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# ELECTRONIC EQUILIBRIUM IN FREE-AIR CHAMBERS AND A PROPOSED NEW CHAMBER DESIGN

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## ABSTRACT

The concept of electronic equilibrium, particularly as applied to free-air chambers, has been frequently used to cover more than one idea. In order to separate and define clearly each idea, definitions are established for "integral charged-particle equilibrium" and "charged-particle compensation." In addition, a definition for "charged-particle equilibrium" is proposed along the lines set forth by Roesch.

A new type of free-air ionization chamber is proposed in which electric-field uniformity plays no role in defining the ion-collecting volume. The chamber is based essentially upon a subtraction method in which two readings are taken of the ionization and the difference is used as a measure of exposure dose. The chamber is collapsible, its midplane being fixed with respect to the x-ray source. The ionization in the two equal air volumes on either side of the midplane of the chamber when in a collapsed condition and the ionization of the two volumes defined by the chamber in an expanded condition are related in such a way that their difference is just the ionization in the extra volume of air created in the middle of the chamber by the expansion of the chamber. It is evident that the end planes of this extra volume of air are not defined by electrostatic lines of force, as is the case for conventional chambers. Consequently, the new chamber has no need for guard plates or other field-shaping electrodes which are typical of conventional free-air chambers. Since the uncertainty about the degree of field uniformity represents the largest single source of error in conventional chambers, its elimination is a considerable advantage.

## PROBLEM STATUS

This interim report stems from work carried out under NRL Problem P03-01; work on this problem is continuing.

## AUTHORIZATION

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## ELECTRONIC EQUILIBRIUM IN FREE-AIR CHAMBERS AND A PROPOSED NEW CHAMBER DESIGN

### INTRODUCTION

The free-air ionization chamber is the standard device employed by national laboratories throughout the world for the measurement of the exposure dose of x and  $\gamma$  radiation (1-3). A number of different designs have evolved, including principally the parallel-plate types, such as those of the U.S., Canada, and the U.K., and the cylindrical types, such as those employed in West Germany and Sweden. All of these chambers have at least two features in common. The first is their dependence upon the existence of charged-particle compensation and integral charged-particle equilibrium in order to measure a quantity equivalent to the exposure dose. The second is their reliance upon guarding-electrodes to produce a uniform electric field, thus defining the region from which the ionization is collected. In this report the concepts of equilibrium and compensation will be discussed, and a new type of free-air chamber will be described in which field-shaping electrodes are not necessary, thus allowing a considerable simplification in construction and a possible improvement in accuracy.

Exposure dose and the roentgen are defined by the ICRU as follows (2):

“Exposure dose of x- or gamma radiation at a certain place is a measure of the radiation that is based upon its ability to produce ionization.

The unit of exposure dose of x- or gamma radiation is the roentgen ( $r$ ). One roentgen is an exposure dose of x- or gamma radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign.”

Thus it is clear that what one would like to measure in determining the exposure dose is the ionization produced everywhere by just those electrons which originate within a specified small volume of air. This is illustrated in Fig. 1. Point P is the point in air for which the exposure dose is to be determined.  $v'$  is a “small,”\* imaginary sphere centered at P. To determine the exposure dose at P, one must collect (by an electric field) and measure the total ionization produced in air by electrons, such as those labeled A, which originate within  $v'$ . One must exclude from the measurement the ionization produced by those electrons originating elsewhere, such as the B electrons shown in Fig. 1. The measured electric charge (of either sign), in esu, divided by the mass of air contained in  $v'$  (in units of 0.001293 g),† will yield the exposure dose at P in roentgens. If  $v'$  remains “small,” the exposure dose at P will be independent of the size of  $v'$ .

It is readily apparent why the type of direct measurement described above is not feasible. The ionization produced by A electrons occurs within the same region of air as that generated by B electrons; thus, the two contributions to the measured charge cannot be separated. It is for this reason that free-air ionization chambers, devised for

\*Its size must be small in comparison with any spatial variations in the radiation field, yet large enough to contain a statistically large number of energy-transfer events during the period of exposure. Whenever the word small is used in this sense, it will be enclosed by quotation marks.

†This is the mass of 1 cm<sup>3</sup> of dry air at 0 °C and 760 mm Hg.

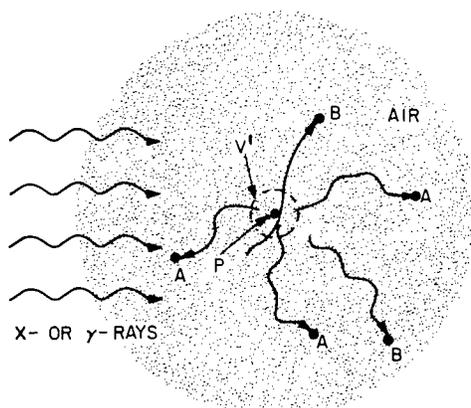


Fig. 1 - The concept of exposure dose

measuring the exposure dose, rely upon both charged-particle compensation and integral charged-particle equilibrium to accomplish their purpose. But before proceeding to a discussion of free-air chambers, it will be worthwhile to explain what is meant by the above and other related terms, some of which have been coined here to help clarify the principles underlying radiation dosimetry in general, and free-air chambers in particular. Appendix A lists these pertinent definitions for convenient reference.

#### CHARGED-PARTICLE EQUILIBRIUM AND CHARGED-PARTICLE COMPENSATION

Charged-particle equilibrium, or CPE,\* is often referred to as "electronic equilibrium" in connection with x- or  $\gamma$ -ray usage. It has usually been defined either as we have defined it in the Appendix or, alternatively (2), as follows: "Electronic equilibrium exists at a point if for each electron leaving an infinitesimal volume surrounding the point another electron of practically the same energy enters." Actually the appendix definition and this definition are not quite the same in meaning. CPE can exist under the former without requiring the latter to be satisfied (e.g., one electron of energy  $E$  may leave and two electrons enter with energy  $1/2 E$ ).

In the present paper we have separated the two concepts. CPE, by the appendix definition, exists at a point if the energy dissipated by charged particles within a "small" spherical volume centered at the point is the same as if all the charged particles originating within the volume had spent their entire kinetic energies there. On the other hand, charged-particle compensation (CPC) (see Appendix, No. 10) exists at a closed boundary if there is a 1-for-1 exchange of charged particles of the same kind and energy across the boundary.

The concept of energy transfer† (see Appendix, No. 3) makes it possible more easily to discuss CPE, among other things, because it allows one to state an even simpler definition of CPE: CPE exists at a point if the absorbed dose equals the energy transfer there. The exposure dose (Appendix, No. 5) is evidently a special case of the energy transfer.

\*The reader will please forgive the liberal use of first-letter abbreviations for several of the terms which occur repeatedly throughout the text.

†Energy transfer has no generally accepted name. Roesch (4) has called it "KERM." It has sometimes been referred to as "first collision dose," but that term has not been consistently defined in the literature and generally has been used for fast neutrons. The author prefers "energy transfer" because it is so descriptive of the process of transferring energy from x-rays or neutrons to charged particles. A further discussion of this and other concepts in dosimetry is given in Ref. 5.

For describing radiation interactions within extended regions (as in a free-air chamber) rather than at local points in an irradiated medium, the integral absorbed dose and integral energy transfer are useful concepts. When these two quantities are equal for a given volume, then integral charged-particle equilibrium (ICPE) exists there. The integral exposure dose and the average exposure dose are both simple extensions of the existing definition of exposure dose. They have been defined here because they are actually involved in the interpretation of free-air chamber measurements.

In general, CPC at the surrounding boundary is a sufficient, but not necessary, condition for the existence of either CPE or ICPE. However, if CPC does exist, one is assured not only that the absorbed dose is equal to the energy transfer (or the integral absorbed dose is equal to the integral energy transfer), but also that the ionization corresponding to those energies is equal as well. This will evidently be true regardless of any energy dependence which  $w$ , the energy per ion pair, may have. Free-air chambers depend upon the existence of both CPC and ICPE, as will be presently shown.

There is a special case of ICPE where CPC exists, but only in a trivial form. This is illustrated in Fig. 2. Here we have the charged particles originating only within volume  $v'$ , located at the center of the larger region  $v$ , of which  $v'$  is a part. The dimension  $d$  is at least as large as the maximum charged-particle range. In this case, ICPE certainly exists in  $v$ . Furthermore, as a trivial case, CPC can be thought of as existing at the boundary of  $v$  where all charged particles crossing the boundary have the same energy ( $=0$ ), and they enter and leave in equal numbers ( $=0$ ). Thus the ionization produced in  $v$  must equal that produced by charged particles originating in  $v'$  (which is obvious, anyhow, in this case).

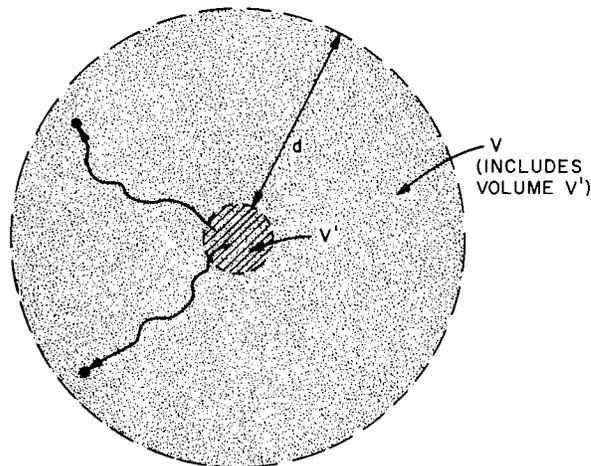


Fig.2 - Integral charged-particle equilibrium without dependence upon charged-particle compensation

It is interesting to note in Fig. 2 that, assuming the radius of  $v'$  to be less than the maximum range of the charged particles, there is no point within volume  $v$  at which CPE exists, even though ICPE is satisfied for volume  $v$ . This illustrates the importance of having separate definitions for CPE and ICPE.

Before proceeding to the discussion of free-air chambers, one more concept and definition should be dealt with. This is relative charged-particle equilibrium (RCPE), which becomes important at high x-ray energies where the electron ranges become comparable with the x-ray mean-free-path  $1/\mu$ . (Here  $\mu$  is the linear attenuation coefficient of the x-rays.)

RCPE exists throughout a region of an irradiated material if at each point within that region the ratio of the absorbed dose and the energy transfer has the same value.\*

This is illustrated schematically in Fig. 3. A broad, parallel beam of high-energy x-rays is shown incident upon a block of material. The rate of transfer of energy from the x-rays to energetic secondary electrons is shown by the energy transfer curve, which is monotonically attenuated as the x-rays penetrate the material. The absorbed dose curve rises with depth initially because the secondary electrons, which deposit the absorbed dose, are projected predominately forward, away from the boundary. A maximum is reached approximately at the depth where the absorbed dose equals the energy transfer (6), and thereafter the absorbed dose decreases with depth. At depths greater than  $d$ , the maximum electron range, the two curves parallel each other. At each depth the ratio of absorbed dose to energy transfer is a constant greater than 1. According to Roesch (4) the absorbed dose  $D$  can be related to the energy transfer  $T$  at any point such as  $P$  by the approximate equation:

$$D \cong T(1 + \mu \bar{x}) \quad (1)$$

where  $\mu$  is the x-ray attenuation coefficient corresponding to the slope of the  $D$  or  $T$  curve at depths greater than  $d$  and  $\bar{x}$  is approximately the distance "upstream" to the point  $P'$ , where the energy transfer is equal to the absorbed dose at the point of interest  $P$ . The distance  $\bar{x}$  can be calculated by methods described by Roesch (4). It is clear from the definition of RCPE that it exists in this case at depths greater than  $d$ .

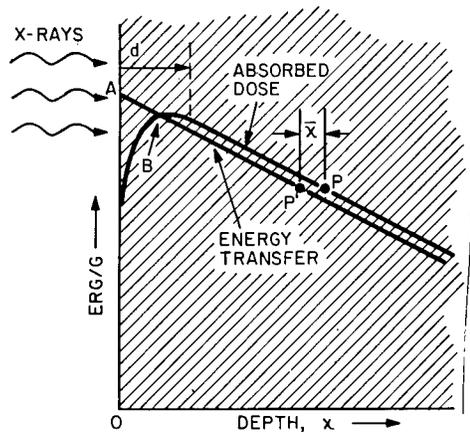
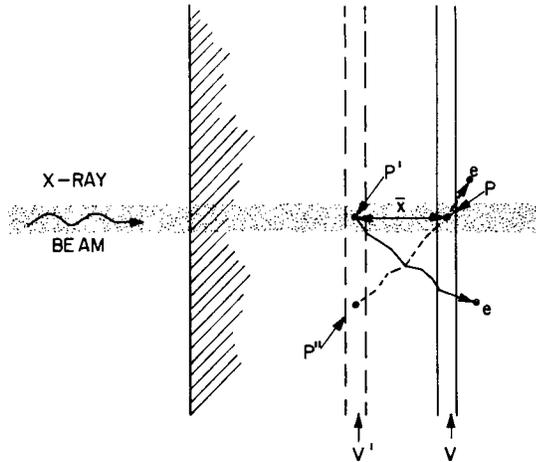


Fig. 3 - Relation between absorbed dose and energy transfer under conditions of relative charged-particle equilibrium (RCPE)

The foregoing case shown in Fig. 3 applies to the central region of a  $\gamma$ -ray beam which is broad relative to the electron range. For a narrower beam (which is the usual situation in free-air chambers) a condition analogous to RCPE can be shown to exist. Figure 4 illustrates this case. It is clear that the absorbed dose and energy transfer at  $P$  will not be related in any simple way, because many of the electrons originating upstream (e.g., at  $P'$ ) will be projected out of the beam at an angle, thus not arriving at  $P$ . In the broad beam case (Fig. 3), these are replaced by other electrons originating elsewhere in the beam (e.g., at  $P''$ ), thus producing RCPE. For the narrow beam case, the simple relationship given in Eq. (1) can be obtained from the integral absorbed dose and the integral energy transfer in a slab-shaped volume like  $V$ . That is, the integral absorbed dose  $D_i$  in  $V$  is approximately  $(1 + \mu \bar{x})$  times the integral energy transfer  $T_i$  in  $V$ , or is equal to the integral energy transfer in a like slab  $V'$  at a distance  $\bar{x}$  upstream. Over an

\* If that value is 1, then CPE also exists.

Fig. 4 - The concept of relative integral charged-particle equilibrium (RICPE)



extended region where all similar volumes satisfy this relationship with a constant  $\bar{x}$ , one can say that relative integral charged-particle equilibrium (RICPE) exists.

In the next sections, the application of these concepts in free-air chambers will be discussed.

THE CONVENTIONAL FREE-AIR CHAMBER

Figure 5 is a schematic diagram of a typical free-air chamber of the parallel-plate type. The cylindrical type is identical in principle.

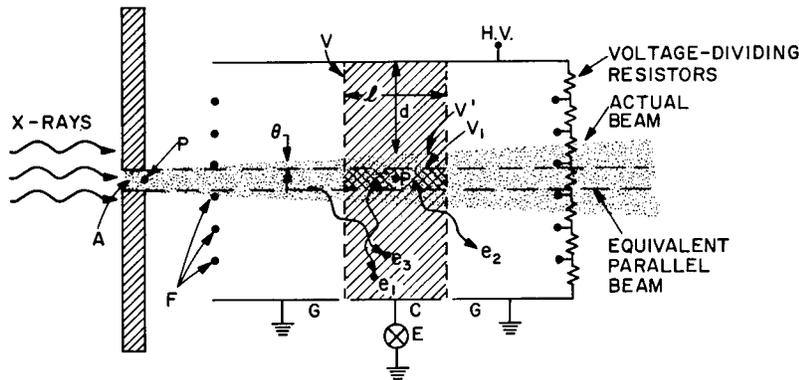


Fig. 5 - The conventional guarded-field, parallel-plate, free-air ionization chamber. Ionization is collected from the volume  $v$ .

Coplanar electrodes G-C-G are operated at ground potential; the opposite plate is operated at a constant high voltage. Collecting plate C is connected to a null-type electrometer circuit. Guard plates G and end-guarding electrodes F are designed to give a uniform field between the plates so that the length  $l$  of the shaded, ion-collecting region  $v$  will be accurately defined. (This region is analogous to the ion-collecting volume  $v$  in Fig. 2.)

The distance  $d$  from the beam to the plates is made large enough to allow laterally-projected electrons like  $e_1$  to spend all their energy in the ion-collecting region without reaching the wall. The distance of the volume  $v$  from either end of the chamber is also made greater than the electron range, for reasons which will presently be evident.

It is interesting to consider the logical basis for the free-air-chamber's ability to measure exposure dose. This will be set forth point by point as follows:

1. Assume that x-rays of constant intensity are passed through the aperture for a certain period of time. If the recombination of ions is negligible, the ionization (of either sign) generated throughout  $v$  will be collected on  $c$  and the total charge measured.

2. This ionization is not necessarily equal to that generated by those electrons which originate in  $v$ . Therefore we must rely upon the existence of CPC over the entire boundary of  $v$ . That is, for every electron such as  $e_2$  which escapes  $v$ , another electron  $e_3$  of the same energy must enter.\* Under these conditions, not only does ICPE exist for volume  $v$ , but also the ionization generated there is equivalent to that generated by electrons originating there. Thus the ionization in  $v$  equals the integral exposure dose there.

3. The integral exposure dose for  $v$  is identical to that for the volume  $v'$ , since no ionizing electrons originate outside the x-ray beam.†

4.  $v'$  is the volume in which the "associated corpuscular emission" (i.e., electrons) originates, as specified in the roentgen definition. Because the x-ray source is generally not a sharply defined point and because of the inverse-square divergence of the beam,  $v'$  will usually be a conic frustum with radial boundaries made indistinct by penumbra effects. The problem of determining its effective volume (and, in turn, the air mass it contains) would be formidable by any direct approach. Instead a simple and accurate trick (9-11) is employed which has the effect of converting the measurement into a determination of the exposure dose at the aperture rather than in the center of the chamber. The actual beam is replaced, for purposes of calculation, by an imaginary parallel beam having the same cross section and intensity at the aperture. The ionization produced in  $v$  by the parallel beam would be very nearly the same as for the actual one, provided that  $\cos \theta \approx 1$  (for example,  $\cos 2-1/2^\circ = 0.999$ ).‡

5. Thus  $v'$  is replaced by the cylindrical volume  $v_1$  which has the cross-sectional area  $A$  of the aperture and a length equal to the effective collector-plate length  $l$ . The integral exposure dose in  $v_1$  is the same as in  $v$ . Dividing by the mass of air in  $v_1$ , expressed in units of 0.001293 g, one gets the average exposure dose in  $v_1$ . If the air attenuation is small enough, it will be nearly linear over the distance  $l$ , and the average exposure dose in  $v_1$  will equal the exposure dose at the midpoint  $P'$ .

6. The exposure dose is the same at all points in the parallel beam, except for the effect of air attenuation. Thus the exposure dose at the aperture point  $P$  can be obtained from that at  $P'$  by an air-attenuation correction for the distance between the two points..

\*According to Ref. 7, this is assured at least up to 500-kv x-rays.

†Actually some electrons do originate outside the beam generated by x-rays scattered by (a) the aperture or (b) the air in the chamber. This contribution to the ionization is determined by a separate measurement and is subtracted out since (a) is not part of the primary beam proceeding through the aperture, and (b) represents x-rays attenuated (i.e., scattered out of the main beam) before reaching volume  $v$ . (See Ref. 8, footnote 3.)

‡If the x-ray source is near the aperture and  $\theta$  becomes large, the path of a ray through  $v$  will become significantly longer than that of a ray entering perpendicularly. Also, the air-attenuation distance from the aperture to  $v$  is lengthened.

This is the basis for free-air chamber operation at x-ray energies low enough so that CPC exists at the boundaries of  $V$ . However, at higher energies, where the ranges of the electrons become comparable to the x-ray "ranges" and the electrons are projected predominantly in the forward direction, CPC breaks down and ICPE does not obtain. There are more electrons coming into the front of  $V$  than are leaving it through the rear, thus giving rise to excessive ionization in  $V$ . This is a case similar to that in Fig. 4. However, in the chamber region lying at least as far from the aperture as the electron range, RICPE will exist. In a properly designed chamber the collecting volume  $V$  will be located in this region. Thus one can use Roesch's formula, Eq. (1), in relating the ionization to the integral exposure dose in  $V$ .

$$D_i = JW \cong T_i (1 + \mu \bar{x}) = R_i W (1 + \mu \bar{x}) \quad (2)$$

or

$$R_i = \frac{J}{(1 + \mu \bar{x})} \quad (3)$$

where

$D_i$  = integral absorbed dose in  $V$  (erg)

$J$  = ionization in  $V$  (esu)

$W$  = energy to produce unit charge in air (erg/esu)

$T_i$  = integral energy transfer in  $V$  (erg)

$R_i$  = integral exposure dose in  $V$  (esu).

Note that under this procedure one still applies an air-attenuation correction for the distance from  $P$  to the midpoint  $P'$ . The net effect is the same as if one instead applied an air-attenuation correction for the distance from  $P$  to a point at a distance  $\bar{x}$  upstream from point  $P'$ , while omitting the correction given in Eq. (3).

#### THE PROPOSED NEW TYPE OF FREE-AIR CHAMBER

The new proposed design of free-air chamber is shown in Fig. 6. It is based upon a subtraction method in which two readings are taken of the ionization and the difference is used as the measure of exposure dose.

In Fig. 6(a) the chamber is shown in its collapsed condition. It may consist of two telescoping cylinders, or a piston within a cylinder. The interior surfaces of the two ends are covered by a layer of "air-equivalent" conducting material, such as graphite or Aquadag-coated Lucite, having a thickness at least equal to the maximum range of the secondary electrons generated by the x-ray energies for which the chamber is designed. The structural material (but not the air-equivalent lining) is penetrated at the center of the two ends by entrance and exit ports for the x-ray beam. The air-equivalent material covering these ports serves the double purposes of (a) excluding electrons which originate outside the chamber, and (b) acting as a source of secondary electrons to replace those lost into the chamber ends. More will be said about this latter function.

The cylindrical wall of the chamber should be made of a fairly low atomic number material (e.g., aluminum) so that the ionization due to scattered x-ray interactions will not be enhanced by the photoelectric effect (see second footnote on page 6).

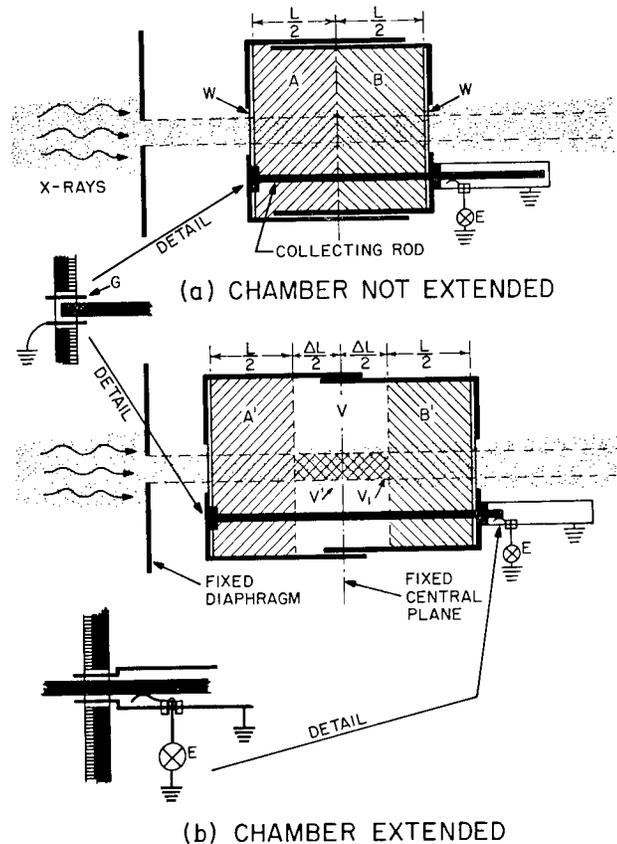


Fig. 6 - The proposed new type of free-air chamber. The defining aperture and the mid-plane of the chamber both remain fixed with respect to the x-ray beam.

The entire chamber wall (front, back, and sides) is operated at a sufficiently high voltage to collect, on an off-center aluminum rod, substantially all of the ionization produced in the chamber. This rod should be large enough in diameter to avoid gas-multiplication of the ionization. It is allowed to slide through an insulating bushing in the back wall of the chamber as the latter is collapsed, thus projecting outside into a grounded electrostatic shield containing a slide contact leading to the electrometer. Both the front- and back-end insulators of the collecting rod are provided with a grounded guard ring G to eliminate the leakage of current across the insulator to the rod. These guard rings are made to extend a short distance into the chamber to also intercept any gas-multiplied ionization occurring in the high-field region immediately adjacent to the collecting rod insulators. As will be pointed out later, the ionization lost to the guard rings is unimportant as long as it is approximately the same at both ends of the chamber.

The internal dimensions of the chamber are dictated by the x-ray energies for which it is to be used. For a chamber covering the x-ray voltage range of 50-250 kv (constant potential), a diameter of 30 cm would be appropriate, reducing the losses due to electrons terminating in the walls to a few tenths of a percent in the worst cases.\* The length of the chamber in its collapsed condition should then also be about 30 cm or more to insure

\* This estimate is based upon data given in Ref. 8. In addition to these losses there will be some electrons which terminate their track prematurely by colliding with the ion-collecting rod. A small correction for this effect should be made by the method described in Ref. 8.

that electrons originating at the center of the chamber cannot reach the walls in any direction. For a high-energy x-ray chamber ( $\approx 1$  Mev) in which the secondary electrons are projected strongly forward, a length-to-diameter ratio greater than 1 (in the collapsed condition) would be indicated. A chamber designed for x-rays of 50 kv and lower would require a diameter of only 4 cm (12).

The x-ray beam is defined by a fixed aperture which does not move with respect to the x-ray beam. In the event the output of the x-ray machine is not strictly constant with time, an auxiliary ionization chamber may be located in a fixed position somewhere in the x-ray beam (e.g., behind the free-air chamber). Measurements will then be normalized to the readings of this monitor chamber.

In Fig. 6(b) the chamber is shown in its expanded condition. The front and back of the chamber are extended equally so that the midplane remains fixed with respect to the x-ray beam and the aperture. This can be accomplished by means of an accurately machined screw, allowing great precision in determining the change in length. A motor drive would provide rapid and convenient operation. The chamber should be vented sufficiently to allow the free flow of air in and out during changes in length, without appreciable changes in the air temperature within.

The change in length  $\Delta L$  should be sufficiently large to allow accurate determination of the difference in ionization. A factor-of-two extension would be a reasonable choice.\*

#### OPERATION OF THE NEW CHAMBER

In order to determine the exposure dose, two measurements of the ionization current are needed. The first is done with the chamber in its collapsed condition, as in Fig. 6(a). Here the ionization can be thought of as consisting of two contributions - the first is the ionization  $J_A$  produced in the forward half of the chamber (volume A) while the second is  $J_B$ , produced in the rear half (volume B).

Bearing in mind that the chamber is constructed symmetrically about its midplane, one can relate  $J_A$  and  $J_B$ . First consider the case where the x-ray attenuation is approximately linear over the change in length ( $\Delta L$ ) of the chamber (i.e.,  $e^{-\mu \Delta L} \approx 1 - \mu \Delta L$ ). This will generally be the case in the medium x-ray energy region from 50 to 500 keV, assuming that  $\Delta L \approx L$ . Under these conditions, CPC will exist at the boundaries of volumes A and B (see Fig. 6(a)). Electrons escaping into the rear wall from volume B will be replaced by those entering from volume A, and so on, thus giving ICPE in both volumes A and B. The net result is that  $J_A$  will be nearly equal to  $J_B$ , except for a small attenuation correction for the x-rays over the length  $L/2$  between centers of A and B. In the present case where the attenuation is linear over the length  $L$ , this correction is completely negligible.  $J_A$  and  $J_B$  do not have to be exactly equal, as small differences tend to cancel out when the chamber is extended, as will be shown next.

Suppose the chamber is extended about its midplane of symmetry by an amount  $\Delta L$ . This midplane and the x-ray beam-defining diaphragm are fixed with respect to the source. A larger ionization current will be observed, consisting of three components:

- $J_{A'}$  : the ionization produced in volume A' (the same volume as A, but moved upstream by a distance  $\Delta L/2$ ),
- $J_{B'}$  : the ionization produced in volume B' (the same as volume B, but moved downstream by a distance  $\Delta L/2$ ),

\* Alternatively, readings of the ionization can be made at several length settings and the slope of ionization vs length determined.

$J_V$  : the ionization produced in volume  $V$ , which is a new volume of length  $\Delta L$  centered at the midplane, introduced by the process of lengthening the chamber.

$J_{A'}$  will be greater than  $J_A$ , because the x-ray beam traverses a shorter air path (by the distance  $\Delta L/2$ ) in arriving at the volume  $A'$  than it does for  $A$ . Thus the x-rays suffer less attenuation. Similarly  $J_{B'}$  will be less than  $J_B$  by that amount, since volume  $B'$  is downstream from  $B$  by the distance  $\Delta L/2$ . Assuming linearity of the x-ray attenuation, we have

$$J_{A'} = \left(1 + \frac{\mu \Delta L}{2}\right) J_A$$

and

$$J_{B'} = \left(1 - \frac{\mu \Delta L}{2}\right) J_B \quad (4)$$

Thus,

$$J_{A'} + J_{B'} = J_A + J_B + \frac{\mu \Delta L}{2} J_A - \frac{\mu \Delta L}{2} J_B \quad (5)$$

It is clear from Eq. (5) that  $(J_{A'} + J_{B'}) = (J_A + J_B)$ , if  $J_A = J_B$ . However  $J_A$  may not exactly equal  $J_B$ . In construction of the chamber, a slight lack of symmetry might inadvertently be built in, e.g., the ionization lost to one guard ring might actually be larger than that to the other. Or, the "air equivalent" material on the front and back walls may not be exactly air equivalent, resulting in a CPC imbalance. Even without these causes,  $J_B$  will be slightly less than  $J_A$  because of x-ray attenuation, so that even if the chamber were otherwise perfectly symmetrical

$$J_B = \left(1 - \frac{\mu L}{2}\right) J_A \quad (6)$$

As an illustration of the effect of  $J_A \neq J_B$ , consider the extreme case where  $J_B = 0.9 J_A$  and  $\mu \Delta L = 0.04$ . From Eq. (5) we have

$$\begin{aligned} J_{A'} + J_{B'} &= J_A + J_B + J_A (.02 - 0.9 \times 0.02) \\ &= 1.002 J_A + J_B \\ &\approx 1.001 (J_A + J_B) \end{aligned} \quad (7)$$

Hence a difference of 10 percent between  $J_A$  and  $J_B$  in this case results in a difference of 0.1 percent between  $(J_{A'} + J_{B'})$  and  $(J_A + J_B)$ . It is reasonable to expect that in any actual situation such a large difference in  $J_A$  and  $J_B$  would not occur. Thus one can generally assume the equality of  $(J_A + J_B)$  and  $(J_{A'} + J_{B'})$ . The difference between the ionization measured after the chamber is extended and that measured before extension is, thus, just  $J_V$ , the ionization from the middle volume  $V$ .

This volume is analogous to the collecting region  $V$  in the conventional free-air chamber (see Fig. 5). All the electrons which produce ionization within it originate in the air, since none can reach it from the end windows of the chamber. For x-rays up to 500 kv, CPC will exist over the boundary surface of  $V$ , so that  $J_V$  will be equal to the integral

exposure dose for V. The same line of argument as was used for the conventional chamber applies here also to arrive at the exposure dose at the x-ray aperture.\*

It is evident that the end planes of volume V are not defined by electrostatic lines of force in this chamber, as is the case for the conventional chamber. Rather, they are the planes parallel to the midplane, located at a distance  $\Delta L/2$  in front and in back of it. The electric field pattern inside the chamber is of no consequence as long as the degree of saturation is not affected by the extension in chamber length. Thus the new chamber has no need for guard plates and other field-shaping electrodes which are typical of conventional free-air chambers. Since the uncertainty about the degree of field uniformity represents the largest single source of error in conventional free-air chambers (2), its elimination is a considerable advantage.

For x- and  $\gamma$ -ray energies above about 500 kev, CPC begins to fail within the new chamber, as in the conventional one. ICPE no longer exists within the chamber but, because of the presence of the air-equivalent end liners, RICPE will be present. That is, the absorbed dose will exceed the energy transfer by a constant ratio for each of the volumes A, A', B, B', and V. The Roesch correction, Eq. (3), is applied in the usual way to derive the integral exposure dose in V from the ionization produced there.

The previous arguments given in relating  $(J_A + J_B)$  and  $(J_{A'} + J_{B'})$  must be revised for the case of high-energy x-rays because  $\Delta L (\approx L)$  may be too large to assume linearity of attenuation. Assuming the difference between  $J_A$  and  $J_B$  to be due only to attenuation of x-rays, we have

$$J_B = J_A e^{-\frac{\mu L}{2}} = J_A \left( 1 - \frac{\mu L}{2} + \frac{(\mu L/2)^2}{2!} - \dots \right) . \quad (8)$$

\*A cautionary word about the small corrections which must be taken into account:

The ionization current saturation as a function of applied collecting voltage should be checked with the chamber both extended and collapsed. In each case, the current vs  $1/\text{voltage}$  is plotted and extrapolated to the  $(1/\text{voltage}) = 0$  axis to obtain the ionization for complete saturation conditions.

The correction for x-ray attenuation and scattering in the air-equivalent window materials can be obtained by observing the effect of adding more material simultaneously to the front and back windows and extrapolating the curve of ionization current vs thickness back to zero thickness.

Correction for the unwanted contribution of x-rays scattered out of the air column within the chamber can be made approximately by use of data given in Ref. 1, or more precisely, by the absorbing-tube method described in Refs. 8 and 12. In the latter case, the measurement is done for both the collapsed and extended chamber.

Note that these corrections are usually of the order of less than one percent and, thus, need not be redetermined with every measurement. The saturation correction may be established once and for all for several representative combinations of dose rate and x-ray quality, and the scattering corrections may be determined for several typical x-ray qualities. These corrections could then be applied routinely to future chamber measurements.

The sum of  $J_{A'}$  and  $J_{B'}$  can be expressed as

$$\begin{aligned}
 (J_{A'} + J_{B'}) &= J_A e^{\frac{\mu \Delta L}{2}} + J_B e^{-\frac{\mu \Delta L}{2}} \\
 &= J_A \left( 1 + \frac{\mu \Delta L}{2} + \frac{(\mu \Delta L/2)^2}{2!} + \dots \right) \\
 &\quad + J_B \left( 1 - \frac{\mu \Delta L}{2} + \frac{(\mu \Delta L/2)^2}{2!} - \dots \right) \\
 &= (J_A + J_B) + \frac{\mu \Delta L}{2} (J_A - J_B) + \frac{(\mu \Delta L/2)^2}{2!} (J_A + J_B) \quad (9)
 \end{aligned}$$

where terms of higher order than  $\mu^2$  have been dropped as negligible.

Combining Eqs. (8) and (9) we have

$$(J_{A'} + J_{B'}) = J_A \left( 2 - \frac{\mu L}{2} + \frac{\mu^2 L^2}{8} + \frac{\mu^2 L \Delta L}{4} + \frac{\mu^2 (\Delta L)^2}{4} \right) \quad (10)$$

And finally, the ratio of  $(J_{A'} + J_{B'})$  to  $(J_A + J_B)$  is

$$\frac{(J_{A'} + J_{B'})}{(J_A + J_B)} = 1 + \frac{\mu^2 [L \Delta L + (\Delta L)^2]}{8 - 2\mu L + \frac{\mu^2 L^2}{2}}$$

Thus we see that this ratio may not be exactly equal to one. In application, this correction factor is to be multiplied by the  $(J_A + J_B)$  observed in the initial chamber measurement and the result subtracted from the final extended chamber measurement, as previously discussed. This correction turns out to be very small, as will be seen in the following two examples:

First consider  $\text{Co}^{60}$   $\gamma$ -radiation. We will assume  $0.400 \text{ g/cm}^2$  to be adequate for the  $L/2$  dimension of the chamber\* (10) and also take  $\Delta L = L = 0.800 \text{ g/cm}^2$ .  $\mu = 0.0576 \text{ cm}^2/\text{g}$  in air for this energy. Then

$$\frac{J_{A'} + J_{B'}}{J_A + J_B} = 1.0006$$

This 0.06 percent is considerably smaller than the Roesch correction of 0.47 percent required at this energy.†

\* Clearly, a high-pressure-type free-air chamber is needed here (13). In the case of the next example, 6-Mev x-rays, no free-air chamber has thus far even been attempted. Recombination of ions would be extremely severe at the very high pressures ( $\approx 100 \text{ atm}$ ) necessary to accommodate such long-range electrons within a chamber of reasonable size ( $L \approx 1/2$  meter).

† Roesch's data (4) are calculated for aluminum but will be approximately correct for air also.

For a second example we take 6-Mev x-rays. We assume  $L = \Delta L = 5.90 \text{ g/cm}^2$  and  $\mu = 0.0250 \text{ cm}^2/\text{g}$ . Thus  $(J_{A'} + J_{B'})/(J_A + J_B)$  becomes 1.0056. The corresponding Roesch correction is 2.3 percent in this case (4), or about four times larger. One concludes that the nonlinearity correction in the new chamber is considerably smaller than is the Roesch correction at the same x-ray energy and is quite straightforward to calculate.

In all the above discussions, the attenuation coefficient  $\mu$  of the x-rays in air was taken to be a single constant value throughout the length of the chamber. In view of the distribution of quantum energies generally present,  $\mu$  will actually be an effective value, usually obtained experimentally for the x-ray spectrum in question or taken from the literature (1,14) for a beam of similar quality. Day and Taylor (14) report some filtering action of air on very low energy x-ray beams (10-kilovolt potential, 1.5-mm beryllium window x-ray tube), but even in this extreme case the assumption of constant  $\mu$  seems to be adequate over an air path length of a few centimeters.

## DISCUSSION

An attempt has been made here to clarify some of the principles underlying the operation of conventional free-air chambers. To do this it was found desirable to define certain quantities and concepts not currently in popular usage. In particular, the term "charged particle (or electronic) equilibrium" has long been used to cover several distinct ideas which really should be recognized as separate.

As for the proposed new type of free-air chamber, one will recognize that it possesses at least one important advantage over a conventional chamber. That is the elimination of the field-uniformity problem. This should result in considerable savings in construction costs, as well as better absolute accuracy.

It has been brought to the attention of the author in private communications with Dr. A. Allisy at the Ecole Normale Superieure in Paris that Allisy, Roux, and Seguin have recently developed a new type of free-air chamber which also incorporates the idea of difference readings of the ionization (15). It was devised to be used in the x-ray energy range from 5 to 50 kv and permits the measurement of ionization as the length of the collecting plate approaches zero. In design it resembles closely a conventional parallel-plate free-air chamber, complete with guard plates and other field-guarding electrodes. However, it has a triangular collecting electrode in place of the usual rectangular one, and the whole composite plate (guard plates + collector) can be moved, in its own plane, in a direction lateral to the x-ray beam. Thus the trapezoidal collecting volume varies in mean length. The advantage of this chamber over conventional chambers is that differences in the length of the collecting region are measured by a precisely machined screw probably with greater accuracy than one can determine the actual length of the collecting region in a conventional chamber. However, this advantage will be lost unless the gaps separating the triangular collecting plate from the guard plates are extremely uniform along their length, thus assuring that "end effects" cancel out.

This problem does not arise in the design proposed in the present paper. Furthermore, all the guard plates and strips still present in the Allisy design have been eliminated, since field uniformity is no longer necessary. The two chamber designs are similar only to the extent that they both measure ionization differences.

A free-air chamber of the new type, to operate between 50 kv and 150 kv, is currently under construction at NRL. Its operating characteristics will be reported upon in a later report.

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## APPENDIX A

## DEFINITIONS OF IMPORTANT TERMS

1. "Absorbed dose of any ionizing radiation is the energy imparted to matter by ionizing particles per unit mass of irradiated material at the place of interest" (2). The unit of absorbed dose is the rad (=100 erg/g) or erg/g. "At the place of interest" can be interpreted as within a small\* sphere centered at the point for which the absorbed dose applies.
2. Integral absorbed dose in a certain region is the energy imparted to matter by ionizing particles in that region (2). The unit of integral absorbed dose is the gram rad (=100 erg) or erg.
3. Energy transfer of x- or  $\gamma$ -radiation† at any point in an irradiated material is the kinetic energy passed on to charged particles through primary interactions within a "small" sphere centered at the point, plus the energy deposited in the material within the sphere by those primary interactions,‡ divided by the mass of material in the sphere. This can be expressed in erg/g.
4. Integral energy transfer of x- or  $\gamma$ -radiation in any region of an irradiated material is the kinetic energy passed on to charged particles through primary interactions within the region, plus the energy deposited in the material within the region by those primary interactions. This can be expressed in erg.
5. "Exposure dose§ of x- or  $\gamma$ -radiation at a certain place is a measure of the radiation that is based upon its ability to produce ionization. The unit of exposure dose of x- or  $\gamma$ -radiation is the roentgen. One roentgen is an exposure dose of x- or  $\gamma$ -radiation such that the associated corpuscular emission per 0.001293 g of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign" (2).
6. Integral exposure dose of x- or  $\gamma$ -radiation in a certain region is a measure of the radiation that is based upon its ability to produce ionization. The unit of integral exposure dose is the 0.001293 g-roentgen, or if the air is specified at 0°C and 760 mm Hg this unit may be expressed more simply as esu of electric charge.
7. Average exposure dose of x- or  $\gamma$ -radiation in a certain region is the integral exposure dose divided by the mass of air contained in the region, expressed in units of 0.001293 g. The unit of average exposure dose is the roentgen.

\* Its size must be small in comparison with any spatial variations in the radiation field, yet large enough to contain a statistically large number of energy-transfer events during the period of exposure. Whenever the word small is used in this sense, it will be enclosed by quotation marks.

† The concept also applies to neutrons and to distributed  $\beta$ -ray and  $\alpha$ -particle sources.

‡ This energy is usually negligible in comparison with the energy given to charged particles.

§ Exposure dose can be regarded as a special case of the energy transfer, where

- (a) The kinetic energy is expressed in terms of the ionization which it produces in air, (assuming energy radiated as bremsstrahlung to be negligible).
- (b) The reference material for which it is defined is always taken to be air, and
- (c) The primary radiation is always x- or  $\gamma$ -rays, with energy not exceeding 3 Mev (2)

8. Charged-particle equilibrium (CPE) (often called "electronic equilibrium" in the case of x- or  $\gamma$ -radiation) exists at a point in an irradiated medium if the energy dissipated by charged particles within a "small" spherical volume centered at the point is the same as if all the charged particles originating within the volume had spent their entire kinetic energies there. An alternative and more concise definition of CPE is that, at the point in question, the absorbed dose equals the energy transfer.
9. Integral charged-particle equilibrium (ICPE) exists for a region in an irradiated medium if the energy dissipated by charged particles within the region is the same as if all the charged particles originating there had spent their entire kinetic energies within that region. Alternatively, ICPE exists if the integral energy transfer equals the integral absorbed dose for the region.
10. Charged-particle compensation (CPC) exists at a closed boundary if for every charged particle of a certain energy which crosses the boundary in one sense there is a similar charged particle of the same energy crossing in the opposite sense somewhere on the boundary. CPC is a sufficient but not a necessary condition for the existence of CPE or ICPE. If there is no flow of charged particles in or out across the boundary, CPC can still be said to exist, but as a trivial case.
11. Relative charged-particle equilibrium (RCPE) exists throughout a region of an irradiated material if at each point within that region the ratio of the absorbed dose and the energy transfer has a common value. (If that constant is 1 then CPE also exists for all points in the region.)
12. Relative integral charged-particle equilibrium (RICPE) exists throughout a region of an irradiated material if for each one of a set of similar subdivisions of that region the ratio of the integral absorbed dose and the integral energy transfer has a common value. (If that constant is 1 then ICPE also exists for each of the subdivisions.)

\* \* \*