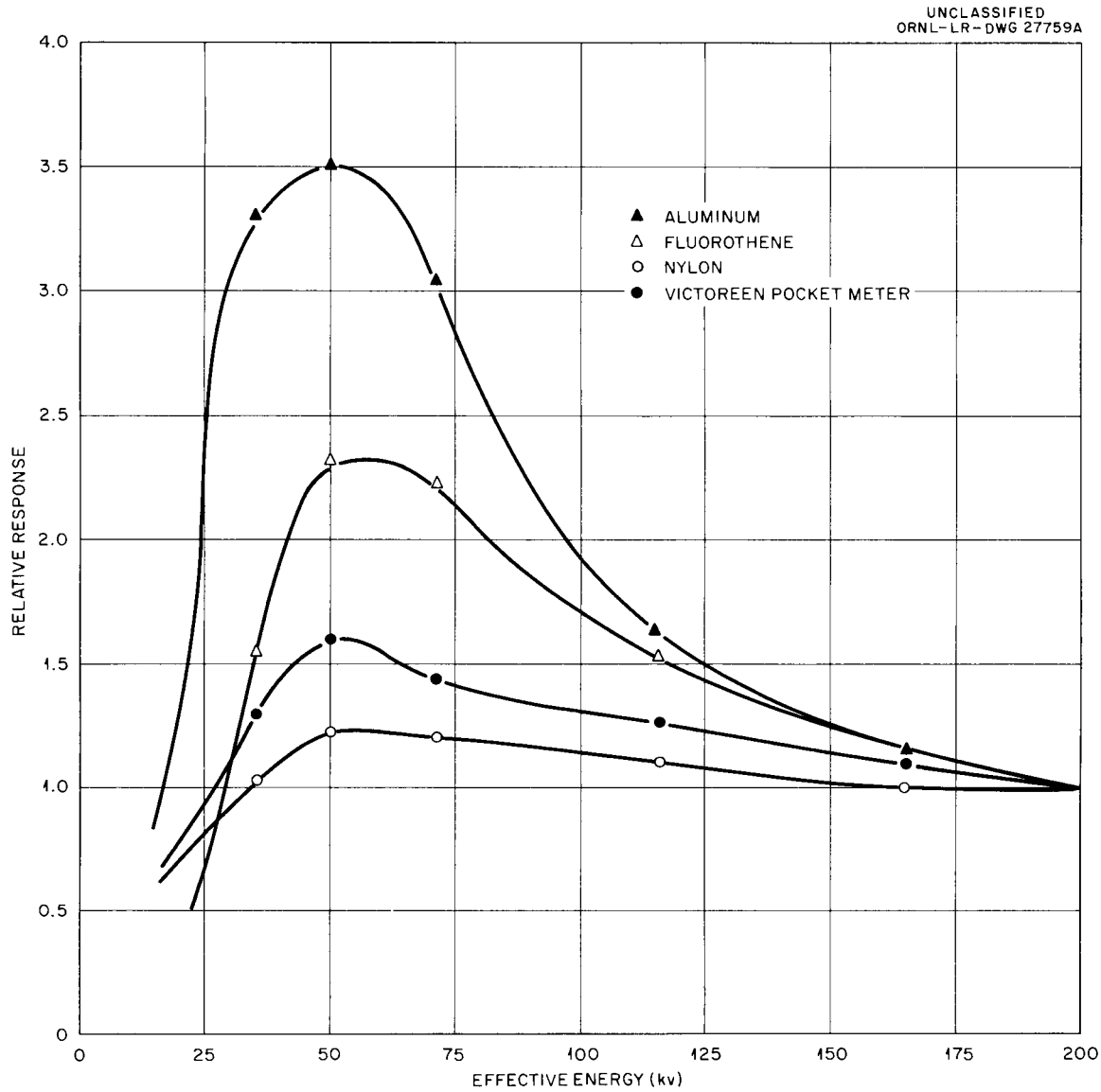

Fig. 14. Variation of Response to X-Ray Energy for Victoreen Pocket Chamber and for New Dosimeter Made of Various Wall Materials.

percentage of the saturation value as a function of the initial charging voltage for a series of uniform X-ray exposures at 165 Kev (eff) and at a rate of 51,000 mr/hr are shown in Figure 15. The ionization chambers are very nearly saturated at about 70 volts and are completely saturated above 100 volts. Thus at dose rates customarily encountered in personnel exposures, no significant recombination losses should occur since the minimum chamber voltage after 200 mr exposure is 63 volts.

In order to minimize leakage, the insulators were washed in detergent, rinsed in distilled water, rinsed again in alcohol, and finally baked under a heat lamp. A flexible insulated diaphragm protecting the charging pin from unintentional discharge due to dust, lint, and other foreign objects was provided in the initial model, as shown in Figure 13. A metal button at the center of the diaphragm permitted momentary contact to be made with the charging pin. Unfortunately, it tended to give a "kick" of from twenty to forty milliroentgens in Minometer readings so that it was removed from subsequent versions.

Leakage was continuously evaluated through several months of testing and calibration. The chambers were charged with a portable Minometer, which was supplied with 110 volts AC by a constant voltage transformer. Dosimeters were charged and set aside for periods of time ranging from 18 to 258 hours. An average leakage rate of 0.208 mr/hr (5 mr in 24 hours) was observed with a standard deviation of

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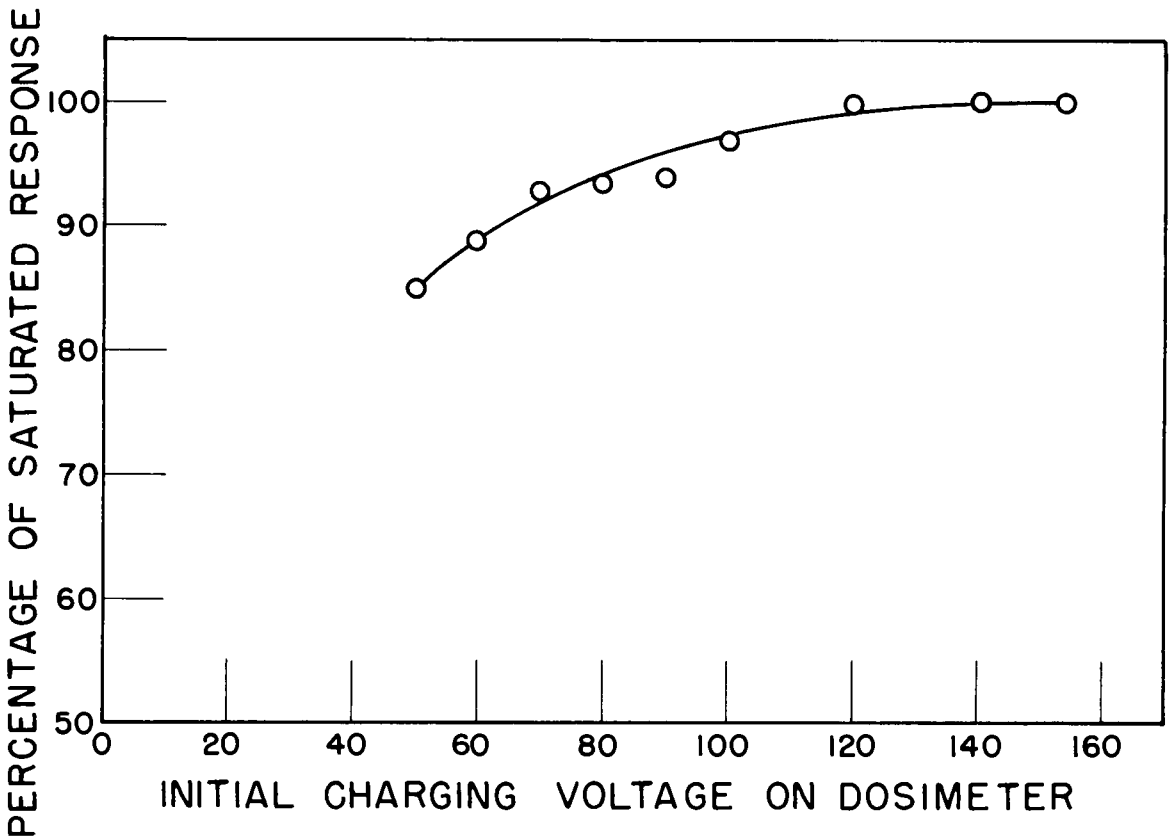

Fig. 15. Saturation Curves for Wrist Chamber.

0.111 mr/hr. Although 50% of the time a leakage rate was observed which was greater than that presently accepted for the Victoreen pocket ionization chamber, it was felt that the elimination of ragged machined edges and the careful sealing of the ionization chamber from dust and lint could reduce leakage in a production version of this type of ionization chamber.

A revised model incorporating several improvements in accordance with the preceding is shown in Figure 16, an exploded view. The inside "liner" of the ionization chamber is made of mylar, vinyl plastic, or paper in order to obtain the desired 7 mg/cm^2 with readily available materials. In production this would probably be a film of vinyl plastic, which is easy to fabricate. Several significant modifications to the initial version are shown. An increase from .250" to .260" in chamber height was made in order to make the volume more nearly equal to the 5.3 cm^3 effective volume of the Victoreen pocket ionization chamber.

The thickness of the base was increased from .160" to .230" and it was partially hollowed (the cavity being filled with Styrofoam to eliminate possibility of ion drift and charging of the insulator surfaces) in order to reduce capacitance from the 5.6 μμf of the initial version to the desired 4.0 μμf.

A plastic plug to protect the charging electrode from dirt, lint, and other causes of leakage or unintentional discharge was substituted for the flexible charging diaphragm of the earlier version. This plug is shown in Figure 16.

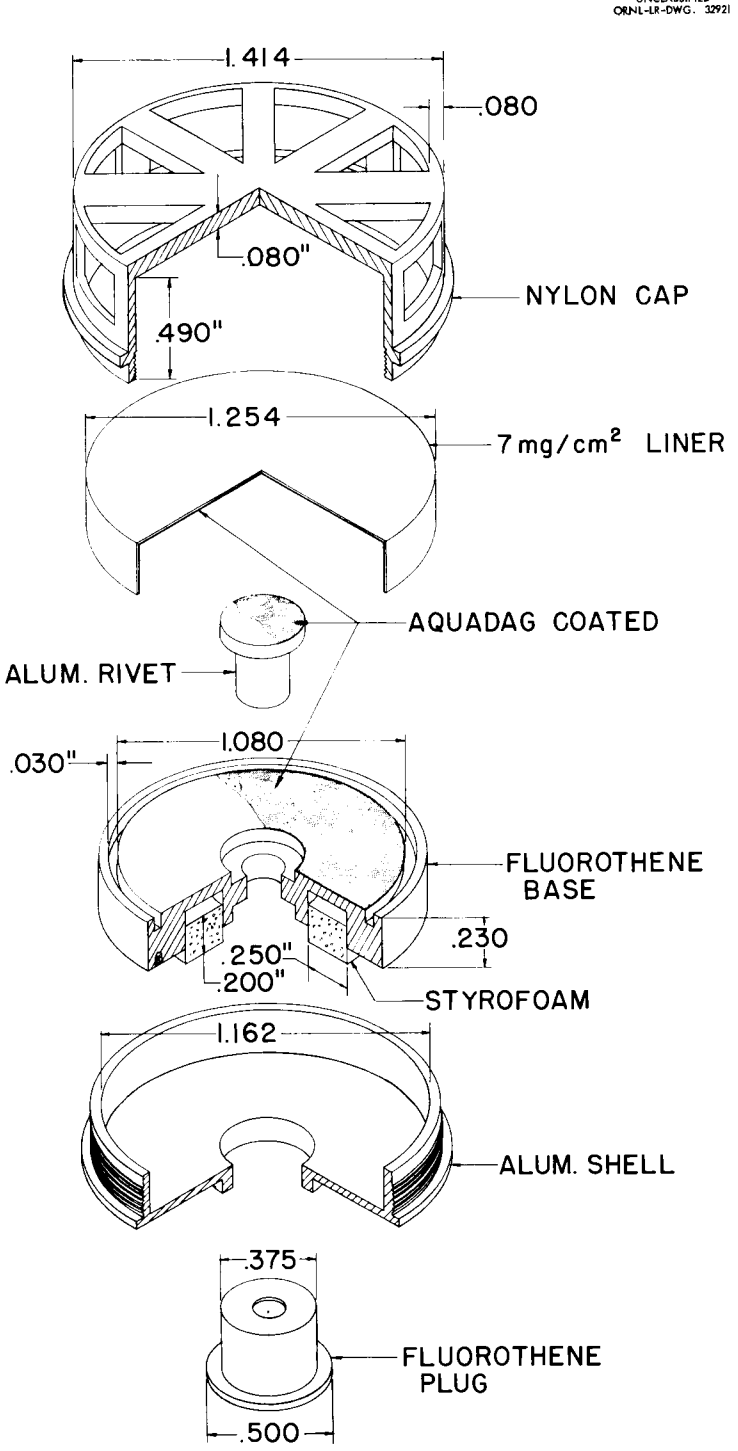

Fig. 16. Second Test Model of Wrist Dosimeter.

The "pillbox" chambers, as it might appear worn on the wrist, is shown in the photograph, Figure 12.

B. Calibration with X Rays, Gamma Rays, and Beta Rays

All calibration data were corrected to N.T.P. Appropriate adjustments for capacitance were also made in order to correct calibration data to those which would have been observed with a combined ionization chamber-Minometer capacitance of 9.4 μμf. Details of these corrections are given in Appendix I.

Standards used in calibration were: for X-ray exposures, a Victoreen Condenser R-Meter and a standard free air chamber; for gamma exposures, the calculated dose from a radium source; and for beta exposures, the calculated air cavity dose in a water solution of pure beta-emitting isotopes whose activity was known from assay[47].

X-ray calibration exposures were made with the standard Westinghouse Quadrocondex X-ray machine. The dosimeters gave a response within about 5% of that of the R-Meter for effective energies above 100 Kev. The maximum deviation was about 30% above the R-Meter reading and occurred at an effective energy of about 45 Kev.

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[47] Thanks are due H. A. Parker of the Isotopes Division of ORNL for providing the radioactive solutions and making the assays.

Gamma calibrations, using a 99.2 mg radium equivalent[48] source, were conducted in the facilities used to calibrate film badges and pocket meters in the ORNL Health Physics Division. For convenience, Victoreen pocket ionization chambers were used as secondary calibration standards, since a literature survey and some experimental work suggested that their observed discharge, in esu per cm^3, agreed very well with the calculated radium dose. An average of .95 of the gamma calibration dose was obtained.

Beta calibrations were based in part on the theory for the average energy in a homogeneous water solution and other data for a number of beta-emitting isotopes available from recently completed work[49]. Table II gives these isotopes, their half lives, maximum energies, average energies, and the average energy of their absorbed flux spectra in a water solution.

The 2π calibration geometry was obtained by suspending the dosimeter in a paraboloidal cavity formed in a rotating plastic cup containing one of the isotope solutions. Details of this rotating cup are given in Appendix III.

The method of calculating the expected dose rate in an air cavity in a water solution of a beta-ray emitter is given in detail in the

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[48] National Bureau of Standards Calibration No. 31046 (1950).

[49] Hubbell, Johnson, and Birkhoff, op. cit. ref. 13-18.

TABLE II. BETA-RAY SOURCES USED IN CALIBRATION

Isotope	Half Life	Maximum Energy T_o (Mev)	Average Energy bT_o (Mev)	Average Energy of Electron Spectrum in Water Solution[50] T_y (Mev)
S^{35}	87.2 d	0.167	0.055	0.052
Ca^{45}	164 d	0.254	0.079	0.079
W^{185}	74 d	0.430	0.130	0.130
Tl^{204}	4.1 yr	0.765	0.243	0.237
Ag^{111}	7.5 d	1.040	0.342	0.317
P^{32}	14.3 d	1.708	0.695	0.506
Y^{90}	2.54 d	2.24	0.900	0.694

[50] Hubbell, Birkhoff, and Johnson, op. cit. ORNL-2158.

reference and summarized in Appendix I. From this reference, where

b = ratio of average beta energy to maximum beta energy, for a thin source spectrum,

T_o = end point beta energy in Mev,

D_a' = air cavity milliroentgen equivalents per second,

Q_m = microcuries of radioactivity per gram of solution.

For 4π irradiation geometry

$$D_a' = 0.660\ Q_m b T_o . \tag{42}$$

Dividing by 2, for 2π geometry and changing to air cavity milliroentgen equivalents per hour, D_a'', a more customary dose rate unit

$$D_a'' = 1.19 \times 10^3\ Q_m b T_o . \tag{43}$$

Values of bT_o are shown in Table II.

Figures 17 and 18 summarize the results for beta-ray calibration. Shown at the top of each graph are the isotopes used and the average energy T_y of the electron flux in the water solution as calculated previously[51]. In Figure 17 the observed doses are compared to those calculated for each isotope from the radioactive assay and bT_o. Points shown for the Standard Victoreen Chambers are taken from ORNL-2158.

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[51] Ibid.

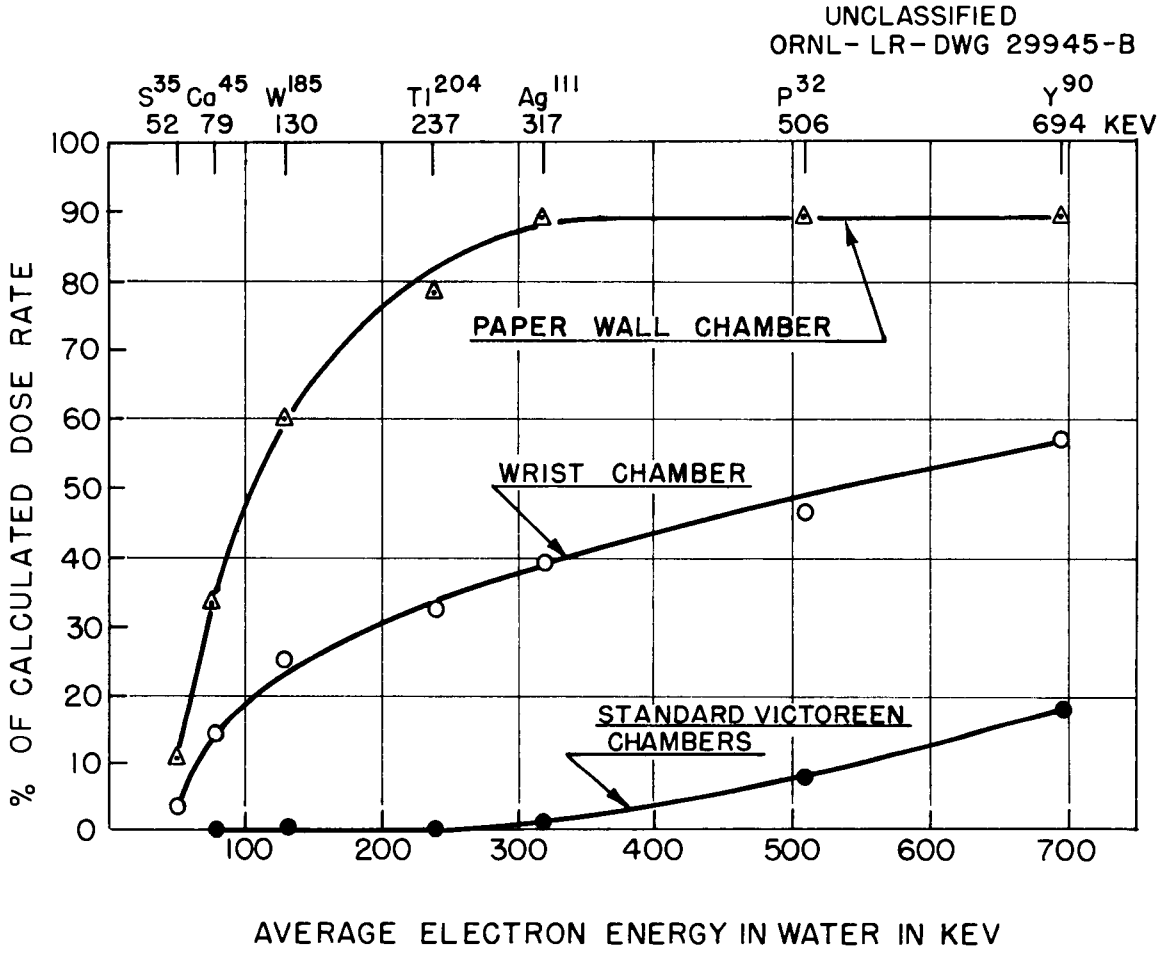

Fig. 17. Response of Chambers Compared to Calculated Response.

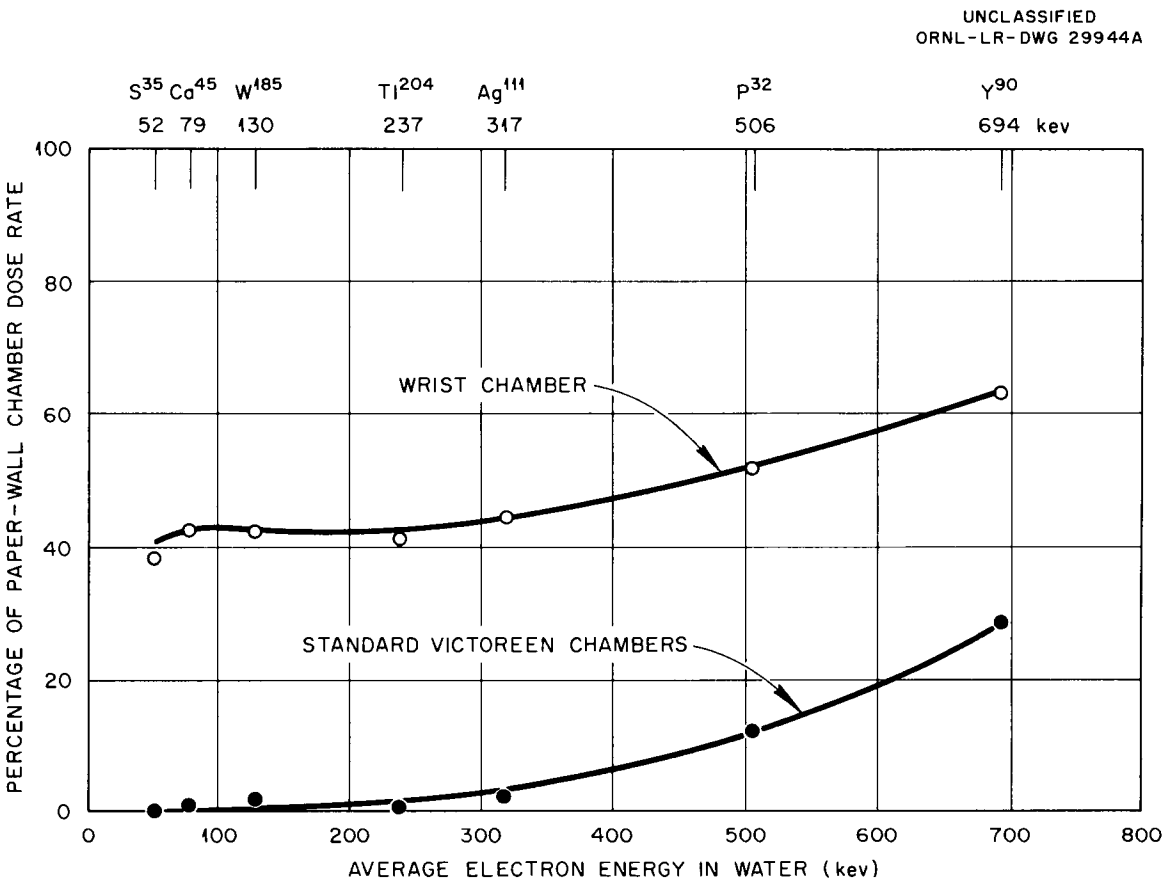

Fig. 18. Response of Chambers Compared to Response of Paper Wall Chamber.

For reasons given earlier the outer wall of the ionization chamber was fabricated so as to transmit only 50% of the incident beta radiation. In order to verify this prediction, an all-paper chamber of 7 mg/cm^2 wall thickness, otherwise identical to the thick-walled chambers, was exposed, and the results are shown in the upper curve in Figure 17. The paper chamber has a rather low response at low energies, rising to a constant response of 90% above 317 Kev. The wrist dosimeter may be seen to record about half the dose given by the paper chamber. In Figure 18 the response of the wrist dosimeter is compared directly to that of the paper chamber. Since the sensitive volume of the paper chamber is shielded by the same thickness as the sensitive layer of the skin, the wrist dosimeter curve represents the per cent of the biologically significant dose which is recorded by the dosimeter. This may be seen to be 50% $\pm$ 13% for average beta energies ranging from 52 Kev to 694 Kev. Comparison of this curve with that for the aluminum and magnesium pocket chambers tested by Hubbell, et al. shows a significant reduction in the high energy sensitivity and thus a more energy independent response. Further advantages of the wrist dosimeter are its considerably greater mechanical strength due to the thick nylon cover, and its smaller size.

VII. SUMMARY

The basic requirements for a satisfactory personnel dosimeter chamber for beta and gamma rays were broken down into four groups. For satisfactory dosimetry the chamber should record correctly any dose of beta or gamma radiation which could penetrate the dead layer of the epidermis, defined as 7 mg/cm^2 thick. The dose reading should be independent of angle of incident or energy of the radiation. Electrical and electric field requirements include proper capacitance, volume, and negligible leakage. Mechanically it should be small, convenient to wear, rugged, and yet have thin walls over half its area. Finally it should be reasonably cheap and easy to manufacture, calibrate, and repair.

The theory of ionization chamber-electrometer systems was summarized, and it was shown that the volume V and capacitance C were related to the electrometer sensitivity S and capacitance c by $S = V/(C+c)$ for correct readings on the electrometer scale. Conditions were given for minimum electric field to collect all ions formed at reasonable dose rates.

A method was developed for calculating the minimum dimensions of the chamber subject to restrictions of either fixed chamber volume and capacitance, or fixed over-all sensitivity with a given electrometer.

The detailed design and the reasons for various design features were given for a practical chamber for wrist or pocket wear. The

device is a shallow pillbox about an inch and a half in diameter and five-eighths of an inch high. The outside is a ribbed nylon cover with 50% open area on the top and sides, and having a liner 7 mg/cm^2 in superficial density, coated inside with colloidal graphite, to define the sensitive volume. The insulated electrode is another graphite coating on the inside of the base, to which electrical contact is made by a rivet through the base. A metal base and the graphite coating on the liner form the outer, grounded electrode. Various other designs were considered, and the reasons for their rejection were explained.

The final chambers were tested with heavily filtered X-rays and radium gamma rays and showed a constant response per milliroentgen exposure within about 20% from 20 Kev to 700 Kev. They were tested with beta rays from radioactive water solutions having effectively infinite thickness. The electrons striking the chamber had average energies from 52 to 694 Kev. Exposures were made over a 2π solid angle in a paraboloidal cavity produced by rotating the cup of solution at 200 rpm about a vertical axis. The device showed an approximately constant response to beta rays of $50 \pm 13\%$ over the whole energy range when compared to the dose to the basal layer of the epidermis.

It was concluded that, subject to pending field tests, the chamber design was satisfactory for routine personnel monitoring of beta and gamma radiations.

APPENDIX I. SAMPLE CALIBRATION DATA AND CALCULATIONS

A. Typical X-Ray and Radium Calibration

TABLE III. DATA ON CHAMBERS OF FIGURE 11.

Applied X-Ray Voltage	Effective Energy*	Exposure Time	Standard Air Chamber **	Victoreen Condenser R-Meter	Chamber Readings			
					1	2	3	4
KVCP	Kev	Seconds	Volts	mr	mr	mr	mr	mr
30	23	30	1.198	172	160	158	149	195
50	37	45	0.570	138	170	155	151	162
		45	0.583	141	172	154	160	185
76	50	45	0.623	157	200	197	195	220
		30	0.632	107	146	146	140	161
100	70	30	0.762	126	156	155	157	171
		30	0.763	126	164	168	167	183
150	116	30	0.827	141	145	150	153	171
		30	0.831	141	151	155	158	178

Continued

* Filters used and data on X-ray beams are given in Villforth, et al., ORNL-2529 (1958) p. 47, except at 76 KVCP. Filters at 76 KVCP were 836 mg/cm^2 Cu, and 216 mg/cm^2 Al. Distance from X-ray target to center of dosimeters and standard air chamber entrance diaphragm was 71 cm.

** Standard air chamber: applied voltage, 497 volts; input resistor, R = 8.77×10^{10} ohms. Drop in input resistor balanced against Rubicon Potentiometer Serial No. 58835; diaphragm diameter, d = 9/16" = 1.429 cm; plate spacing 10.0 cm.

Victoreen Condenser R-Meter model 70 serial no. 2913, 0.25 r chamber. Dosimeter Chambers (see table next page). Dosimeters read on Victoreen Minometer serial no. 287-1754.

TABLE III. DATA ON CHAMBERS OF FIGURE 11 (Continued).

Applied X-Ray Voltage	Effective Energy*	Exposure Time	Standard Air Chamber **	Victoreen Condenser R-Meter	Chamber Readings			
					1	2	3	4
KVCP	Kev	Seconds	Volts	mr	mr	mr	mr	mr
200	159	30	1.299	203	197	202	208	230
		24	1.420	177	175	180	185	210
250	200	24	1.290	163	160	161	167	195
		24	1.285	163	160	162	166	190
Radium	700	83	89 mr***	88****	82	85	82	101
		88	94.3 mr***	95****	88	82	82	108
		88	94.3 mr***	93****	80	88	82	105

* Explained on previous page.

** Explained on previous page.

*** Dose calculated from source strength, shielding, and distance.

**** Victoreen Pocket Chamber Model 362.

Dosimeter Chambers

No. 1, Nylon cap 50% open top and sides conducting paper liner 8.05 mg/cm^2;

No. 2, Nylon cap like No. 1, mylar liner coated with Aquadag 3.75 mg/cm^2;

No. 3, Mylar like No. 2, no cap;

No. 4, Paper like No. 1, no cap. Paper bulged, making volume too large, hence giving high readings.

B. Sample Calculations

1. Standard Air Chamber

Calculation of X-Ray Exposure

$$D[mr] = \frac{v[volts]\ t[sec]\ 3 \times 10^{9}[esu/coul]\ 10^{3}[mr/r]}{R[ohms]\ \frac{\pi}{4}\ d^{2}[cm^{2}]\ h[cm]} \frac{760}{p} \frac{(T + 273)}{(273)}$$

$$D = \frac{vt\ (3 \times 10^{9})\ 10^{3}\ (760)(25.1 + 273)}{(8.77 \times 10^{10})\ \frac{\pi}{4}\ (1.429)^{2}\ (5.00)(736.7)\ 273}$$

$$D = 173 \text{ mr}$$

2. Victoreen Condenser R-Meter or Pocket Chamber

Temperature and Pressure Correction to STP.

The readings on the Condenser R-Meter are stated by the manufacturer to be correct at 760 mm, 22° C. It is assumed that the same is true for the Minometer.

$$D = D_{o}\ \frac{760}{p}\ \frac{(T + 273)}{(295)}$$

$$D = 172\ \frac{760}{736.7}\ \frac{(25.1 + 273)}{(295)}$$

$$D = 179 \text{ mr.}$$

3. Dosimeters

The measured capacitances were too small for correct sensitivity on the Minometer. The correction is therefore the product of the temperature-pressure factor, assuming the scale is correct at 760 mm, 22° C, and the total capacitance ratio. The Minometer scale was assumed to be correct for a total capacitance of 9.4 μμf.

$$D = D_o \frac{760}{p} \left[\frac{(T + 273)}{(295)} \right] \frac{C + c}{9.4} .$$

For example, for Number 1:

$$D = D_o \frac{760}{736.7} \left[\frac{(25.1 + 273)}{(295)} \right] \frac{3.95 + 4.90}{9.4}$$

$$D = \alpha D_o = 0.95 \ (160) = 152 \text{ mr.}$$

TABLE IV. CAPACITANCE AND STP CORRECTIONS FOR DOSIMETERS USED IN X-RAY CALIBRATION

Dosimeter	C μμf	$\frac{C + c}{9.4}$	α
Number 1	3.39	0.91	0.95
Number 2	3.65	0.94	0.98
Number 3	3.39	0.91	0.95
Number 4	3.74	0.95	0.99*

* No correction made for excessive volume.

4. Radium Source Calibration and Dose Rate

Source in Health Physics Calibrations Building No. 2007; Source Number E-862 calibrated at National Bureau of Standards, 1950, certificate number 31046, source contained in 1 mm monel when calibrated. Later 1/8 inch aluminum holder added. Certified as 99.2 mg Ra equivalent plus 3.5% for monel shielding = 102.8 mg Ra. Deduct 4% for aluminum shielding in using formula below[52], i.e., k = 0.96

$$D[mr] = \frac{0.88 \times 10^4 \, Mkt}{60 \, d^2}$$

M = mg Ra equivalent,

d = source to detector distance = 15 cm,

t = time in minutes,

$$D = \frac{0.88 \times 10^4 \, (102.8) \, 0.96 \, t}{(15)^2 \, 60} \, ,$$

$$D = 64.3 \, t[mr].$$

5. Dose Rate in a Cavity in a Water Solution of a Beta-Ray Emitter

A complete derivation of the expected dose rate in an air cavity in a water solution of a beta-emitting isotope is given in Hubbell,

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[52] Davis, D. M., Gupton, E. D., and Hart, J. C., ORNL-332, First Revision, p. 130 (January 1, 1954).

et al.[53] If there are Q_m microcuries of radioactivity per gram of solution, the dose rate in water D_w, in ev/gm-sec, is

$$D_w = 3.7 \times 10^4 \, Q_m \, bT_o \times 10^6$$

where b is the ratio of the average energy of thin source spectrum $\overline{T}$, in Mev, to the maximum energy T_o, in Mev.

The dose in an air cavity, D_a, may then be calculated, using the Bragg-Gray principle that energy deposited per gram of air in a small cavity in an irradiated medium is equal to the energy deposited per gram in the medium, multiplied by the ratio of the stopping power per gram of air to that per gram of medium, as

$$D_a = 3.7 \times 10^{10} \, Q_m \, bT_o \, \frac{\rho_a}{\rho_w B_w} \quad .$$

B_w, the average ratio of mass stopping power of the medium to that of air may be taken as 1.02, ρ_a as 0.001293 gm/cm^3 and ρ_w as 1.00 gm/cm^3. The dose rate in the cavity may be expressed in air cavity milliroentgen equivalents per hour as

$$D_a' = 3.7 \times 10^{10} \, Q_m \, bT_o \, \frac{\rho_a}{\rho_w B_w} \, \frac{e}{w} \, (3600)$$

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[53] Hubbell, Johnson, and Birkhoff, op. cit. ORNL-2158.

where e is the electronic charge, 4.80×10^{-10} esu, and W is the average number of electron volts expended in producing an ion pair in air, 34.1 ev.

Hence for 2π geometry

$$D_a'' = 1.19 \times 10^3 \, Q_m \, bT_o \quad .$$

C. TABLE V. RESULTS FROM TYPICAL X-RAY DATA

Effective Energy	Average Percent of Standard Air Chamber					Average Percent of Victoreen Condenser R-Meter			
		Wrist Dosimeter				Wrist Dosimeter			
Kev	Victoreen Condenser R-Meter	# 1	# 2	# 3	# 4	# 1	# 2	# 3	# 4
23	103	88	90	82	112	85	87	79	108
37	117	130	122	119	137	112	105	101	117
50	122	147	150	141	168	120	123	116	137
70	119	139	144	140	159	116	121	117	133
116	123	117	125	123	145	95	101	101	117
159	118	105	111	111	131	89	94	94	109
201	115	103	107	107	128	89	93	93	112
700	103*	86**	90**	85**	112**	83†	87†	81†	108†

* Pocket chamber reading.

** Percent of calculated dose.

† Percent of pocket chamber.

D. TABLE VI. P^{32} FIRST SAMPLE, Data Taken May 17, 1958

Chamber Number	Exposure Time		Reading	Corrected Dose[55]	Calculated Dose	Corr. D / Calc. D
	Start	End	mr	mr	mr	Per Cent
1	1550	1600	110	104	272	38
	1620	1630	110	104	272	
2	1600	1610	235[54]	222	272	82
	1612	1618	144	139	163	
	1647	1653	140	132	163	
3	1700	1710	139	137	272	48
	1735	1745	131	129	272	
4	1710	1718	180	177	217	86
	1724	1730	150	148	163	

Corrected Barometer, 739 mm; thermometer 24° C; correction factor to 760 mm, 22° C = 1.038.

Chamber No. 1, liner of photo paper, nylon cap with holes like Figure 16;
Chamber No. 2, photo paper liner, no cap;
Chamber No. 3, liner of mylar with Aquadag, nylon cap with holes like Figure 16;
Chamber No. 4, liner of mylar with Aquadag, no cap.

[54] Estimated. More than full scale.

[55] Corrected to 760 mm, 22° C, for capacitance corrections see next page.

E. Corrections

1. Wall Thickness Correction

No material was readily available having 7 mg/cm^2 superficial density. Test dosimeters were made with liners of the following materials, and the expected response for a dosimeter with 7 mg/cm^2 walls was calculated by linear interpolation. Mylar (coated with colloidal graphite "Aquadag") 3.75 mg/cm^2; black photographic wrapping paper, 8.05 mg/cm^2; Condulon (vinyl chloride), 9.20 mg/cm^2 (not used with all sources).

A sample calculation of the correction of data to a 7 mg/cm^2 wall thickness is given below:

Nylon cap, mylar wall 3.75 mg/cm^2 response of Chamber No. 3	48%
Nylon cap, photo paper wall 8.05 mg/cm^2 response of Chamber No. 1	38%
	10%

$$\frac{8.05 - 7}{8.05 - 3.75} (10\%) = 2\%$$

Interpolated response of 7 mg/cm^2 $\quad 38 + 2 = 40\%$.

2. Capacitance Correction for Dosimeters Used in Beta-Ray Calibration

These are not the same chambers used in the X-Ray data of Part A.

TABLE VII. CAPACITANCE CORRECTIONS FOR DOSIMETERS USED IN BETA-RAY CALIBRATION

Number	Capacitance μμf	Correction Factor
1	3.7	0.91
2	3.7	0.91
3	4.0	0.95
4	4.05	0.95

3. Decay Factor

If the dose rate at arbitrary zero time is $(D_a')_o$, then the dose rate at some later time t is given by

$$D_a' = (D_a')_o \, e^{-0.693t/T_{\frac{1}{2}}}$$

where $T_{\frac{1}{2}}$ is half life and t is time since zero in the same units. For the first sample of P^{32}, Q_m = 2.0 μc/ml at 0800 hr May 17, 1958, T = 14.3 d, bT_o = 0.695 Mev. Exposures were made from 1530 to 1745 on May 17th, or t = 0.33 d.

$$D_a' = 1.19 \times 10^3 \ (2.0)(0.695)e^{-0.693(0.33)/14.3}$$

$$D_a' = 1630 \text{ mr/hr} \quad .$$

APPENDIX II. SUMMARY OF CALIBRATION RESULTS

A. TABLE VIII. X-RAY CALIBRATION

Effective X-Ray Energy	M = Normalized Relative Response in Per Cent[56]							
	Wrist Dosimeter with No Holes in Cap Colloidal Graphite Coating Inside Cap						Victoreen Condenser R-Meter	Victoreen Pocket Chamber (F. H. Day[57])
	Bare Al	Al	Fluorothene C_2ClF_3	Nylon	Polyethylene C_2H_4	Teflon C_2F_4		
23	169	79	49	81	81	74	96	83
37	331	213	159	102	107	139	108	139
50	351	290	230	123	127	148	108	158
70	297	262	223	119	122	144	115	139
116	161	160	147	112	115	124	110	123
159	110	111	116	101	103	102	101	107
200	100	100	100	100	100	100	100	100

[56] Values of M in the table were computed as follows:

$$M_i = \frac{D}{D_s} \cdot \frac{d}{d_s} \cdot \frac{S_i}{S} \times 100$$

where D is the dose measured by the standard free air chamber for the given X-ray energy, corrected to STP;

D_s is the dose measured by the standard free air chamber for 200 Kev effective X-rays, corrected to STP;

d is the dose observed with the given dosimeter for the given X-ray energy;

d_s is the dose observed with the given dosimeter for 200 Kev effective X rays;

S_i is the sensitivity of the given dosimeter-Minometer combination, as defined by equation (8);

and S is the sensitivity of the Victoreen-Minometer combination.

[57] Day, F. H., "X-Ray Calibration of Radiation Survey Meters, Pocket Chambers and Dosimeters," National Bureau of Standards Circular 507 (1951).

B. TABLE IX. DOSIMETER SATURATION TESTS

Charging Volts	% of Saturation[58]				
	Fluorothene	Nylon	Polyethylene	Teflon	Average
50	81	88	81	91	85
60	83	91	87	93	89
70	92	92	92	96	93
80	94	94	91	95	93.5
90	94	93	93	96	94
100	98	99	97	95	97
120	100	100	100	100	100
140	100	100	100	---	100
157	100	---	100	100	100

[58] Doses also read with Condenser R-Meter and Standard Frèe-Air Chamber. Dosimeter readings corrected to unit dose and normalized to 100% at saturation level, usually 157 volts. The differences between the results with the various cap materials are probably not significant.

C. TABLE X. DOSIMETER RESPONSES TO BETA RAYS EXPRESSED AS PERCENTAGES OF VARIOUS REFERENCE VALUES

Isotope	Average Electron Energy in Water Kev[59]	Response in Per Cent[60]		
		Paper Wall Chamber D_P/D_c	Wrist Dosimeter	
			D_w/D_c	D_w/D_P
S^{35}	52	10.5	4	38
Ca^{45}	79	33	14	42
W^{185}	130	60	25	42
Tl^{204}	237	78	32	41
Ag^{111}	317	89	39	44
P^{32}	506	89	46	52
Y^{90}	694	89	56	63

[59] See Table II.

[60] D_P = Measured dose in paper wall chamber, corrected to 7 mg/cm^2 wall, to STP, and to design sensitivity of system, S.
D_c = Dose in air cavity in solution, calculated from assay of solution, as explained in section B-5 of Appendix I.
D_w = Measured dose in wrist dosimeter, corrected in the same manner as D_P.

APPENDIX III. DESIGN OF THE BETA-IRRADIATION FACILITY

Beta calibrations of survey and personnel monitoring devices present several difficulties. Either a "point" or a plane source of sufficiently high activity for calibration purposes is of such a thickness that it does not emit an undistorted thin source spectrum due to self-absorption within the source. The limited range[61] of betas in air, 12.5 cm at 100 Kev beta energy and 3.81 meter at 1 Mev, and the approximate nature of the coefficients of absorption of air for beta rays, also serve to make calibration in air unsatisfactory.

These calibration problems were partially solved[62] by the use of a very thin-walled cavity in a homogeneous water solution of a beta-emitting isotope. The use of this thin-walled cavity was not entirely satisfactory since the wall acted as a beta absorber and since some of the beta activity tended to plate out of solution onto the wall surface.

In order to eliminate these wall effects, the wrist dosimeter was irradiated at 2π geometry by inverting it over a paraboloidal cavity formed in the open water surface of the beta-emitting isotope. The cavity was formed by rotating the plastic cup container[63]. The shape of the parabolic surface can be shown by elementary methods to be a function of rotational velocity. As illustrated in Figure 19, if

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[61] Spencer, L. V., Phys. Rev. 98, 1597 (1955).

[62] Hubbell, Johnson, and Birkhoff, op. cit.

[63] Hurst, W. M., ORNL-1155 (Feb. 26, 1952).

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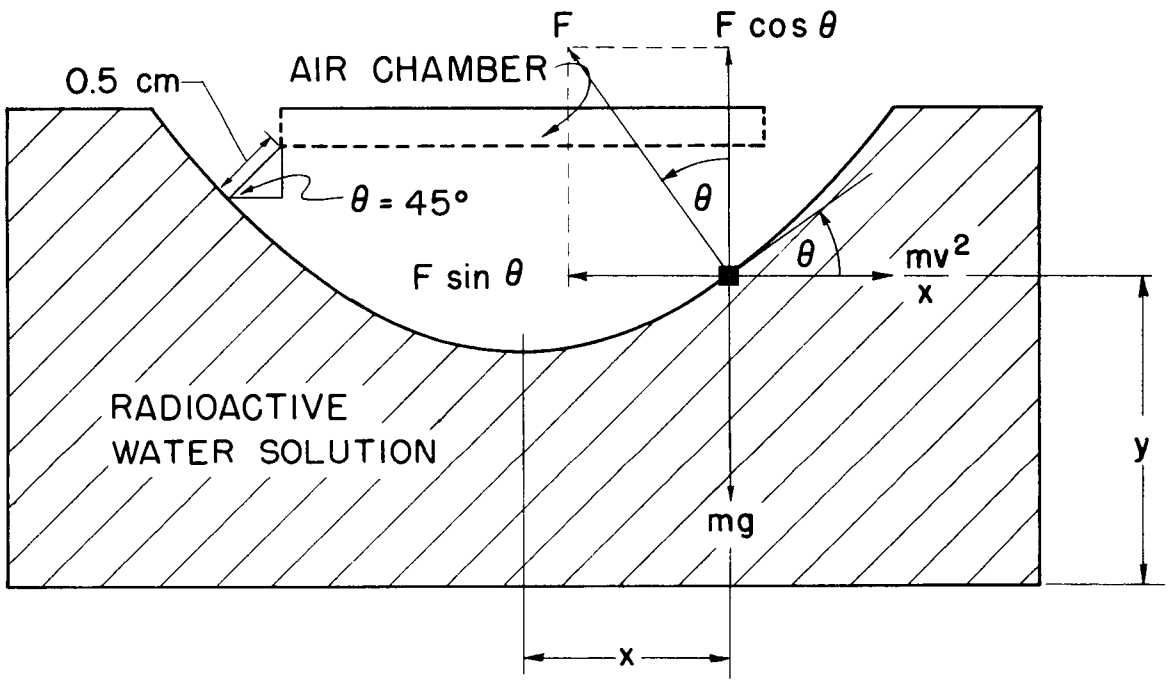

Fig. 19. Sketch of Rotating Solution Geometry.

$\mathbf{F}$ = force on an element of volume at the surface,

f = frequency of revolution,

g = acceleration due to gravity,

m = mass of an element of volume,

v = tangential velocity of a surface volume element,

θ = angle between tangent to surface and horizontal,

ω = rotational velocity,

then for any element of volume at the surface, the force due to hydrostatic pressure must be normal to the surface so that

$$F \cos \theta = mg \qquad (a)$$

and

$$F \sin \theta = \frac{mv^2}{x} \quad . \qquad (b)$$

These may be combined to give

$$\tan \theta = \frac{v^2}{gx} \qquad (c)$$

and substituting $\tan \theta = dy/dx$ and $v = \omega x$, the differential equation describing the surface is

$$\frac{dy}{dx} = \frac{\omega^2}{g} x \quad . \qquad (d)$$

This may be integrated to give

$$y = \frac{\omega^2}{2g} \quad x^2 + C \quad . \qquad (e)$$

As an initial boundary condition, the minimum thickness of the water solution at x = 0 was required to be equal to or greater than the maximum beta range in the solution, about 1.3 cm. If at x = 0, y = 1.3, then C = 1.3 cm.

Since each cm of air path between the surface and the dosimeter is equal to an absorber of 1.293 mg/cm^2 (at STP), it is desirable that the distance between the surface and the dosimeter be held to a minimum. It was therefore required that the angle of the tangent at the point on the surface closest to the dosimeter be equal to 45°. A perpendicular distance of 0.5 cm was allowed at the edge of the dosimeter, as shown in Figure 19. This point on the surface closest to the dosimeter was determined to be an abscissa distance equal to 1.6 cm, the radius of the dosimeter, plus (0.5 cm)(sin 45°), or x ≈ 1.95 cm. If this value of x and dy/dx = 1 are substituted in equation (d), then ω = 22.4 radians/sec, and equation (e) becomes

$$y = .257 \quad x^2 + 1.30 \quad . \qquad (f)$$

However,

$$\omega = 2\pi f \quad . \tag{g}$$

So f, for the above conditions, is 3.57 rev/sec or 214 r.p.m.

Since a constant speed motor of 200 r.p.m. was readily available, a calculation for 200 r.p.m. was made. Substituting in equation (e)

$$y = .2236 \ x^2 + 1.30 \quad . \tag{h}$$

In order to limit the exposure to a 2π solid angle geometry, the plastic container was provided with a top lip, the lower surface of which was even with the base of the dosimeter. This also provided a uniform tissue equivalent backscatter at the elevation of the plastic dosimeter base. The device is shown in cross section in Figure 20.

The volume of solution under the desired surface was calculated for the irradiation chamber of radius R = 4 cm and height H = 3 cm. The radius x_1 at which the parabolic surface intersects the plastic lip, at which point y_1 = H = 3 cm, was determined from equation (h) to be 2.76 cm. The volume under the parabolic surface, V, between x_o = 0 and x_1 = 2.76 cm may be found by integration. If a washer-like element of volume, dV, is

$$dV = 2\pi \, xy \, dx \quad , \tag{i}$$

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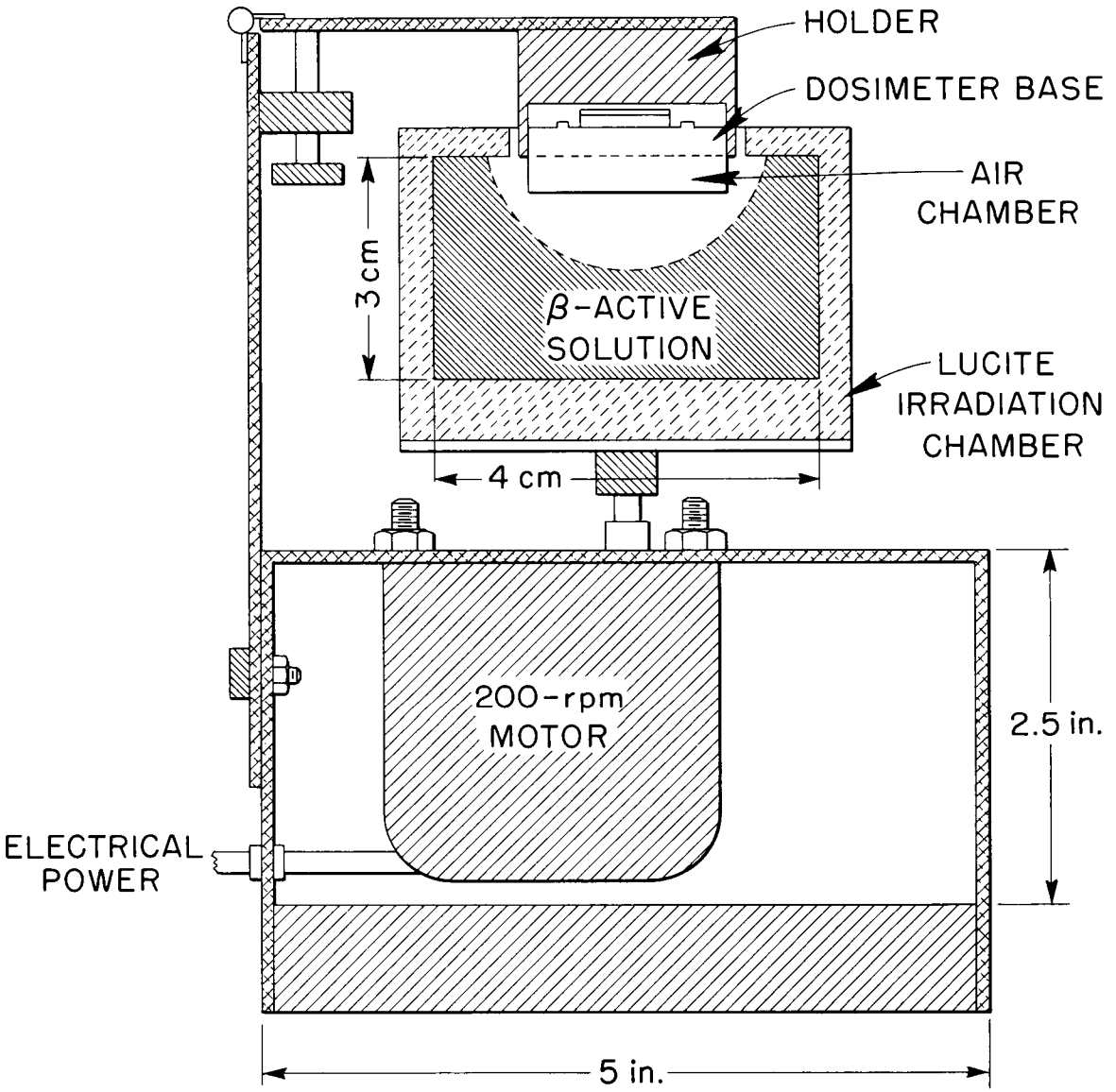

Fig. 20. Beta-Ray Exposure Device.

and, substituting equation (h) for y

$$V_1 = 2\pi \int_0^{2.76} (0.2236\ x^3 + 1.30\ x)\ dx = 51.5\ cm^3 \ . \quad (j)$$

The annular volume V_2 between $x_1 = 2.76$ cm and $x_2 = R = 4$ cm is simply

$$V_2 = \pi(x_2^2 - x_1^2)(H) = 78.8\ cm^3 \ , \quad (k)$$

and the total solution volume V_T is

$$V_T = V_1 + V_2 = 130.3\ cm^3 \ . \quad (m)$$

A run using 130.3 cm^3 of non-radioactive water was made to compare the observed surface with that expected from the calculations. Measurements were made with the facility in rotation by lowering a pointed probe from a known reference level until it intersected the surface, causing a readily detected ripple. These are plotted with the calculated surface, on Figure 21.

At no time during the several hundred observations made for beta calibration was a dosimeter accidentally contaminated by the solution despite the small air gap between the dosimeter and the surface.

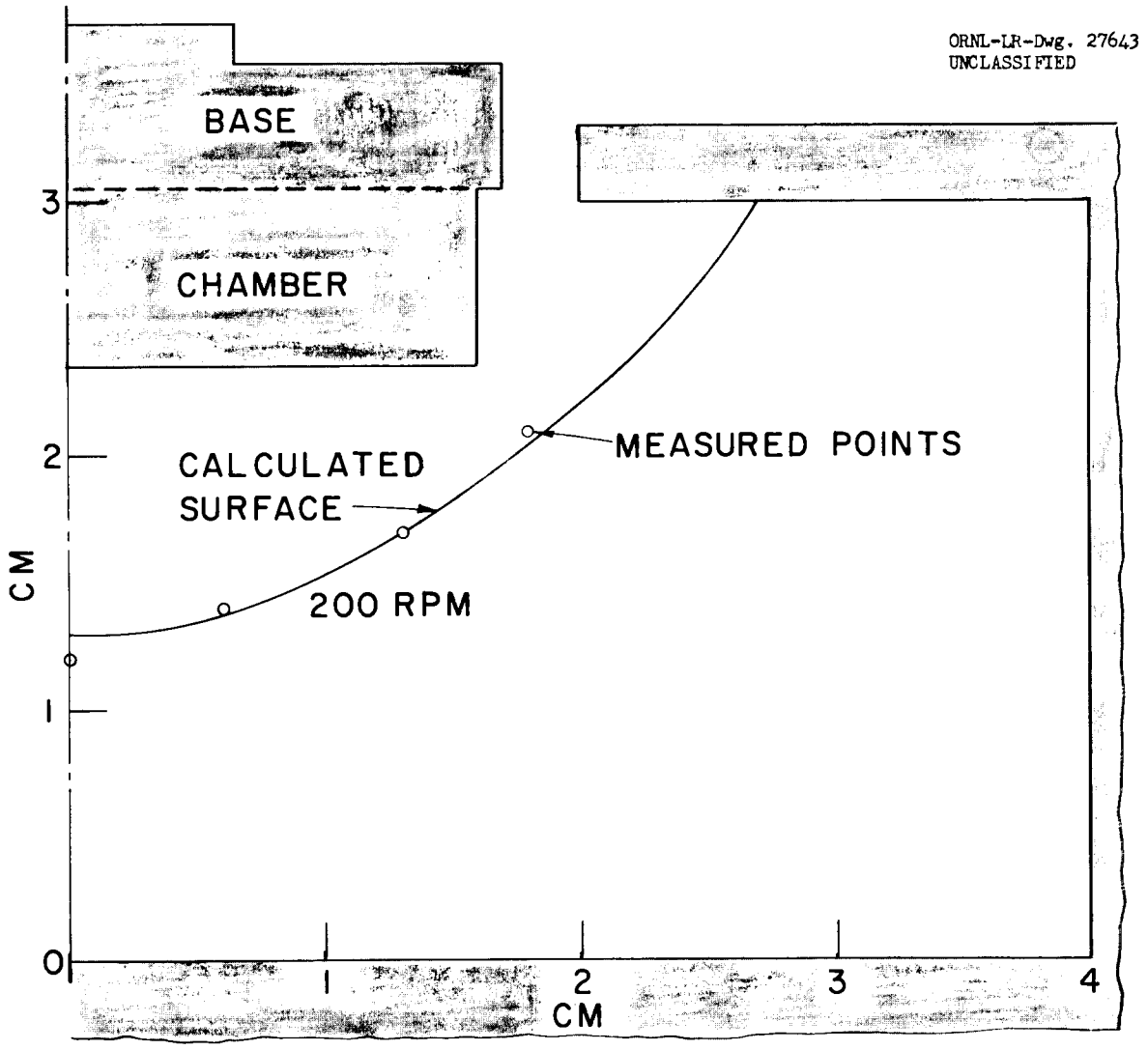

Fig. 21. Solution Level in Beta-Ray Exposure Device.

APPENDIX IV.

ANGULAR RESPONSE OF A PARTIALLY-SHIELDED CYLINDRICAL DOSIMETER

Many cylindrical dosimeters have very thin walls and are partially shielded by a reinforcing structure[64]. If the tops and sides of the dosimeter are unequally shielded, the response of the dosimeter will depend upon the angle between the plane of the cylinder base and the direction of the incident radiation. For instance, a cylinder with unshielded top and opaque sides will admit all radiation incident perpendicular to the plane of the base, but none incident parallel to the base. If the fraction of the volume irradiated through the top and the fraction irradiated through the sides are known separately as functions of the angle of incidence, the total irradiated volume of a shielded dosimeter and hence its response may be determined as a function of the angle of incidence of the radiation. These fractions are derived below.

In the diagram, Figure 22, θ is the angle between the direction of the incident radiation and the plane of the base of the cylinder, and ϕ is an angle in the plane of the base between a radius parallel to the plane containing the incident radiation and a radius drawn to the point on the circumference where the radiation intersects the base. If p is the radius, a plane at a distance $x = p \sin \theta$ from the axis of the cylinder and parallel to the reference direction forms the base of an

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[64] Happer, W., and Birkhoff, R. D., op. cit.

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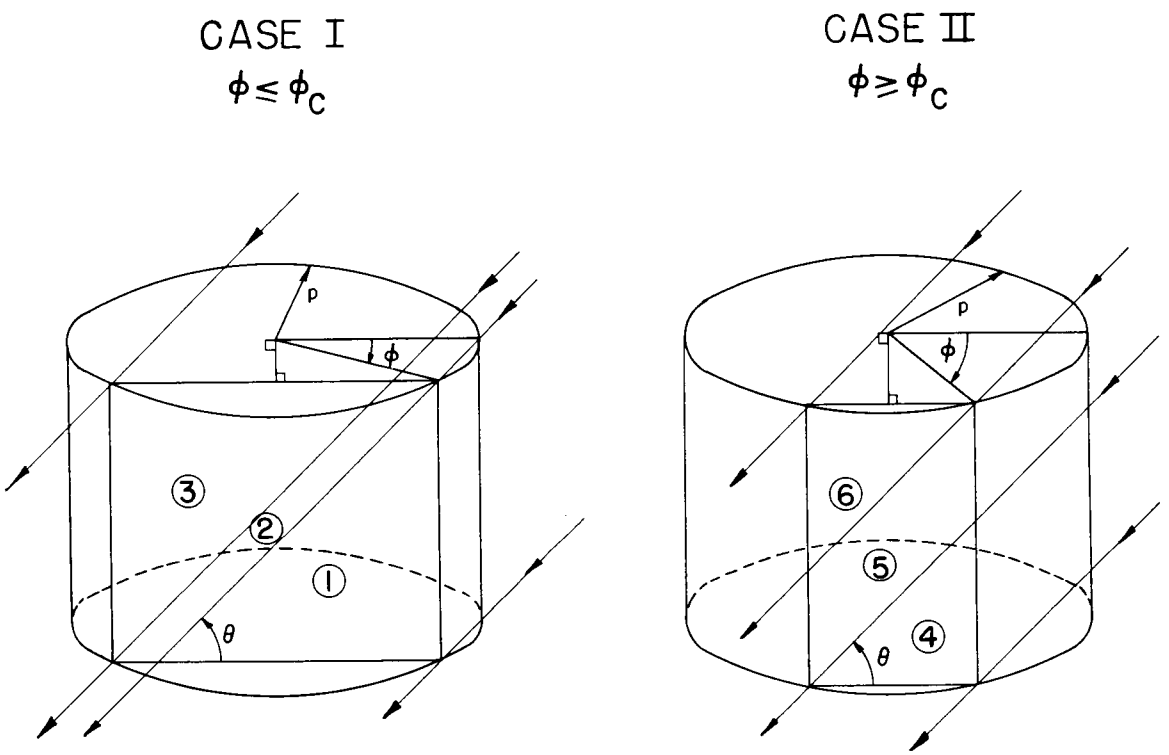

Fig. 22. Geometry of a Cylindrical Ionization Chamber for Radiation Incident at an Angle θ to the Base.

infinitesimal rectangular volume element. It is convenient to consider two cases.

Case I

$$\cos \phi \geq \cos \phi_c = \frac{h}{2p \tan \theta}$$

or $$\phi \leq \phi_c \quad .$$

Case II

$$\cos \phi \leq \cos \phi_c$$

or $$\phi \geq \phi_c \quad .$$

These two cases are illustrated in Figure 21. The infinitesimal rectangular volume elements have been divided into three regions in both cases. In Case I it is obvious that region (1) will be irradiated through the side while regions (2) and (3) will be irradiated through the top. Similarly in Case II regions (4) and (5) will be irradiated through the side, while region (6) will be irradiated through the top.

In Case I the infinitesimal volume element of region (1) is

$$dV_1 = \frac{h^2 p \cos \phi d\phi}{2 \tan \theta} \qquad (a)$$

where h is the height of the cylinder. The volume element of region (2) is

$$dV_2 = \left[2p \cos \phi - \frac{h}{\tan \theta} \right] hp \cos \phi d\phi \qquad (b)$$

and the volume element of region (3) is

$$dV_3 = dV_1 \ . \qquad (c)$$

In Case II the volume element of region (4) is

$$dV_4 = 2p^3 \tan \theta \cos^3 \phi d\phi . \qquad (d)$$

The volume element of region (5) is

$$dV_5 = 2p^2 \cos^2 \phi d\phi \left[h - 2p \cos \phi \tan \theta \right] , \qquad (e)$$

and the volume element of region (6) is

$$dV_6 = dV_4 \ . \qquad (f)$$

Now the volume irradiated through the top will be

$$V_{top} = 2 \int_{o}^{\phi_c} (dV_2 + dV_3) + 2 \int_{\phi_c}^{\pi/2} dV_6 \quad , \tag{g}$$

and that through the side will be

$$V_{side} = 2 \int_{o}^{\phi_c} dV_1 + 2 \int_{\phi_c}^{\pi/2} (dV_4 + dV_5) \quad . \tag{h}$$

The solutions of these integrals are

$$\frac{V_{top}}{\pi p^2 h} = \frac{2\phi_c}{\pi} + \frac{\sin 2\phi_c}{\pi} - (h/p) \frac{\sin\phi_c}{\pi \tan\theta} + \frac{4 \tan\theta}{\pi(h/p)}$$

$$\left[\frac{2}{3} - \sin \phi_c + \frac{\sin^3 \phi_c}{3} \right] \tag{i}$$

and

$$\frac{V_{side}}{\pi p^2 h} = 1 - \frac{V_{top}}{\pi p^2 h} \tag{j}$$

where

$$\phi_c = \cos^{-1} \frac{(h/p)}{2\tan\theta} \quad . \tag{k}$$

Note the dependence of the fractional irradiated volumes on the parameter (h/p), the "tallness" of the cylinder. The functions

$$\frac{V_{top}\,[\theta,\ (h/p)]}{\pi p^2 h} \qquad \text{and} \qquad \frac{V_{side}\,[\theta,\ (h/p)]}{\pi p^2 h} \qquad (m)$$

have been plotted in Figure 23 for several values of the parameter (h/p) including h/p = 0.521, which applies to a beta dosimeter of this report. The two curves for any value of (h/p) represent respectively the fraction of the volume which received radiation through the top of the cylinder for an angle of incidence θ, and the fraction which received radiation through the side. The sum of the two ordinates at any θ must be unity.

If A_{top} is the unshielded area of the top and S_{side} is the unshielded area of the side, then the irradiated volume $V_{eff}(\theta)$ at an angle of incidence θ is

$$V_{eff}(\theta) = \frac{A_{top}}{\pi p^2} \cdot V_{top}(\theta) + \frac{A_{side}}{2\pi ph} \cdot V_{side}(\theta) . \qquad (n)$$

Two assumptions must be made to use $V_{eff}(\theta)$ to determine the percentage of the radiation incident which is recorded in the cylindrical chamber: first, the "shielding" cover must contain a large number of holes whose dimensions are small compared to those of the cylinder; and second, the diameter of the holes must be large compared to the thick-

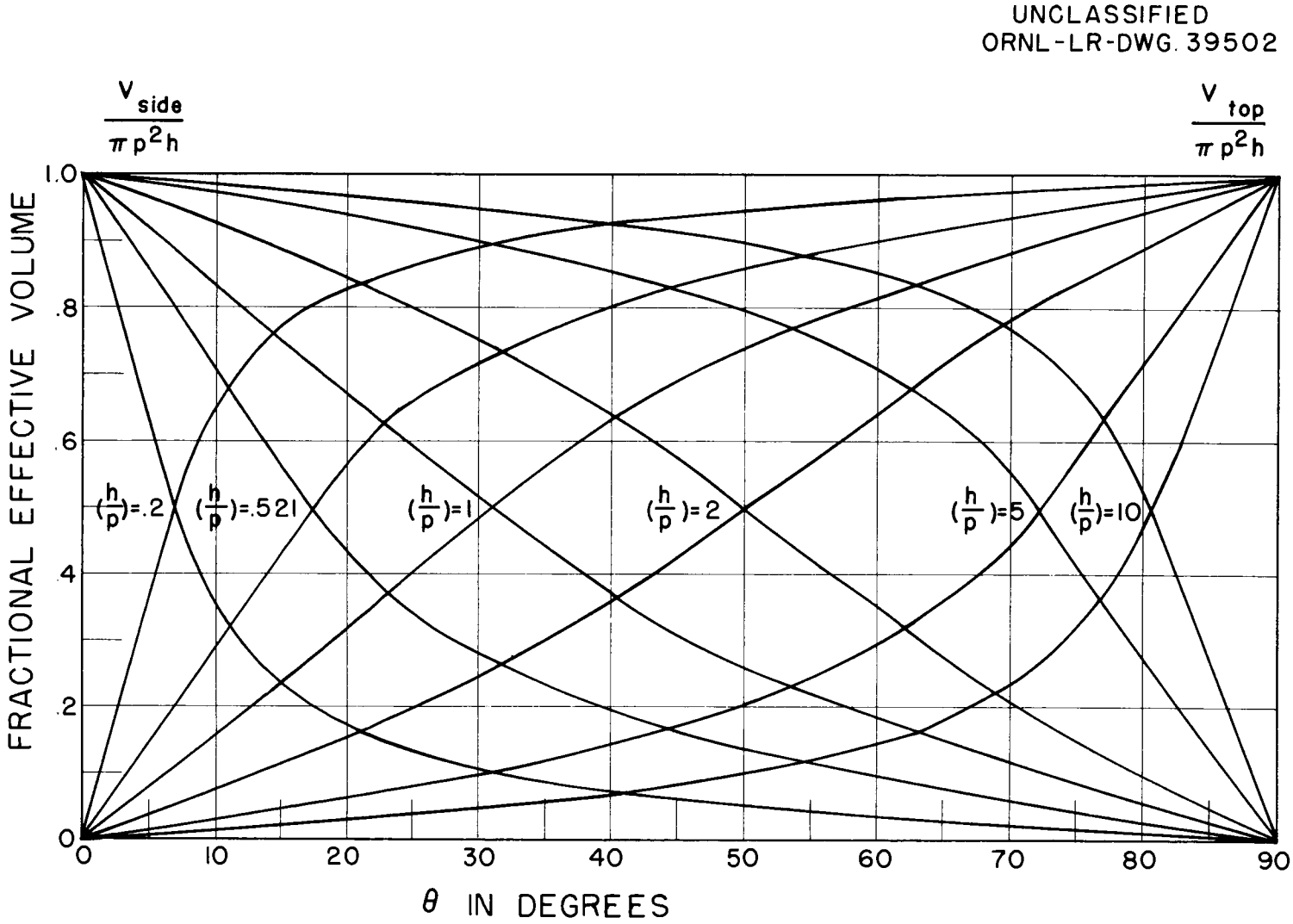

Fig. 23. Fractions of the Volume of a Cylindrical Ionization Chamber Receiving Radiation Through the Sides and Top.

ness of the cover. These requirements are necessary in order that the transmission through any one hole vary at the same rate as the projection of its area on a plane perpendicular to the direction of incidence. This projection was used in deriving the formula for $V_{eff}(\theta)$. With these restrictions, the curves offer a convenient method of finding the angular dependence of the response of a cylindrical chamber.

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