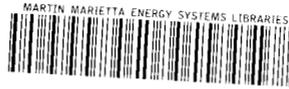


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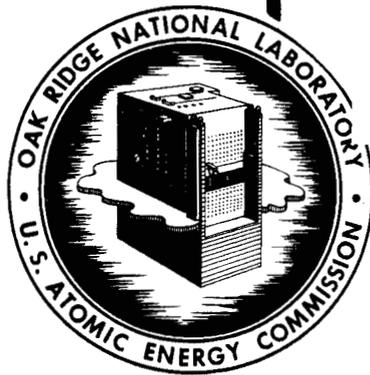
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A THIMBLE TYPE GAMMA-RAY DOSIMETER AND  
THE MEASUREMENT OF THE RADIATION FROM  
LUMPED AND DISTRIBUTED TYPE SOURCES

EDGAR B., DARDEN, Jr. and C. W. SHEPPARD

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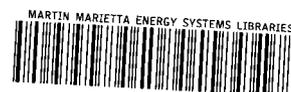
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## FOREWORD

The following material is the result of a  $\gamma$ -ray standardization program intermittently conducted in the Biology Division of Oak Ridge National Laboratory during the past 3 years. At first it was thought that little original information would be forthcoming from the completion of radiation measurements which follow closely the familiar techniques and principles already familiar to radiological physicists. As the work progressed many important points were discovered which are not readily found in the literature, and which are of sufficient interest to warrant their presentation at this time. We wish to acknowledge the assistance of several people who made a material contribution to the work. Mr. R. E. Zedler of the Instrument Department contributed most of the basic mechanical and electrical design features of the thimble chamber. Mr. Roland K. Abele obtained a portion of the data in the course of other studies.

A THIMBLE TYPE GAMMA-RAY DOSIMETER AND THE MEASUREMENT OF  
THE RADIATION FROM LUMPED AND DISTRIBUTED TYPE SOURCES

Edgar B. Darden, Jr. and C. W. Sheppard

Accurate physical measurements in radiation dosimetry are becoming increasingly important with the growing quantitative accuracy of techniques for studying radiation effects on living organisms. For  $\beta$ -ray work a precise method for the determination of surface ionization intensities of sources has been developed (17), so that with relatively simple apparatus accurately known doses may be administered to biological material in the form of a thin plane layer. In X-ray work up to 250 kvp, dosimetry studies (18) have been carried out in this laboratory including calibrations of Victoreen condenser-type meters against a standard free-air chamber. Based on these calibrations a standard position was established inside the lead enclosure around a medium intensity  $\text{Co}^{60}$  source for periodically checking the various laboratory Victoreen chambers.

For determining dose due to  $\gamma$  radiation, the Victoreen method cannot be relied upon since these chambers are normally calibrated only up to 200 or 250 kvp. Since long-lived  $\gamma$ -ray sources do not require daily calibrations, the ruggedness of a routine instrument is less important. The standard parallel-plate or free-air type of ionization chamber with which X-ray calibrations of  $\pm 1$  per cent accuracy may be obtained can be employed for air dose measurements of  $\gamma$  radiation but is required to be of impractically large dimensions (10). To avoid this difficulty small thimble ionization chambers have been developed to serve as standard as well as practical

$\gamma$ -ray dosimeters. By means of the Bragg-Gray cavity principle the electromagnetic energy absorbed in the walls and dissipated as ionization in the gas inside the chamber may be quantitatively related to the energy absorbed in surrounding tissue or tissue-like material. The intensity of the dose in roentgens per second may be calculated from a knowledge of the ion current and the volume of the cavity with suitable corrections for attenuation and other wall effects.

In this report a thimble chamber of this type is described in some detail beginning with a brief review of the physical principles underlying absorption and ionization, particularly in light-weight media. The cavity principle is discussed with practical application to the design and function of the chamber. An exploded view drawing of the chamber assembly is appended to clarify constructional details. A brief discussion is included of the principal factors affecting the practical performance of the chamber in collecting ions. The report is concluded with a resumé of the work that has been carried out in the Biology Division with  $\gamma$ -ray thimble chambers including calibration tests, Sievert dose determinations, experiments on the effects of backscatter, and the use of the chamber for determining the intensities of dose given to biological material exposed to external sources, and also inside certain distributed type sources of  $\gamma$  radiation.

Energy Absorption in an Irradiated Medium.—Before considering specific details about the use of  $\gamma$ -ray thimble chambers it is well to review briefly some essential principles involved, beginning with the mechanism of absorption of nuclear radiations in matter. A thorough treatment of this subject is given by Heitler (9). Somewhat more elementary presentations can be found

in texts of nuclear physics such as Cork (2). General discussions of the elementary radiobiological aspects of energy absorption are to be found in texts by Robertson (15a) and Stuhlman (20), while detailed information on specific effects of radiation on biological materials is given in Lea's book (12). Finally Siri (19) is a good reference source of information on both the physical and biological aspects of nuclear radiation and absorption, particularly with regard to the necessary instrumentation.

When nonosseous biological material is irradiated with hard X or  $\gamma$  rays, from 78 to 92 calories are absorbed per gram of tissue per roentgen, depending on the energy of the radiation and the composition of the material (12). Absorption of radiation energy in the material is accomplished by one or more of three fundamental mechanisms: photoelectric absorption, Compton absorption, and electron-pair production. The first two processes are important for biological material; the third can be ignored unless the  $\gamma$  radiation is extremely hard, since the threshold energy required for production of a positive and negative electron pair is 1.02 mev. Pair production even for fairly high energies is not apt to be very important in tissue, since its probability of occurrence is found to decrease with decreasing atomic weight of the medium.

The photoelectric process is responsible for most of the low energy X-ray absorption, particularly in materials of high atomic weight. The process occurs when an orbital electron in an atom of the medium is ejected by an incident photon, so that the atom is left in an ionized state. The energy of the photon is thereby imparted as kinetic energy to the electron according to the Einstein photoelectric equation:

$$h\nu = P + \frac{1}{2}mv^2 \quad \text{Eq. 1}$$

where  $h\nu$  = incident energy of photon of frequency  $\nu$   
 $h$  = Planck's constant ( $6.62 \times 10^{-27}$  erg seconds)  
 $P$  = work function of the material  
 $m$  = mass of electron  
 $v$  = velocity of ejected electron

Since the electron energy  $\frac{1}{2}mv^2$  is usually  $\gg P$ , practically the entire incident energy of the quantum is transferred to the electron. At low energies the most probable direction of photoelectric emission is at right angles to the beam of radiation, but the forward component of velocity tends to increase with increasing energy of the quantum. This is important, for example, in assessing the relative importance of the photoelectric scattering through various angles from any shielding surrounding biological material exposed to X or  $\gamma$  radiation. For  $\gamma$  energies greater than about 0.5 mev, the exact energy depending on the atomic number of the absorbing medium, the absorption coefficient or electronic cross section for the photoelectric process is approximately given by (19)

$$\tau_e = \frac{KZ^4}{E^3} \quad \text{Eq. 2}$$

where  $K$  = proportionality constant  
 $Z$  = atomic no. of absorbing medium  
 $E$  =  $\gamma$ -ray energy

This strong dependence on  $Z$  and  $E$  should be borne in mind when using a thimble chamber to measure  $\gamma$ -ray dose in biological material. The presence of any nearby heavy material, such as lead shielding, may subject the tissue and chamber to photoelectron bombardment and adversely affect the accuracy of the results.

The most important means by which X and  $\gamma$  radiation are absorbed in materials composed of atoms of low atomic weight is Compton electron production. In this process, which is independent of the atomic number of the absorber, a free or loosely bound electron in the medium is acted upon by a primary quantum so that a definite proportion of the primary energy is carried off as kinetic energy by the electron, while the rest appears as a second quantum of longer wave length. By treating each of these entities as particles subject to the classical laws of conservation of energy and momentum, the following expression may be derived:

$$\Delta\lambda = \lambda - \lambda' = \frac{h}{m_0c} (1 - \cos \theta) \quad \text{Eq. 3}$$

where  $\Delta\lambda$  = difference in wave length between the primary and scattered quanta of wave lengths  $\lambda'$  and  $\lambda$  respectively

$\theta$  = angle made by direction of scattered quantum with original direction of photon

$m_0$  = rest mass of electron

$c$  = velocity of light

This gives the relation between wave length and angle of scattering. The probability of scattering through a given angle is given by the Klein-Nishina formula (9). It should be noted that the maximum primary energy is transferred to the electron only in cases of head-on collision. The average Compton or recoil electron energies are always less than that of corresponding photoelectrons for a given energy and composition of medium. For energies above 30 or 40 kev the recoil process overshadows the photoelectric process in elements of low atomic weight and is, therefore, the one of most importance in living tissue and tissue equivalent materials used in the construction of thimble chambers. The relative importance of these two mechanisms of absorption for producing ionization in tissue-like materials was recognized over 25 years ago by Fricke

and Glasser (4) in their development of the first practical thimble chambers for X-ray dosage measurements. They reported that, in water irradiated with 62.5 kev X rays, about 50 per cent of the total electron production was due to recoil electrons, while with rays twice as energetic all the absorption was by this means. According to more recent experiments it appears that the percentage of recoils for the lower energy X ray should be not 50 but at least 90 (12).

Measurement of Radium  $\gamma$  Emission.—Until fairly recently the principal source of  $\gamma$  radiation for medical and biological use has been some form of radium preparation, hence most of the conventional terms used to describe  $\gamma$  rays refer to those emanating from radium in equilibrium with its products. Radium sources were used as standards for most of the dosimetry studies described in this report. It will aid in the understanding of the data to discuss briefly certain of these terms.

For radiological purposes the intensity of  $\gamma$ -ray emission is usually measured in terms of the intensity produced at a given point in the radiation field of a point radium source in accordance with the inverse square law. The unit of intensity is often designated as the intensity-millicurie or Imc. This unit is defined as the intensity of  $\gamma$  radiation at a distance of 1 cm from 1 mg of radium considered as a point source, filtered by 0.5 mm of platinum to remove the corpuscular elements of the radiation. At a distance of  $r$  cm from  $Q$  mg of radium the intensity is therefore  $\frac{Q}{r^2}$ . The integrated dose when 1 Imc is delivered for 1 hour is referred to as a 1 cm-mg-element hour or cmgh, the 0.5 mm platinum filtration understood. This quantity of dose is sometimes referred to as the Sievert dose. No allowance is made for the radiation scattered from the container or the self-absorption of the radium salt, or the absorption

of the primary radiation in the air, since for conventional type radium needles these corrections will be small. To obtain the corresponding intensity for arbitrary values of filter thickness, the following expression (11) may be used where M mg is the weight of the radium filtered by t mm of platinum.

$$r/hr = (8.98 - 1.17 \text{ mm}^{-1} t) M \quad \text{Eq. 4}$$

This gives 8.4 r as the mean value of the cmgh dose based on the results published by a number of individual investigators.

A more appropriate unit for designating source strength for radiobiological purposes is the rhm, an abbreviation for roentgens per hour at 1 meter, since here is represented a definite measure of the effect of the radiation. Thus, 1 mc of radium undergoes  $3.7 \times 10^7 \times 3600$  disintegrations per hour which produce approximately  $8.4 \times 10^{-4}$  rhm in air, so the cmgh dose is equivalent to  $8.4 \times 10^{-4}$  rhm.

Measurement of Energy Absorption.--When radiative energy is absorbed by a medium, it is transformed primarily into atomic and molecular excitation, followed by ultimate degradation into heat. In the case of gases, it is known that about half the energy absorbed in hydrogen, oxygen, and nitrogen is diverted to the formation of ions. It is probable that in irradiated tissue also, more than half the energy absorbed goes into ionization, and many believe that this is the principal mechanism through which ultimate biological changes are brought about as a result of exposure to radiation. Regardless of the internal means by which this energy is utilized to produce these effects, quantitative measurements of the energy absorbed are essential for evaluating them.

Since the Imc unit is a measure of the intensity of emission of a radium source, it gives little if any information as to the quantity of energy absorbed,

i.e., the dose administered at a given point in the radiation field. The most direct means of measuring the energy absorbed would be a calorimetric method. The quantity of heat energy released, however, is very small and would be extremely difficult to determine in tissue material. Even if successful, this method would not be adapted to routine medical or biological applications, although calculations of the amount of energy absorbed in a metallic medium as a result of ionization produced by  $\gamma$  rays are in agreement within the limits of error of the method with the results of calorimetric measurements (7). Various methods of dosimetry both modern and obsolete, based on chemical, thermal, and electrical effects are interestingly reviewed by Quimby (14b). Of all the means that have been employed for measuring radiation dosage, the ionization method, up to now, has proved superior to the others, although recent work with scintillation detectors and new chemical dosimeters is beginning to show promise.

The standard unit of dose based on the production of ions in a unit volume of air is known as the roentgen or r-unit. As defined by the Fifth International Congress of Radiology in 1937, it is the quantity of X or  $\gamma$  radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 esu of electricity of either sign. It should be emphasized that the ions referred to may be produced some distance away from the 1 cc of air referred to as well as within the latter. The roentgen is determined by measuring the ionization produced in a known volume of air by a collimated beam of X rays directed between two charged plates of a standard parallel-plate ionization chamber. A general description of this method of measuring X-ray intensities can be found in the books on radiological physics cited; specific details are included in a report on X-ray calibration in the Biology Division by Sheppard, Maupin, Oster, and Conger (18). The following points are emphasized because of

the bearing they have on thimble chamber measurements.

First, the measured ionized volume of air should be in electronic equilibrium with the surrounding air. This means that the number of secondary electrons that pass out of the ionized volume should be compensated for by an equal number that pass into the volume from the outside during a given interval. For this condition to exist, the volume should be located at least a distance from the origin of the beam equal to the maximum range in air of the electrons generated along the path of the beam. Second, the space between the beam and the charged plates should be large enough so that only a negligibly small number of secondaries originating within the ionized volume are able to reach the plates.

If a standard free-air chamber is used to determine an r-unit of  $\gamma$  rays, it must be of unwieldy dimensions. This is because the definition of the unit implies that all the ions generated by the secondary electrons originating in 1 cc of air at standard conditions be included in the measurement. Some of the secondaries due to  $\gamma$  rays from radium may produce ions meters away, so that a chamber having a plate spacing on the order of 2 meters, with the source located 5 or 6 meters distant, has been found to be necessary for conditions of equilibrium to be satisfied in the region between the plates (10). By putting the air under a pressure of about 10 atmospheres a conventional size free-air chamber has been successfully used as a standard chamber with  $\gamma$  rays (21). The problem of using the free-air chamber with  $\gamma$  rays has been well summarized in a critical analysis by Failla and Marinelli (3).

For routine biological and chemical dosimetry requirements small, inclosed, thimble ionization chambers have been developed of which the Victoreen chamber

is an example. The use of the latter in X-ray dosimetry is described in detail in a previously cited report (18), although less is known of the response of Victoreen chambers to  $\gamma$  rays.

To avoid the difficulties arising from the relatively long ranges of the secondaries from  $\gamma$  radiation, small "air-wall" thimble chambers, so called because the effective atomic number of the solid wall material is near to that of air, have been developed to serve as practical  $\gamma$ -ray dosimeters. By means of the Bragg-Gray cavity principle, the ionization produced in the chamber cavity may be quantitatively related to the intensity of the energy absorbed in the surrounding medium. Fortunately for the application of the principle in biological material, the effective atomic number of most living tissue approximates that of air so that air-equivalent material is likewise nearly tissue equivalent. For thimble chambers composed of light-weight materials, the almost complete absence of photoelectric absorption with hard radiation permits the quantity of energy absorbed per cc or per gm in the surrounding medium to be measured by means of the cavity principle with an error of less than 5 per cent, provided the composition of the medium is approximately equivalent to that of the chamber wall.

The cavity principle was first recognized, more or less intuitively, by W. H. Bragg (1) and later by Fricke and Glasser (4) in their early developmental work on thimble chambers. Bragg's ideas were applied by Mayneord (13) in his investigation of methods for improving the accuracy of ionization measurements of  $\gamma$  radiation. However, it was not until the reformulation of the principle in rigorous mathematical form and subsequent experimental verification by Gray (5,6,7,8) that measurements of  $\gamma$ -ray dose by the thimble chamber

method were placed on a reasonably satisfactory theoretical as well as experimental basis. A more convenient approach to the problem of measuring hard X- and radium  $\gamma$ -ray intensities was proposed shortly thereafter by Laurence (11) based on the cavity principle and the Bloch theory (9) of stopping power of fast electrons.

The following description of the cavity principle is based largely on the original presentation of it by Gray.

Imagine a large extent of homogeneous medium in a radiation field of uniform intensity. The density of the resulting secondary corpuscular radiation is then likewise uniform. A gas-filled cavity with dimensions which in the ideal case are vanishingly small is introduced into the medium. It can be rigorously proved that the introduction of the cavity will not disturb the distribution of velocities and directions of the electrons crossing the boundary, as long as the cavity is small compared to the range of the electrons in the gas. The experimentally justifiable assumption is made that, in the solid, an individual beta particle will lose as much energy in travelling  $\Delta X$  cm, a distance small compared to its range, as it will in travelling  $\rho \Delta X$  cm in the gas. The quantity  $\rho$  is defined as the ratio  $\frac{S_s}{S_a}$  of the stopping power of the solid to that of the gas and is further assumed to be independent of the energies of the electrons.

The average energy of formation per ion pair in the gas is  $W$ , approximately 32.5 ev, and the number of ions of one kind formed per cc is  $J$ , so that the energy given up by the beta particles per cc of gas is  $JW$ . The corresponding energy loss  $\Delta E_s$  in the solid is then

$$\Delta E_s = \rho JW$$

If the cavity is large enough so that direct production of ionization in the gas by the  $\gamma$  radiation is appreciable, it can be shown (6) that this conclusion is not altered as long as the absorption of energy in the solid and in the gas is exclusively by the Compton process.

The stopping power  $S$  of a substance for ionizing particles is defined as the loss of energy of the particles per cm of path in the material. Several approximate formulas have been proposed for  $S$  of which the one due to Bloch (9) is recommended by Laurence as yielding integrated values most consistent with experimental results. The differential expression according to the Bloch theory of energy loss of electrons in matter may be stated as follows:

$$-\frac{dE}{dX} = S = \frac{2\pi N Z e^4}{m_0 c^2 \beta^2} \left[ \log \frac{(E - m_0 c^2) E^2 \beta^2}{2 m_0 c^2 P Z^2} + \left( \frac{m_0 c^2}{E} \right)^2 \right] \quad \text{Eq. 6}$$

where  $Z$  = atomic number of the medium

$e$  = charge on the electron

$m_0$  = rest mass of the electron

$c$  = velocity of light

$\beta$  = ratio of the velocity of the electron to that of light

$E$  = energy of the electron

$PZ$  = effective ionization potential of the atom

$N$  = number of atoms per cc of medium.

Thus the stopping power for a given mean energy of the particles, except for a slowly varying  $\log Z$  term, is a direct function of  $N$  and  $Z$ , or, since  $N = 6.02 \times \frac{10^{23} g}{A}$ ,  $S$  is also a function of the density  $g$  and the ratio  $\frac{Z}{A}$  of

the atomic number  $Z$  to the atomic weight  $A$ . For small variations in atomic number the stopping power per electron  $eS = \frac{S}{N Z}$  has been shown to vary by not more than 4 per cent from the mean over a wide range of energies (6), hence the justification for assuming  $\rho$  constant for a given material.

The relative value of  $\rho$  for different light-weight materials was investigated experimentally by Gray (6). He compared the ionization intensities in thimble chambers of similar construction having walls composed of various substances with atomic numbers ranging up to  $Z = 29$  but of individual thicknesses adjusted to give equal electron contents. According to Equation 5, the ionization produced in chambers of similar volume but of different wall materials should be proportional to  $\frac{1}{eS}$ . \* The experimental values for  $J$  in most cases fell close to the theoretical curve for  $eS$  based on a formula similar to that of Equation 6. The value of  $\rho$  was found to decrease with increasing  $Z$  by about 18 per cent over the range studied. The graph could be used to determine  $\rho$  with respect to  $\rho$  air taken as unity for any material with an atomic number falling within the limits of the curve.

Sometimes  $\rho$  can be expressed in terms of the atomic stopping power  $S^a$  of the media, then  $\rho = \frac{g_s S_s^a A_a}{g_a S_a^a A_s}$  where  $A$  is the atomic weight,  $g$  is the density in grams per cc. The quantity  $S^a$  is not known with certainty, but if the

$$* \Delta E = E (\sigma_a + \tau)$$

where:  $E = \gamma$ -ray energy flux.

$$= ENZ (\sigma_e + \frac{\tau}{e})$$

$\sigma_a + \frac{\tau}{e} =$  recoil and photoelectric absorption coefficients.

$\sigma_a =$  recoil absorption coefficient per electron,

If  $\tau$  is negligible, then, since  $\sigma_a$  is independent of  $Z$

$$J = \frac{\Delta E}{W\rho} = \frac{ENZ \sigma_a}{W \frac{S_s}{S_a}} \propto \frac{1}{eS}$$

atomic composition of the solid can be made similar to that of air (eff.  $Z = 7.20$ ), then  $\rho$  will be merely the ratios of the densities for the usual case in which the ratio  $Z/A$  of the atomic number to the atomic weight is  $1/2$ . In the case of water the presence of hydrogen having a  $Z/A$  value of  $1$  causes the value of  $\rho$  to be about 11 per cent high (19).

A correction can be made for the wall of a thimble chamber not possessing exact air equivalence according to a derivation given by Laurence (11) in which specific numerical quantities are used in place of the approximations originally employed by Gray. The derivation and resulting calculations are based on the following additional conditions:

(a) The collecting electrode of the chamber according to Laurence is to be a fine metallic wire with a surface area negligibly small compared to that of the walls. In practice, a central electrode made of the same material as the wall has been found to be actually superior, even if its surface area is not small. The use of a large electrode permits a more uniform electrical field for ion collection.

(b) Absorption and scattering of the primary radiation in the walls are small, and a correction can be made for the resulting decrease in intensity.

(c) The thickness of the walls is sufficient to exclude all secondary electrons originating outside the chamber.

The ionization in roentgens per second may be expressed as follows:

$$r = \frac{I \text{ (stat amps)}}{BV_0 \text{ (cc)}} \quad \text{Eq. 7}$$

where  $I$  = ionization current observed

$V_0$  = volume of air in the cavity reduced to standard conditions

$B$  = Laurence correction factor for the nature of the wall material.

The expression derived for thimble walls of various light-weight materials whose approximate atomic composition is known is

$$B = 1 + 2 \log Z_w/Z_a F + (2 \log Z_w/Z_a)^2 G \quad \text{Eq. 8}$$

$Z_w$  and  $Z_a$  are the effective atomic weights of the wall medium and of air respectively. For materials composed of several kinds of atoms the effective atomic weight  $\bar{Z}$  is given by

$$\bar{Z} = \frac{N_1 Z_1 \log Z_1 + N_2 Z_2 \log Z_2 + \dots + N_m Z_m \log Z_m}{N_1 Z_1 + N_2 Z_2 + \dots + N_m Z_m} \quad \text{Eq. 9}$$

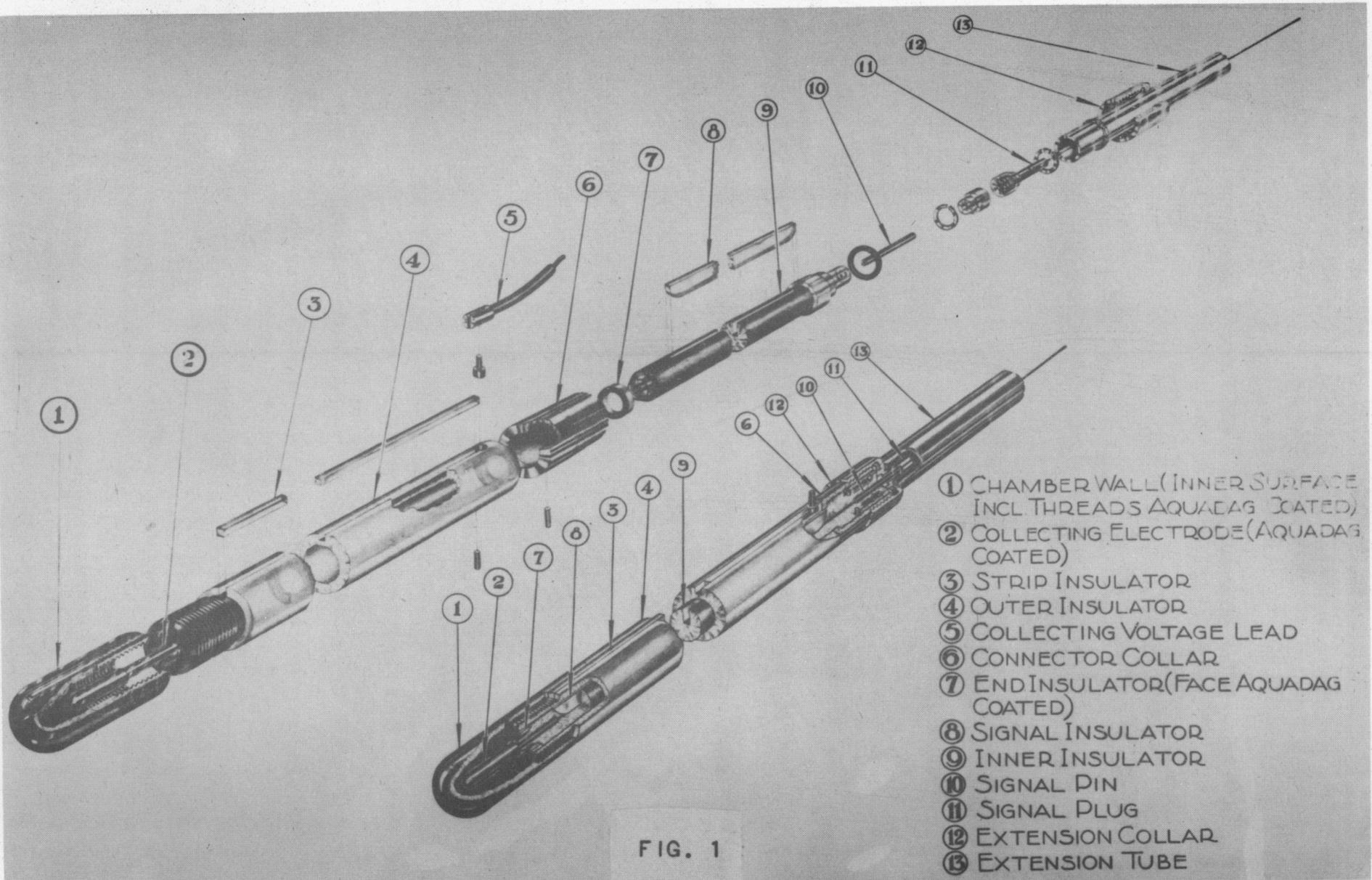
The quantities F and G Laurence derived by numerical integration of an expression based on the Bloch formula (Equation 6) and the Klein-Nishina theory of modified scattering. It should be noted that Laurence's Equation 8 (11) obtained by the substitution of numerical values in the stopping power formula contains an error, although it does not appear to be reflected in his final expression for B above. The values of F and G obtained for the total energy emission from radium in equilibrium with its products are 0.0644 and 0.0039 respectively. For materials that are nearly air equivalent, B is within a few per cent of unity. In the case of polystyrene ( $C_8H_8$ ),  $\bar{Z}_w = 4.65$ , which with  $\bar{Z}_w$  for air taken as 7.20 gives for B a value of 0.947.

#### Construction and Function of the Standard $\gamma$ -Ray Thimble Chamber.--

The design of the standard chamber to be described resembles one given by L. H. Gray (6). Details of the chamber and its shank, which together compose the chamber assembly, and the coupling to the aluminum extension tube are shown in exploded view drawings in Fig. 1. A diagrammatic longitudinal view of the assembly is provided in Fig. 2 to indicate more clearly the conducting surfaces and their relation to each other. Polystyrene and colloidal graphite

**Figure 1**

Exploded and cut-away views of the thimble chamber assembly.



- ① CHAMBER WALL (INNER SURFACE INCL THREADS AQUADAG COATED)
- ② COLLECTING ELECTRODE (AQUADAG COATED)
- ③ STRIP INSULATOR
- ④ OUTER INSULATOR
- ⑤ COLLECTING VOLTAGE LEAD
- ⑥ CONNECTOR COLLAR
- ⑦ END INSULATOR (FACE AQUADAG COATED)
- ⑧ SIGNAL INSULATOR
- ⑨ INNER INSULATOR
- ⑩ SIGNAL PIN
- ⑪ SIGNAL PLUG
- ⑫ EXTENSION COLLAR
- ⑬ EXTENSION TUBE

FIG. 1

(Aquadag) were the only materials used in the construction of the forward portion of the assembly, so that no metallic parts which might act as sources of abnormal scattered radiation are closely associated with the chamber.

The long shank adds greater flexibility to the use of the chamber for purposes such as depth-dose measurements. For measurements inside distributed type sources the irradiated medium may be filled with tissue equivalent material; and, with the nearly tissue equivalent composition of the ion chamber, a minimum of disturbance is imparted during the process to the radiation field in the surrounding medium. The basic parts of the chamber are the wall, #1, and the collecting electrode, #2. The wall, besides functioning to supply most of the ionizing electrons, was coated on its inner surface with a thin layer of Aquadag to serve as the outer electrode labeled E in Fig. 2. A sufficiently large potential difference was maintained between the two electrodes to ensure that essentially all ions formed in the cavity were collected to produce the ion current. The guard ring G, at essentially the same potential as #2, shielded the base of the latter and the center conductor C from extraneous electrical disturbances. The narrow, annular air gap A surrounding the base of #2 effectively isolated it from the effects of any polarization potentials in the surrounding dielectric.

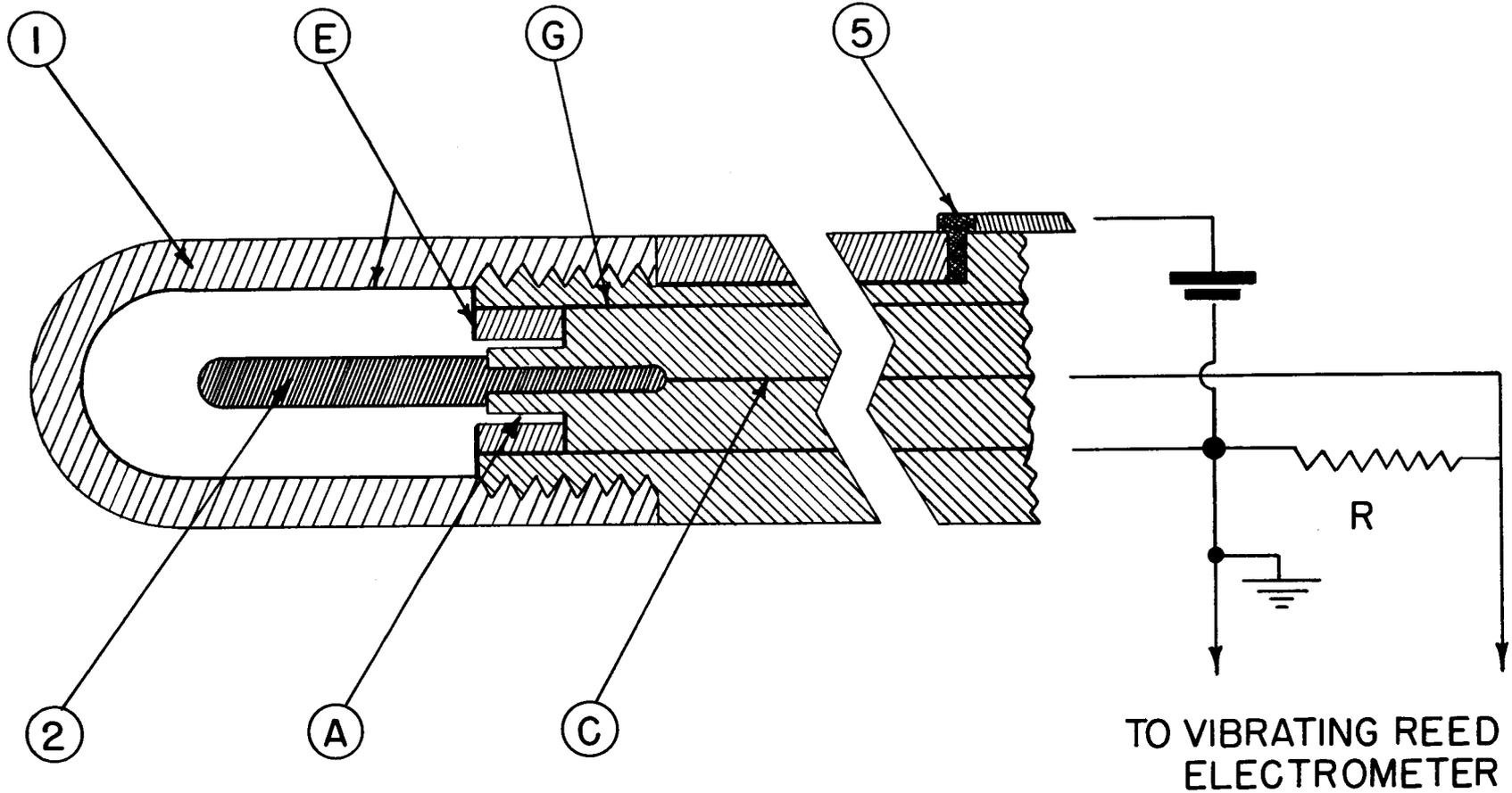
Another more important reason exists for the choice of a material of low atomic number, such as graphite, for the inside coating on the wall of the chamber besides its ability to conduct electricity. According to evidence submitted by Gray (8a) the proportion of secondary electrons furnished by the innermost 0.2 mm of the wall in a graphite chamber exposed to radium  $\gamma$  rays may be as much as twice as great as contributed by the remainder of the wall. It is, therefore, possible for a very thin coating on the inner surface

**Figure 2**

**Diagrammatic section of conducting surfaces in thimble chamber assembly.**

**Sections through conducting strips and surfaces are indicated by heavy lines. Numbers have the same significance as in Fig. 1. Meanings of letters are given in text.**

23



- 1- CHAMBER WALL
- 2- COLLECTING ELECTRODE
- A- AIR GAP
- C- CENTRAL CONDUCTOR
- G- GUARD RING
- E- WALL ELECTRODE

FIG. 2

TO VIBRATING REED  
ELECTROMETER

of a thimble chamber wall to markedly affect the ionization characteristics of the chamber if the atomic composition of the coating is not essentially equivalent to that of the wall. This is not true of the Aquadag coating since carbon and polystyrene differ by only 3 per cent in their degree of air equivalence. (B carbon=0.977 as compared to B polystyrene=0.947 as calculated from Equation 8.)

The absorption and scattering of radiation in the walls of small enclosed  $\gamma$ -ray chambers has been extensively investigated under various experimental conditions (3,8a,13,15b). Under a constant primary radiation intensity for a chamber with walls of a given composition, the thickness of the wall required to produce maximum response is a compromise between two opposing conditions to be met. First, the wall is to be thin enough that the primary radiation is not excessively attenuated and, second, to be thick enough for the  $\gamma$  radiation to be in equilibrium with the secondaries ejected from the wall. Failure to attain either requisite violates basic assumptions of the cavity principle. If the primary radiation is absorbed in a thin wall in accordance with the general law of absorption, the initial intensity  $I_0$  after passing through  $d$  cm of material with a coefficient of linear absorption  $\mu$  is approximately equal to  $I_0 (1-\mu d)$ . The fraction absorbed, assuming  $\mu$  to remain unchanged by the softer scattered radiation, is proportional to  $d$ . However, equilibrium thickness for  $\gamma$  rays from a radium source filtered by 0.5 mm platinum is 3 or 4 mm in light-weight substances. If  $d$  is made much less than this, the ionization capacity of the chamber is considerably reduced and the measurement of the ion current made more difficult, particularly if the primary intensity is weak to begin with. In order to satisfy the two previously stated conditions

so that the integrated ionization current may be expressed in r-units, wall attenuation is compensated for by adding close-fitting shells of the same material to increase the effective thickness of the wall and then extrapolating to zero thickness the intensities observed. A graph of this type made with our standard thimble chamber is shown in Fig. 3. It shows that maximum ionization did not occur until the first shell was added, indicating that the unthickened wall was deficient in the electron content required for equilibrium. With increasing wall thickness, the intensity is seen to fall off more or less linearly due to attenuation. The attenuation factor  $100 \frac{\Delta I}{I}$ , where  $\Delta I$  is the difference in the zero-thickness intensity  $I_0$  and the value  $I$  obtained with the unthickened wall was found to be about 3 per cent as averaged from a number of independent determinations. This is about 1 per cent higher than the average factor that was obtained for walls of comparable material but of approximately equilibrium thickness (8a,14).

In most of the earlier work with ion chambers, ion currents were measured by the Townsend method by determining the time required to charge a precision standard condenser of capacitance  $C$  to a given voltage  $V$ . The magnitude of the current  $I$  is proportional to the reciprocal of this time.

$$I = \frac{CV}{t} \propto \frac{1}{t}.$$

The chief source of error is in the calibration of  $C$ . With the development of high-megohm resistors capable of fairly accurate calibration a more convenient method was made available. The voltage drop due to the ion current flowing through the resistor is measured by means of a vibrating reed electrometer. The reed input capacitance is on the order of  $10^{-11}$  farads and  $R$  may be as much as

Figure 3

Graph of relative ion current as a function of effective wall thickness (abscissas).

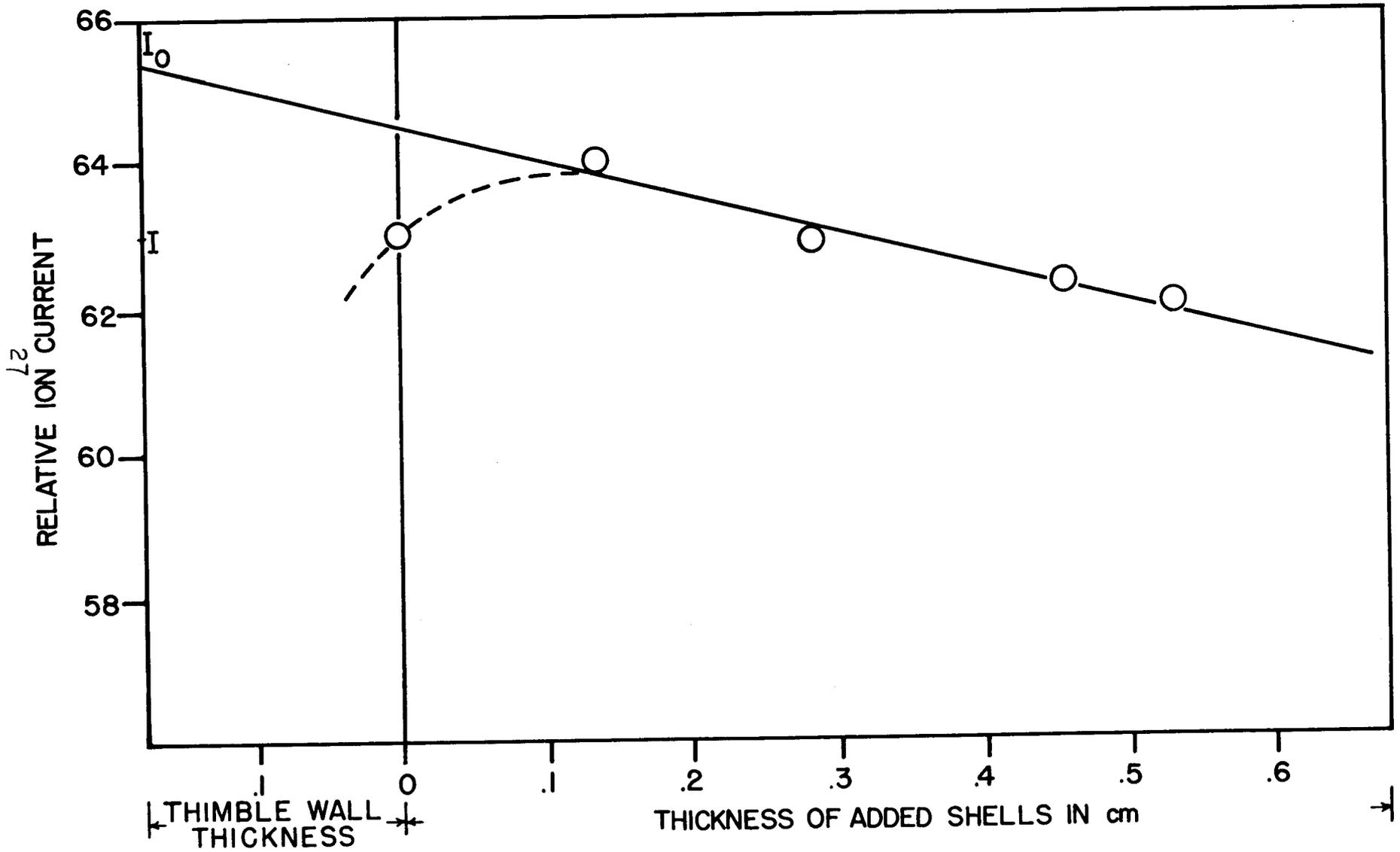


FIG. 3

$10^{12}$  ohms. The circuit may, therefore, have a fairly large time constant, so that it may be necessary at times to wait for the attainment of the steady-state condition, after which the voltage is measured. Details as to the use of the vibrating reed electrometer for ionization intensity determinations are described in a report on a method developed by Sheppard and Abele (17) for the measurement of the surface exposure of phosphorus-bakelite  $\beta$ - ray sources.

The collection of ions formed in the cavity of the chamber must be essentially 100 per cent if the ion current is to be converted into roentgens per second on an absolute basis. In the graph of ionization intensity versus collecting voltage shown in Fig. 4, the thimble chamber is about 99 per cent saturated at  $22\frac{1}{2}$  volts and completely saturated at double that voltage. For the radium calibrations, however, the saturation potentials were generally less, since most of the observations were made at lower primary intensities than the one used in the preparation of the curve.

Calibration of Thimble Chambers with Radium.—One index of the efficiency of a thimble chamber for collecting ions is given by comparing the geometrical volume of its cavity with the effective volume as determined with a source of known strength. The difference between the two is the dead space, or that portion of the cavity which for one reason or another is apparently not utilized for ion collection. In studies by Sheppard with a predecessor of the present model of standard chamber the chamber was exposed to a radium source and the equivalent ionization current expected for a chamber of that volume compared with the current actually observed. The apparent dead space, which amounted to about 22 per cent, was found to be due primarily to a fault in the design of the guard ring surrounding the collecting electrode. The guard ring was arranged so that it tended to partially shield the base collecting electrode

Figure 4

Graph of relative ion current as a function of collecting voltage.

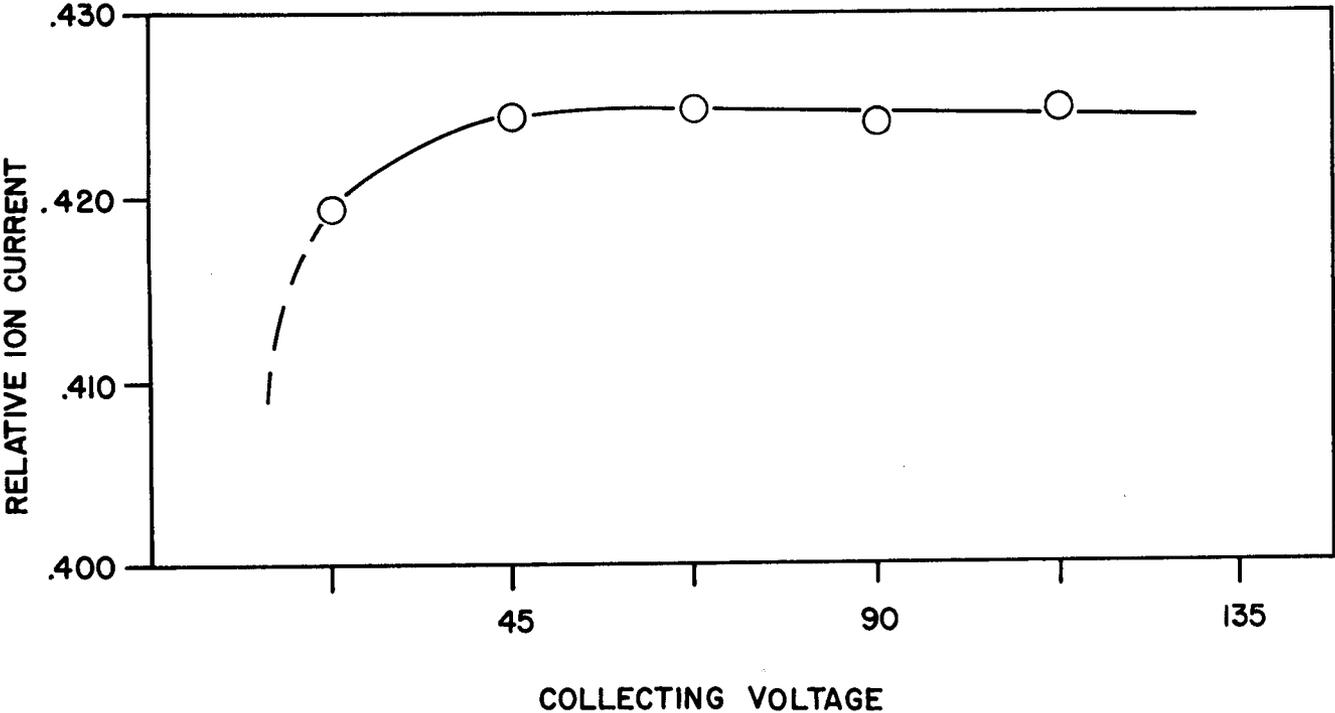


FIG. 4

from the electric field across the cavity. In the present model chamber, the guard ring has been redesigned to eliminate this condition. Typical values of the effective volume of the new chamber determined from sources of various strengths are given in Table 1. The sources were standard radium needles with platinum-iridium walls 0.5 mm thick containing known quantities of a radium salt. The intensity of each source as certified by the National Bureau of Standards is also given by Equation 4.

Verification of the cmgh Dose.--As a means of testing the validity of the response of the new chamber, the  $\nu$ -ray intensity from a known quantity of radium was measured by R. K. Abele using a vibrating reed electrometer. The mean value obtained for a 25.54-mg source, including a correction for attenuation, was 183.5 r/hr at 1 cm. The Laurence correction factor though given for only 0.5 mm platinum filtration would probably increase this figure by 4 or 5 per cent so that the resulting value of intensity, 193 r/hr corresponding to a cmgh value of about 8.1 r is about 3 per cent lower than the accepted value, 199.5 r/hr based on Equation 4.

Recently further determinations of this sort with different quantities of radium have been carried out under similar and also somewhat varied experimental conditions.

In the first group of measurements done in the X-ray laboratory of the Biology Division, the source needle was attached end-on with beeswax to a thin glass wand supported about a meter above the floor, several meters away from any other large objects which could serve as sources of scattered radiation. The centers of the source and the chamber were located on a vertical line so that the exact distance between the two could be measured with a

Table 1

Comparison of true and effective volumes of thimble chamber

Intensity of source in r/h at 1 cm	Equivalent current per unit volume (amps/cc)	Measured current corrected for volume at standard conditions	Effective volume (cc)	True volume (cc)	Effective volume after correction for air-wall conditions and attenuation	Percentage difference between true and effective volume
8.39	$0.777 \times 10^{-11}$	$1.54 \times 10^{-11}$	1.98	2.17	2.16	0.4
164.1	$1.52 \times 10^{-11}$	$2.96 \times 10^{-11}$	1.94	2.17	2.11	2.8
166.8	$1.54 \times 10^{-11}$	$3.14 \times 10^{-11}$	2.04	2.17	2.22	2.3

minimum of exposure to the observer, by the means of a cathetometer placed some distance away.

Some results of intensity measurements with sources of different strengths are given in table 2. The values in roentgens/hr at 1 cm were computed from Equation 6 as below:

$$\begin{aligned}
 r/\text{hr} &= \frac{3600 I K}{B V} = 3600 \times 3 \times 10^9 \frac{E T_1 P_0 d^2 K}{R B V P_1 T_0} \\
 &= \frac{10.8 \times 10^{12} \times 1.03 \times 760 E P_1 d^2}{0.947 \times 2.17 \times 273 R T_1} \\
 &= 15.1 \times 10^{12} \frac{E P_1 d^2}{R T_1}
 \end{aligned}
 \tag{Eq. 10}$$

where E = voltage on reed

R = resistance

V = volume of chamber cavity (2.17 cc)

d = distance in cm between source and chamber centers

T<sub>1</sub> = absolute temperature

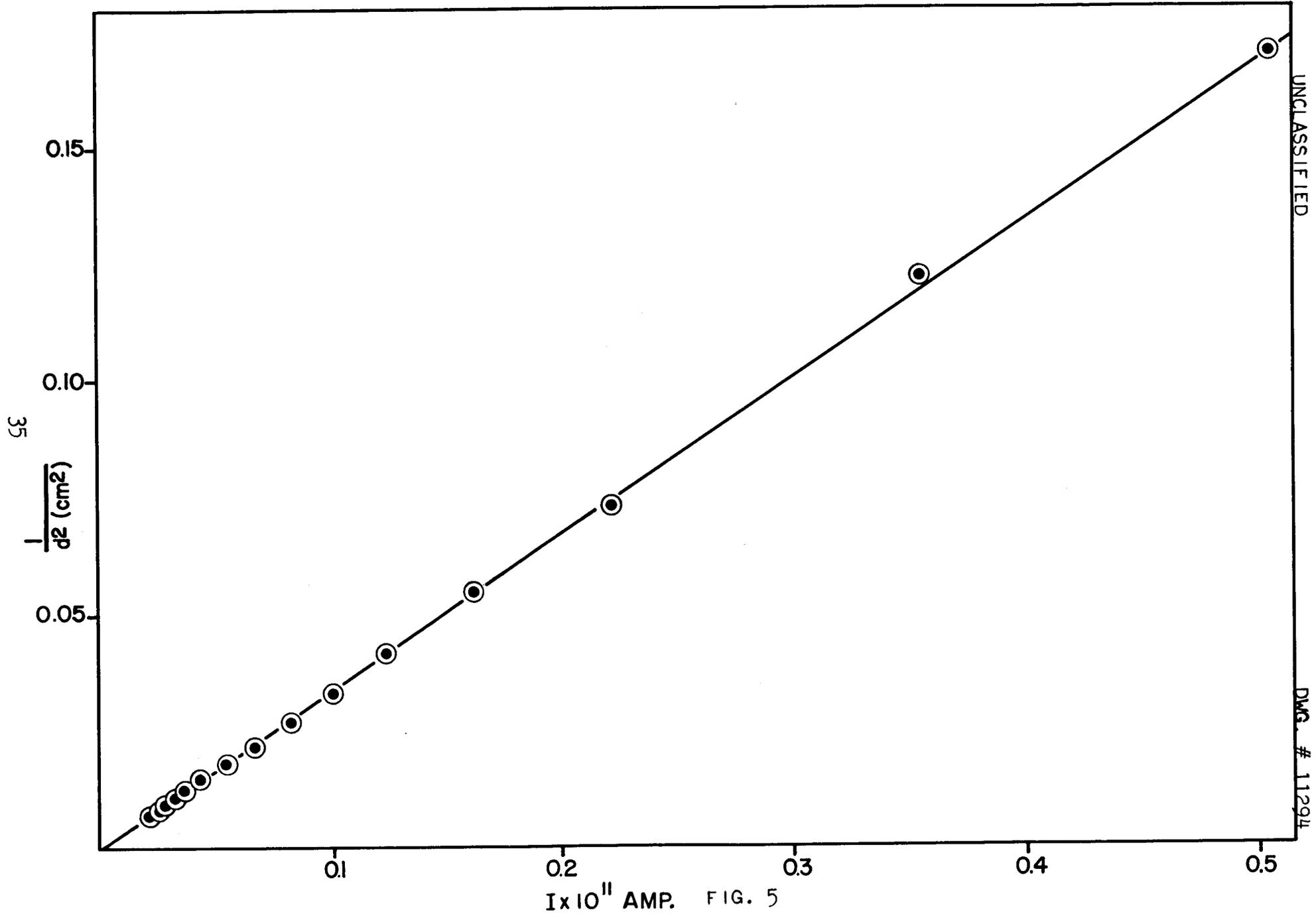
P<sub>1</sub> = pressure in mm of Hg

K = wall attenuation factor: 1.03

The experimental intensities given in the table are mean values based on the slope of a graph plotted from three or more measurements at different distances from the source. Fig. 5 is a typical example. The graphs indicated that the response followed the inverse-square law up to within 3 to 6 cm of the source.

Figure 5

Graph of ion current as a function of the inverse square of the distance between the geometrical centers of the source and chamber.



$I \times 10^{11}$  AMP. FIG. 5

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The first four trials in Table 2 were made with a voltage of  $22\frac{1}{2}$  volts on the collecting electrode, so that according to the saturation curve (Fig. 4), the ionization was possibly as much as 1 per cent low. Correction is made for this so that in the last column all values correspond to conditions of complete saturation.

Trial no. 4 was made with a double-strength source consisting of two needles attached end-on, so that the distance between source and chamber could be increased. The larger value found can probably be attributed to a greater quantity of scattered radiation resulting from the increased ratio of platinum to radium present.

Table 2

## Measurement of Sievert dose

The first series of determinations was made in the X-ray room

Trial no.	mg of radium	Average temperature Centigrade	Intensity in r/hr at 1 cm		Experimental Sievert Dose
			Calculated from Eq. 4	Experimental	
1	9.98	28	8.39	8.34	8.44
2	19.55	23	164.1	160.2	8.28
3	19.84	24	166.8	162.0	8.26
4	39.39	23	330.9*	339.0	8.68
5	19.84	23	166.8	169.5	8.54
Mean of nos. 1, 2, 3 and 5:					8.38 r/hr

\* Assuming that the two needles are equivalent to one containing the same total quantity of radium.

In Tables 3, 4, and 5 are reported some additional determinations of radium dose with the source set up inside a large lead enclosure normally used to shield a medium intensity cobalt  $\gamma$ -ray source when in operation. Among other reasons the work was undertaken to obtain information about the effects of backscatter from the lead.

The enclosure is supported about  $1\frac{1}{2}$  meters above the floor. It is hexagonal in shape and open at the top with walls 60 cm high, 10 cm thick, and an inside space, wall to wall, of about 142 cm. In the center of the lead floor, which is surfaced with a half-inch layer of lucite, is an aperture through which the cobalt source may be elevated from its normal location inside a lead safe to irradiate samples placed inside the enclosure. When the source is in this position, its vertical intensity is normally reduced by an overhead shield consisting of lead bricks piled on a low iron table 45 cm square located over the source position. With the source lowered, radiation through the aperture is blocked by a lead gate immediately underneath. The thimble chamber assembly was mounted horizontally on one of the platforms used to support the samples. The platform can be rolled in and out along a radial shaft by means of external controls. The displacement along the track is indicated by a dial system to an estimated accuracy of  $\pm 0.04$  cm. The chamber assembly was connected to the vibrating reed electrometer by means of the extension tube which passed through a hole in the lead wall and connected with the resistance box. The preamplifier unit and reed head along with the resistance box were attached as a unit to a travelling microscope stage capable of movement along a line parallel to the axis of the thimble chamber, so that the assembly could be displaced as a unit in and out from the center of the enclosure.

Background radiation due to the presence of the cobalt source was negligible outside the enclosure in the vicinity of the electrometer; inside the enclosure with the aperture gate closed the background was detectable but small and essentially constant over the region available to the thimble chamber.

In Table 3 are recorded radium measurements made with the table of lead bricks over the center of the enclosure removed. A comparison with Table 2 indicates that the increase in the mean intensity, presumably due to the surrounding lead walls and floor, was not more than 2 per cent.

Table 3

Cobalt source enclosure with overhead shield removed

Trial no.	mg of radium	Average temperature Centigrade	Intensity in r/hr at 1 cm		
			Calculated from Eq. 4	Experimental	
6	19.84	20	166.8	167.1	
7	19.84	20	166.8	169.2	
8	19.84	18	166.8	165.8	
9	19.84	16	166.8	172.5	
				Mean:	168.6

In Table 4 are shown a similar series of determinations except that the lead brick shield was left in place over the center of the enclosure. The radium needle, and also the chamber when moved in close, were thus surrounded by lead above and below as well as on the sides. The data in the tables show that the intensity of the ionization was increased about 2 per cent by the presence of the lead bricks. As a matter of individual

comparison trials no. 6 and no. 11 performed the same day showed a difference of only 1 per cent.

Table 4

Cobalt source enclosure with overhead shield present

Trial no.	mg of radium	Average temperature Centigrade	Intensity in r/hr at 1 cm	
			Calculated from Eq. 4	Experimental
10	19.84	24	166.8	169.8
11	19.84	19	166.8	169.3
12	19.84	16	166.8	176.3
13	19.84	14	166.8	<u>173.7</u>
			Mean:	172.3

The data in Table 5 justify the assumption that the presence of the cobalt source under the enclosure did not affect the readings. The conditions were the same as for Table 3 except that the safe containing the  $\text{Co}^{60}$  had been removed. The difference in mean intensities is seen to be less than one per cent.

Table 5

Cobalt source enclosure without overhead lead, lead shield and cobalt safe

Trial no.	mg of radium	Average temperature Centigrade	Intensity in r/hr at 1 cm	
			Calculated from Eq. 4	Experimental
14	19.84	26	166.8	168.5
15	19.84	24	166.8	168.7
16	19.84	18	166.8	<u>170.8</u>
			Mean:	169.3

Mention should be made of several possible sources of error other than those connected with the design of the chamber itself. These include the displacement of the effective centers of source and chamber from the geometrical centers, temperature effects on the auxiliary equipment, drifting of resistor values, and backscatter from the walls of the room and surrounding objects.

An apparent displacement of the effective center from the geometrical center of a chamber is caused by the inverse square variation of the radiation with distance from a point source. The two centers are essentially the same at large distances but, as the distances approach the same order of magnitude as the dimensions of the chamber, the effective center migrates appreciably toward the source. A sufficiently accurate correction usually can be made, if necessary, by determining the limits of the displacement experimentally and taking an average over-all value for a correction factor (8a,14a). If the chamber has a simple spherical or cylindrical shape, derived factors may be of some help. According to Laurence (11) the displacement of the geometrical center of a chamber of volume  $V$  toward a point source  $d$  cm away is on the order of

$$\Delta^d \approx \frac{1}{2} \frac{V^{2/3}}{d} \text{ cm.} \quad \text{Eq. 11}$$

Suppose that the chamber is treated as a thin spherical shell of radius  $a$  on each element of which the intensity due to radiation from a point source  $d$  cm away varies according to the inverse square law. Then the displacement

is found to a close approximation to be

$$\Delta d = \frac{a^2}{6d} \text{ cm.} \quad \text{Eq. 12}$$

For  $a$  to equal 1 cm and  $d$  as little as 10 cm, the displacement is 1 per cent or less, depending on whether Equation 11 or Equation 12 is used. In the present case the hemispherical nose of the chamber was pointed at the source, and since that part of the wall incident to the radiation was responsible for most of the ionizing electrons, the assumption of a spherical shell appeared to be valid. The average displacement error was theoretically less than 0.5 per cent, since out of a total of about 100 individual ionization measurements about 15 were at distances  $< 10$  cm while about 30 were at distances  $> 20$  cm. The fact that this source of error was not important experimentally was demonstrated by the linearity of the inverse square plots almost up to the source, as shown in Figs. 5 and 6.

A small error is made in assuming point-source conditions for a radium needle. It is more nearly correct to treat the needle as a line source in which case the intensity,  $I$ ,  $d$  cm away and on a perpendicular through the center of a source of length  $l$  is proportional to  $\frac{1}{d} \tan^{-1} \frac{l}{d}$ . The displacement of the effective center of ~~radium~~<sup>radiation</sup> is to a close approximation

$$\frac{l^2}{24d} \text{ cm in a direction away from the receiver.}$$

The effect of temperature changes on the current measuring equipment, particularly the standard resistors, is believed to be the most important single source of the discrepancies observed between individual groups of measurements. From a comparison of the tabulated intensities and the corresponding temperatures, as well as results not listed, relatively low

Figure 6

Displacement of origin of an inverse square plot as  
a result of room scatter.

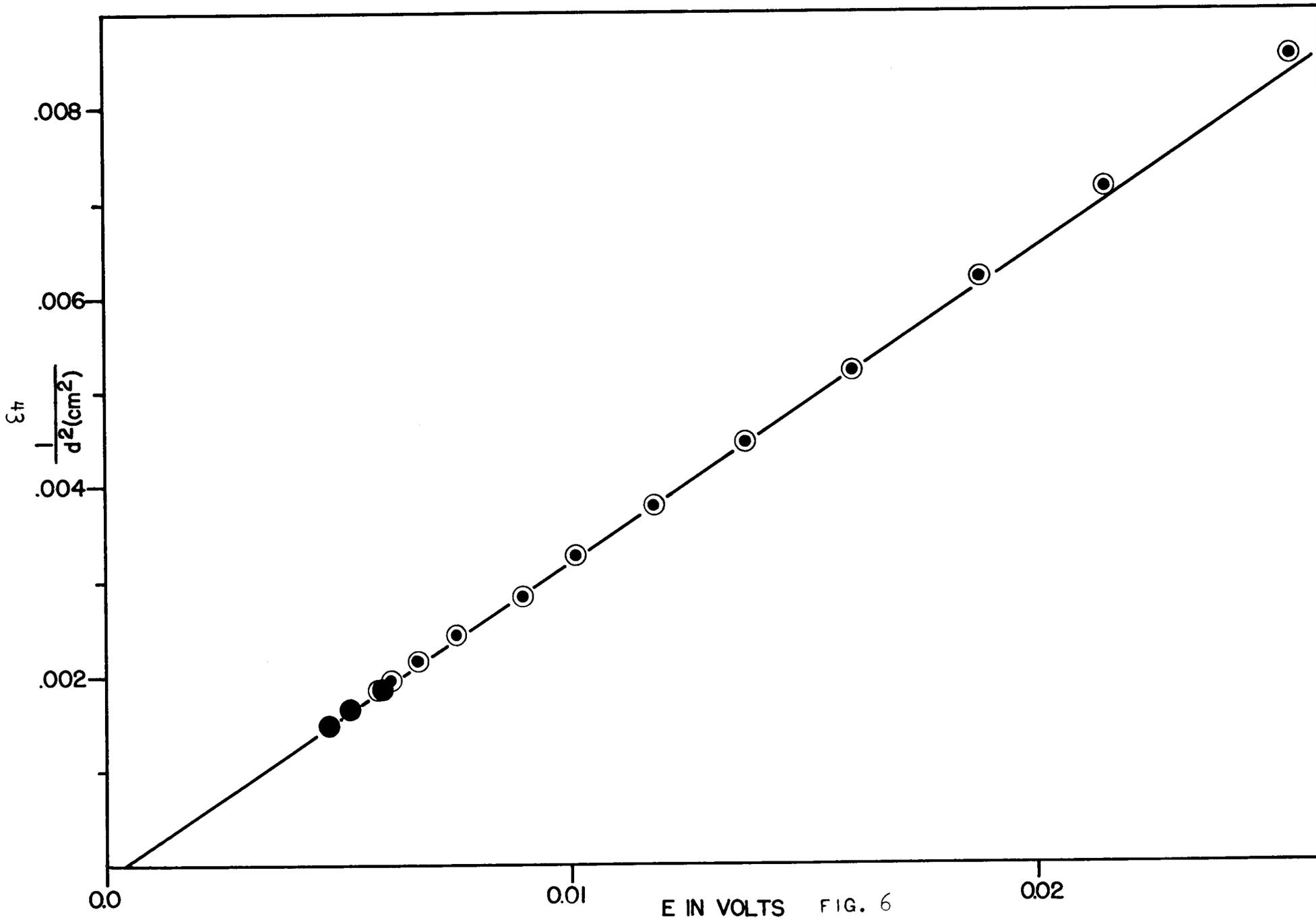


FIG. 6

ambient temperatures in general appear to be correlated with the higher intensity values. It is consistent with the results to attribute this variation to the relatively large temperature coefficient of resistance (-0.18 per cent per degree) given by the manufacturer for the vacuum-sealed resistors. The effect is rather clearly demonstrated by a comparison of values for determinations made below  $18^{\circ}$  and at  $18^{\circ}$  and above: in the first group the mean Sievert dose is 8.28 r/hr, in the second 8.51 r/hr, a difference of 3 per cent.

A more gradually appearing source of error is resistor drift. Since the data reported were taken over a period of several months, the possibility of a change of a few per cent in the resistance unit was considered. A type of drift has been experienced in which the rate was satisfactorily slow though appreciable (2 per cent) over a period of 6 months and then suddenly increased several more per cent within a few weeks; consequently, it is sound practice to have these resistors recalibrated at least quarterly. This factor may have been partially responsible for the error in the value of the intensity calculated from Abele's data. The value of R used by him was based on the original calibration of the resistance unit by the Instrument Department. A second calibration was made 9 months later. This calibration, on which the calculations in this report are based, indicated that the values of the  $10^{11}$  and  $10^{12}$  ohm resistors were about 4 per cent less than in the original calibration. A third calibration 6 months later showed no appreciable change. If the second calibration value is used for Abele's data, his answer appears to be within a per cent or so of the accepted figure. One might criticize the original calibration but for the fact that it was arrived at by averaging

closely agreeing measurements made on three different bridges and was found to give satisfactory results in other types of measurements also.

The effect of backscatter on the response of a thimble chamber to  $\gamma$  radiation is generally considered to be negligible when the distance between the chamber and source is small compared to the dimensions of the room or the distance to any large objects which might act as sources of backscattered radiation (3,8a,14a,15b). For a source and chamber  $d$  cm apart and an average distance of  $D$  cm from the walls of the room, the ratio of the backscattered radiation intensity  $I_s$  to the primary intensity  $I_p$ , assuming 100 per cent reemission from the walls, is easily shown (14) to be on the order of

$$\frac{I_s}{I_p} = \frac{d^2}{D^2} \quad \text{Eq. 13}$$

The corpuscular fraction of  $I_s$  should be negligible even in a fairly small room, since the secondaries produced are primarily Compton electrons lacking sufficient velocity to penetrate the chamber. The electromagnetic fraction is not so easily dispensed with, however, and has proved difficult to correct for if  $d$  is an appreciable fraction of  $D$  (15b). In Fig. 6, which is based on some earlier measurements of intensity made in a small room, the effect of room scatter is shown by the straight line failing to pass through the origin. In the work represented by Tables 3, 4, and 5 the source and chamber were also located in a confined space. In addition, the region was bounded principally by surfaces composed of a material superior to plaster or brick in producing secondary radiation, yet the increase in intensity due to the lead, according to the tables, did not amount to more than 2 or 3 per cent. It was surmised that the lucite covering over the lead floor was

rendering the latter largely ineffectual as a source of secondary radiation despite its large area and proximity to source and chamber. A wall of lead bricks 40 cm high and 10 cm thick was therefore built parallel to the source-chamber axis at a distance from the latter equal to its height (14 cm) above the floor. The resulting increase in the ion current, approximately 2 per cent, compared favorably with the results of a similar experiment reported by Mayneord and Roberts (14a). A sheet of lucite  $\frac{1}{2}$  inch thick was then placed against the front face of the wall and the ion current was observed to decrease to approximately its former value. The presence of the lucite sheet by itself appeared to exert no significant influence on the response of the chamber.

Since appreciable increases in response were observed to occur only with unobstructed lead surfaces present near the chamber, it appears that the additional ionization was due primarily to photoelectrons ejected from the lead. Some of these, unlike Compton secondaries, would have enough energy to penetrate the chamber unless their paths were blocked by a sufficient thickness of lucite or other appropriate material. Electrons from the more distant lead walls of the enclosure apparently would have too little energy left after crossing the air space to penetrate the chamber. The iron table used for the work of Table 4, while effective in blocking photoelectrons from the lead bricks on top of it, presumably contributed some of its own. The increase in chamber response due to the table of bricks was, therefore, less than would be expected for fully exposed lead.

Use in Distributed Type Sources.--The standard thimble chamber, in addition to its effectiveness in measuring the intensity of  $\gamma$  radiation from open sources is also well adapted for determining intensities inside distributed

type  $\gamma$ -ray sources. Those in use here have the basic form of a long hollow cylinder about 2 inches in diameter into which can be inserted a core of polystyrene containing the sample to be exposed. It can be shown that the  $\gamma$ -ray flux inside the cylinder is uniform along the axis in the central region. However, intensity measurements inside this kind of source are complicated by the presence of the measuring device itself. When a foreign object is introduced into a field of radiation, some disturbance of the field generally results. This effect can be minimized in an open space, but distortion of the flux distribution may be appreciable in a restricted space within a radioactive medium. In the case of a Victoreen chamber, the metallic shank particularly is objectionable in this respect. This difficulty may be avoided by using materials for the instrument of approximately the same atomic composition as that of the medium surrounding it. The standard thimble chamber is well suited for this purpose (with its polystyrene composition). Thus, when the thimble chamber is inserted into the polystyrene core, the shank in effect disappears, leaving the chamber cavity surrounded by a homogeneous medium. Also the region between cavity and source is of one material and scattering due to boundaries between different kinds of media is avoided. Under these conditions, together with the assumption of a uniform flux in the region of the cavity, the elementary form of the Bragg-Gray principle as stated in Equation 5 gives directly the relation between the ion current observed in the chamber and the rate of absorption of energy in the surrounding medium. Consequently, if the region into which the thimble chamber is inserted is filled with an aqueous suspension of biological material and exposed in the source, the intensity of the dose delivered the sample is almost the same as given by Equation 5 for the polystyrene medium, since the stopping power of

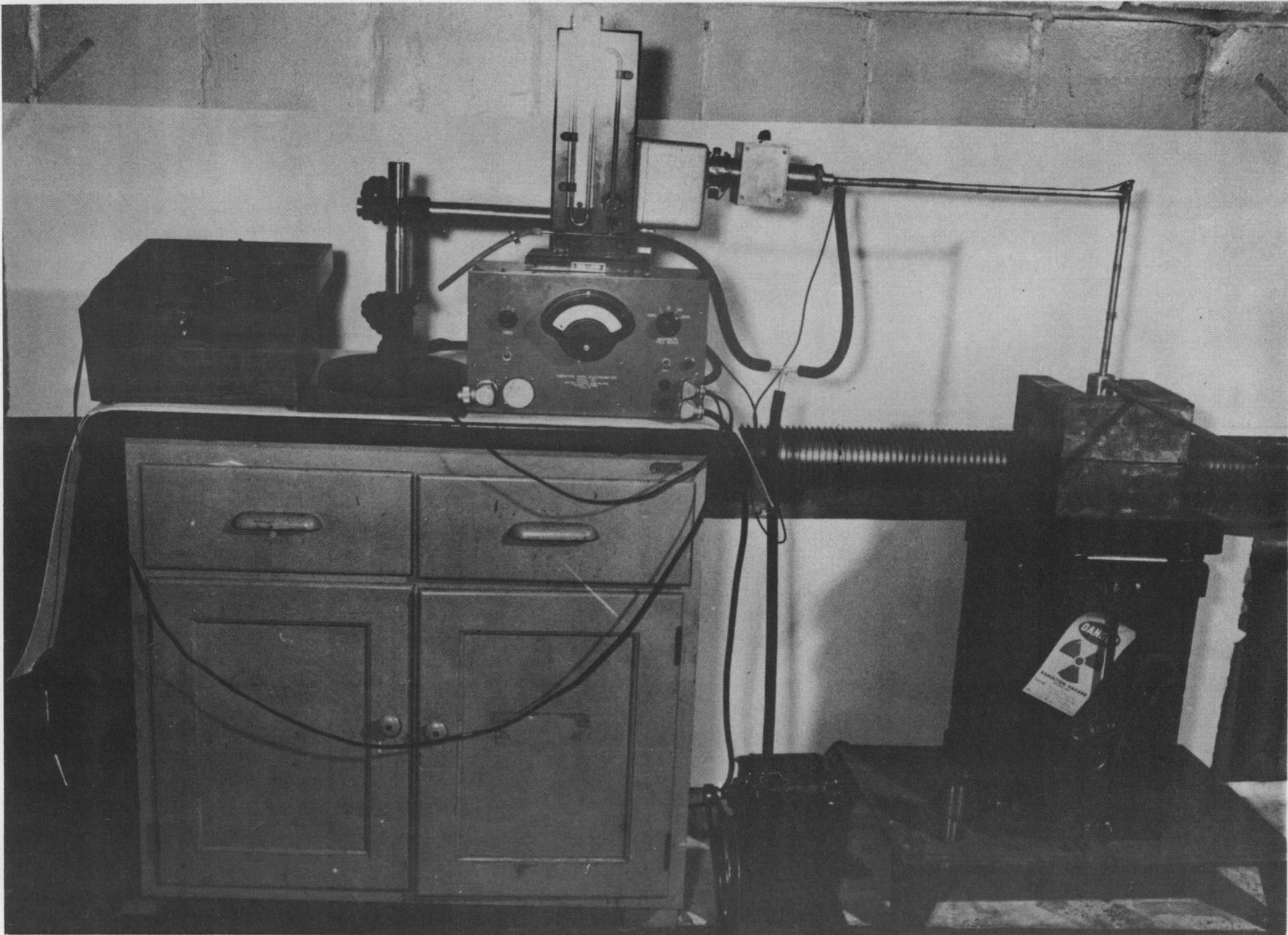
polystyrene with respect to water is about 1.05 (16).

Sources of  $\text{Co}^{60}$  and  $\text{Au}^{198}$  have been used here in this manner. The cobalt-aluminum alloy cylinders employed are of low enough intensity to permit measurements to be made without introducing a shielding problem. A typical arrangement of apparatus set up for this purpose is pictured in Fig. 7, showing the polystyrene cylinder fitted over the thimble chamber assembly without the source cylinder in place. The  $\text{Au}^{198}$  source was used in an exposure assembly developed by Sheppard (for subjecting biological material, particularly blood, to a much higher intensity of  $\gamma$  radiation—16). The source was in the form of a cylinder of gold foil supported in a specially designed graphite aluminum holder. This holder was placed in the reactor to activate the gold after which it was kept in a 4-inch-walled lead safe. The cylindrical core with its contents could be lowered into the source through a hole in the lid of the safe. The setup for making intensity measurements is shown in the photograph in Fig. 8. A thorough experimental study of the relative variation of intensity inside the source was made, using calibrated film and Victoreen ion chamber measurements. These methods agreed in showing that the field was flat within  $\pm 5$  per cent of the mean over approximately the middle third of the axial region of the core (16).

The relative precision of the measurements with the thimble chamber is illustrated in the decay curve for  $\text{Au}^{198}$  shown in Fig. 9. This series of plots was based on observations of the intensity at intervals over a period of about one half life. The close agreement with the theoretical rate of decay is shown by the linearity of the points and the resulting half-life value 67.0 hours as compared to the accepted value of 64.6 hours, a difference of  $< 3\frac{1}{2}$  per cent.

Figure 8  
~~Figure 7~~

Typical experimental arrangement for making  $\gamma$  -ray intensity measurements inside a cylindrical cobalt source. The cobalt cylinder is not shown. The resistance unit, reed head, and preamplifier are shielded with lead bricks.



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Fig. 8  
FIG. 7

*Figure 7*  
*Figure 8*

Arrangement for making gamma-ray intensity measurements  
inside a high intensity gold source exposure unit.

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Fig. 7  
Fig. 8

## Figure 9

Graph showing decay of gold source based on ionization measurements with the standard thimble chamber.

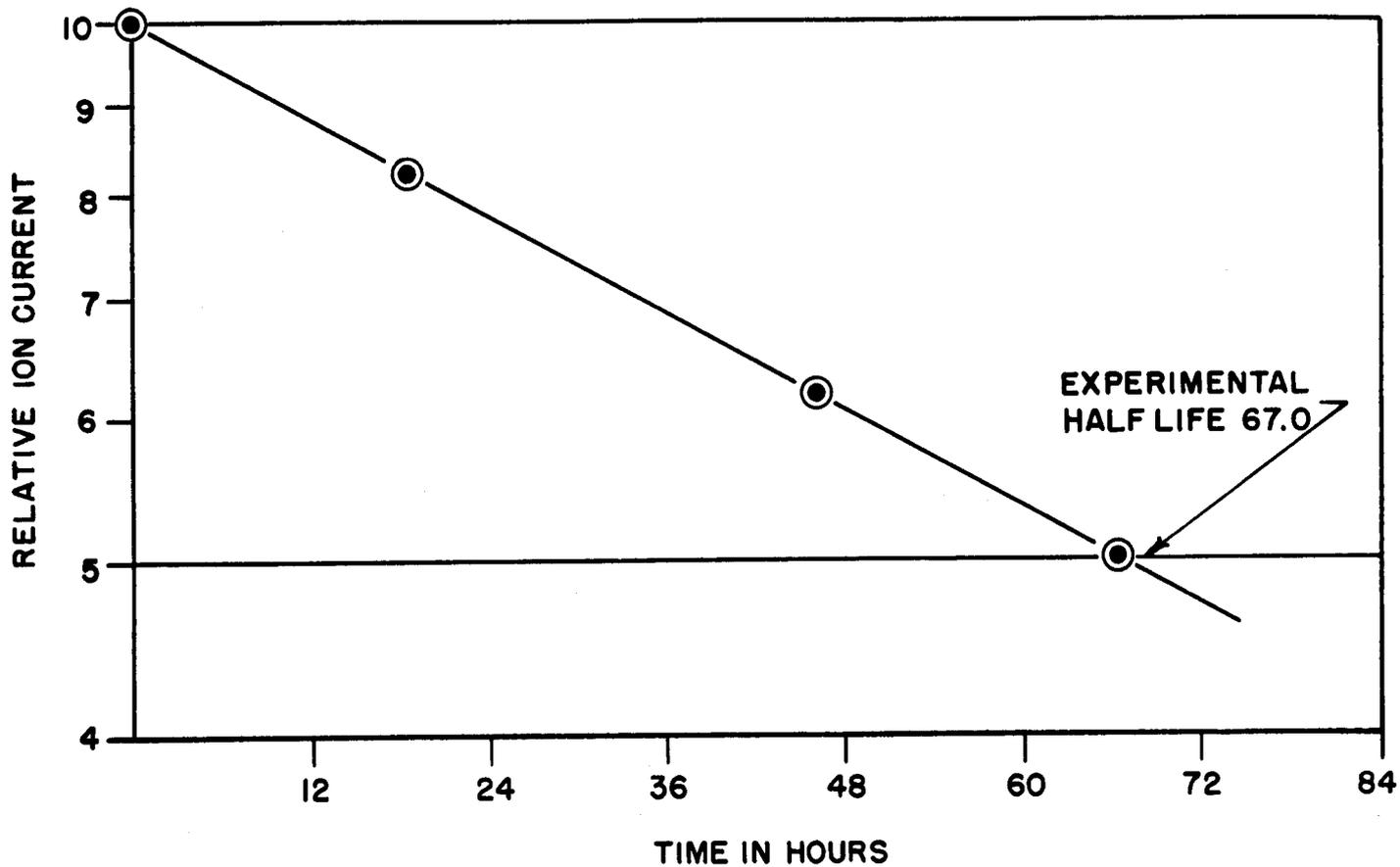


FIG. 9

Absolute Accuracy of the Thimble Chamber Method.—In spite of improvements that have been made in methods and means for measuring  $\gamma$  ray dose in roentgens, the precision is still inferior to that ( $\pm 1$  per cent) which has been available for many years in making X-ray calibrations with the standard parallel-plate chamber. The over-all accuracy of the cavity principle of ionization measurement with a small air-filled chamber is given as about 5 per cent (8a), although, as shown by our results, the use of specific quantities in the Laurence formula increases this accuracy somewhat when a properly filtered radium source is used.

For the purposes of this report, 8.4 r/hr as calculated from Equation 4 is taken as the accepted value of the Sievert dose. However, the group of values from which this equation was generalized, obtained by various investigators, actually represented a spread for which the mean deviation was about  $2\frac{1}{2}$  per cent (11). A more recent determination of the Sievert dose very carefully carried out by Taylor and Singer (21) at the National Bureau of Standards, utilizing a parallel-plate chamber under pressure, yielded a value of 8.16  $\pm$  0.04 r/hr, just within the mean deviation referred to. Apparently then, no justification exists (although results are usually given to 3-place accuracy for convenience) for now assigning an absolute accuracy greater than  $\pm 3$  per cent to any intensity measurements of  $\gamma$  radiation from radium or any other source.

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