THE MEASUREMENT OF LOW-VOLTAGE X-RAY INTENSITIES [1]

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ABSTRACT

A special type of chamber has been designed to measure the ionization produced by 3 to 12 kv X rays in a known volume of unrestricted air, thus making it possible to express the intensity of the X-ray beam in roentgens per minute. By the use of a very small guarded field ionization chamber (5 by 5 cm), the air-absorption correction is reduced several fold, and hence errors in its determination are not so serious in the final result sought. It is shown that air-absorption corrections must be determined separately for each beam of radiation used, and the chamber is so designed that the necessary corrections may be determined without recourse to other special apparatus. Examples are given showing in detail the methods of making measurements with the chamber described. Compared at higher voltages (40 to 90 kv) with a large primary standard ionization chamber, the small type here described shows a divergence of about ±0.5 per cent which is believed to be the over-all error present in its use. In order to obtain this close agreement it is necessary to take special precautions in the construction and measurement of the limiting diaphragm and the collector electrode.

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I. INTRODUCTION

With the increasing clinical use of soft X rays, excited by potentials of 3 to 12 kv (peak), arises the necessity for their more accurate measurement such as obtains with the higher voltage radiations. This is particularly important in view of the fact that such radiation may furnish an erythema dose in one or two minutes. In fact errors in measurement assume even greater importance than for high-voltage X rays.

Although several investigators have reported on the measurement of soft X rays (so-called grenz rays), they have given but few essential details of the methods they employed.[2 3 4] This obscurity led us to construct an open-air ionization chamber capable of measuring soft

[1] Presented at annual meeting of Radiological Society of North America, St. Louis, December, 1931.
[2] H. Kustner, Strahlentherapie, vol. 27, p. 124, 1928.
[3] B. Rajewsky and G. Gabriel, Strahlentherapie, vol. 30, p. 20, 1928.
[4] Otto Glasser, Chap. III of Grenz Ray Therapy, by Gustav Bucky, Macmillan, 1929. See also Radiology.

X rays, and to compare it with the standard used for measuring high-voltage X rays.[5] A chamber has, therefore, been designed which measures reliably X rays excited by voltages ranging from 3 to 80 kv (peak), covering not only the "grenz-ray therapy" (3 to 12 kv) but also the lower "diagnostic X-ray range" (60 to 80 kv).

Open-air chambers lacking a guarded field are not readily applicable to the measurement of soft X rays because the large air absorption correction involved can not be determined with desired accuracy. The principle of the guarded-field air-ionization chamber [5] renders it, however, particularly adaptable by permitting the air path between diaphragm and collector plates to be reduced to a minimum. The points essential to its successful application to low-voltage X rays are worked out in the present investigation.

II. DESCRIPTION OF CHAMBER

Described briefly, the guarded-field ionization chamber furnishes adequate field uniformity over the width of the collector electrode of a parallel plate ionization chamber by means of properly charged guard wires stretched across the open faces of chamber, the potentials of the wires being divided in equal successive steps between zero (at collector) and the plate potential. It has been shown that such a system permits the use of grounded metal parts (case, diaphragm, etc.) much closer to the electrodes than would otherwise be possible. In the present case the shielding and the limiting diaphragm may be brought to within 5 cm of the center of the collector plate, and air-absorption correction need be made only for this small distance.

A cross section of this special ionization chamber for soft X rays is shown in Figure 1. The electrode system consists of the high-potential plate, *A*, the two grounded guard plates, *B*, and the collector electrode, *C*, all mounted as a unit, similar to the larger type of guarded field chamber. The 4 rectangular guard wire loops, *a*, *b*, *c*, *d*, made of 10-mil aluminum, are maintained at equal potential steps, respectively, between earth and the potential of *A* by means of 5 half-megohm resistors, *r*, *r*, mounted on a hard rubber supporting frame. The entire electrode system can be slid the length of the box, *D*, on two guide rods, and its position read on the scale, *S*, which also serves as a "handle" with which to move the system from the outside.

The box, *D*, is of ⅛-inch brass, which provides sufficient radiation protection for lower-voltage X rays. For higher-voltage X rays it is further shielded with about 15 mm of lead. The rod, *H*, is connected to a source of sufficiently high potential to produce saturation current in the chamber and makes contact with the plate, *A*, through a sliding spring. Similarly the collector electrode, *C*, is connected by a sliding contact to *E*, which leads to the electrometer system. The rod, *E*, is shielded over its entire length, as shown by the section *X*, for the purpose of preventing any ions not formed within the electrode system from reaching the electrometer system. The adequacy of this shielding was tested experimentally.

The diaphragm, *n*, has an 8-mm orifice with the limiting edges cylindrical and about 1 mm thick. The chamber as a whole is

[5] L. S. Taylor and G. Singer, B. S. Jour. Research, vol. 5 (RP211), p. 507, 1930.

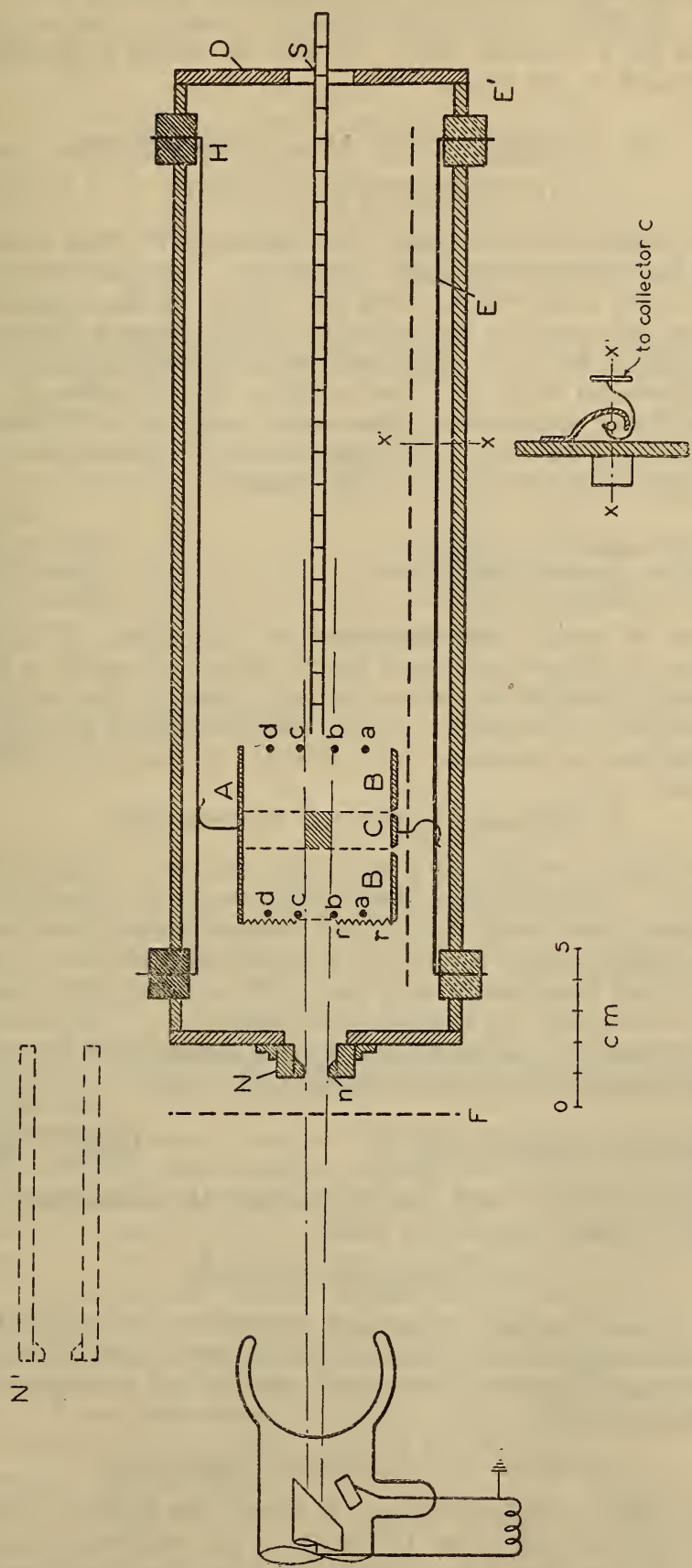

FIGURE 1.—*Cross section of special guarded-field ionization chamber for measuring low-voltage X rays or grenz rays*

mounted on a base that slides in a direction parallel to the X-ray beam axis. A series of aluminum filters, *F*, about 3 cm in diameter, are mounted on a celluloid disk, the axis of which is independently movable parallel to the axis.

III. CALIBRATION MEASUREMENTS

1. COLLECTOR ELECTRODE

Since the chamber is so small, it is imperative that its essential dimensions be known with high accuracy. The collector electrode being only about 1 cm wide, along the length of the beam, an error of 1/10 mm in determining its effective width (true width plus one-half the width of both air gaps between collector and guard plate) would introduce an error of 1 per cent in the effective air volume. The necessity for determining this with accuracy is obvious. Accordingly, through the help of the gage section of this bureau, the following typical measurements were obtained:

	mm
Width of collector electrode	9.492±0.005
Separation between guard plates	9.904± .005
Effective collector width	9.698± .005

Furthermore, to avoid field distortion at the edges, it is essential that the faces of the collector and guard plate lie exactly in the same plane. Field distortion at these edges presents one of the most serious obstacles to accurate current measurements in case, during the compensation of current, it is difficult to hold the collector at zero potential.

2. CHAMBER-LIMITING DIAPHRAGM

This diaphragm consists of a coin-gold sleeve, *n*, held in a Pb-Bi alloy ring, *N*. Its orifice was made and measured in two ways—the first by lapping the inner surface and then measuring by the plug-gage method; the second by forcing a standard steel ball through an orifice which had been previously turned to a diameter of one or two thousandths of an inch less than the ball diameter. The latter method burnished the surface and at the same time determined its size. The measured diameters of two such diaphragms were:

	mm at 68° F.
Diaphragm 1 (plug-gage method)	7.8608±0.0001
Diaphragm 2 (steel-ball method)	7.9375± .0001

It is seen that the accuracy in determining the diaphragm area by either method is about 1 part in 9,000.

3. SATURATION VOLTAGE

Voltage to saturate the ionization chamber was supplied from a 1,300-volt d. c. generator. Curve *A* in Figure 2 shows that saturation was reached at about 300 volts; hence, for normal operation, 500 volts was applied.

4. EFFECT OF SCATTERED RADIATION

In chambers for higher-voltage X rays the limiting diaphragm must be placed at least 10 to 15 cm from the collector to avoid the influence of X rays and β rays scattered from the diaphragm edges. Since the radiation from low-voltage X-ray tubes must, in general,

be measured so close to their source that a comparatively divergent beam enters the chamber, the customary type of chamber diaphragm is not satisfactory.

The diaphragm placed as shown in N by Figure 1 is satisfactory, provided the scattering from its walls is negligible. This was tested by measuring the ionization with the diaphragm in place, then again after shifting it to the end of a 10 cm extension tube, N', the chamber being shifted so as to maintain the distance from N to N' to the tube target the same. Correction was made as shown later for absorption in the 10 cm additional air path. Measurements at 40 kv (eff) gave the following results:

Intensity, diaphragm at normal position	0. 964±0. 0033
Intensity, diaphragm shifted to 10 cm	. 970± . 0027
Difference	. 006

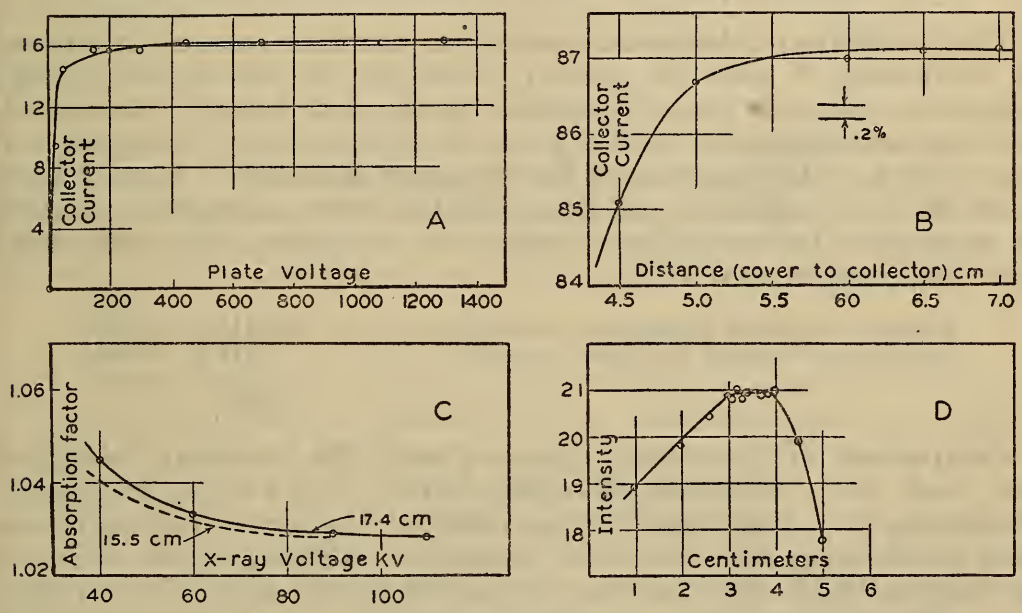

FIGURE 2

a, Saturation curve for special ionization chamber; *b*, variation of measured ionization with distance between diaphragm and ionization chamber; *c*, air absorption factor for calibration of special ionization chamber; *d*, X-ray intensity along cross section of beam used in calibrating ionization chamber.

The observed difference being of the same magnitude as the error of observation but in the direction opposite to that to be expected,[6] it is assumed that the two arrangements give identical results for the comparatively narrow beams used. In other words, the scattering effect from the walls of the diaphragm orifice is negligible.

Use of the divergent beam exposes the guard wires to the direct radiation, and this may have a scattering effect. To test for scattering from this source, two strands of 20-mil aluminum wire were suspended, insulated, in the beam between the 10-mil guard wires *b* and *c*, hence did not influence the field. The following measurements were obtained at 40 kv (eff), with no filtration:

Intensity, wires in beam	0. 295±0. 0016
Intensity, wires out of beam	. 294± . 0008
Difference	. 001

[6] This is probably due to error in the air-absorption correction.

The difference being of the magnitude of the experimental error, no appreciable effect arises from permitting the beam to strike the guard wires.

5. FIELD DISTORTION

To determine how close the electrode system may be brought to the front end of the box without introducing appreciable field distortion, X-ray intensities were measured at each of several successive positions of the electrodes with respect to the box front. Curve *B*, Figure 2, shows the observed increase in ionization as the distance from collector electrode to the diaphragm is increased. Beyond 5 cm, further change is only about 0.2 to 0.3 per cent, a magnitude smaller than the experimental error in these particular measurements.

IV. COMPARISON WITH STANDARD CHAMBER

The reliability of the special ionization chamber was finally proved by comparing it with the primary standard on the higher voltage radiation. Since it was not feasible to do this directly, the special chamber was compared with a guarded field secondary chamber and this, in turn, with the guarded field primary standard. For the same beam of 70 kv unfiltered radiation, the following measurements show an agreement between the primary and secondary chambers closer than the experimental error:

Primary standard ionization current	0.1315 ± 0.00026
Secondary standard ionization current	.1316 ± .00030
	.0001

Comparison of the special chamber with the secondary standard was made with unfiltered radiation excited by 40 to 90 kv (peak). To eliminate as many variables as possible, the same diaphragm was used interchangeably on both chambers. Likewise, the collector electrode of each chamber was connected to the same electrometer. Saturation voltages were supplied separately. Both chambers were placed in a fixed position and the tube shifted on a track, so that the same beam could enter either chamber as desired. To have this beam moderately well defined, a diaphragm 16 mm in diameter was placed about 2 cm from the wall of the 200 kv thin-walled Coolidge tube used.[7]

Ionization currents were measured by means of a null electrostatic compensator, such as was used in previous work,[8] wherein the ionization charge was compensated over a known interval of time. However, instead of exposing the chamber for a given time by means of an electrically operated shutter in the X-ray beam, the electrometer was connected to the chamber for a definite period by means of an electrically operated switch [9] located at E' (fig. 1). The chamber and electrometer were connected by a shielded rubber cable.

The effective length along the beam of the collector of the secondary standard was 4.975 cm, so that, for the same diaphragms, the effective air volumes ionized in the special and secondary chambers were in the ratio 0.9698 to 4.975. All readings with the secondary chamber were

[7] L. S. Taylor, B. S. Jour. Research, vol. 2 (RP56), p. 771, 1929.
[8] L. S. Taylor, B. S. Jour. Research, vol. 6 (RP306), p. 807, 1931.
[9] L. S. Taylor, B. S. Jour. Research, vol. 8 (RP397), p. 9, 1932.

therefore divided by 5.129 to reduce to the same effective air volume as the special chamber.

The distance between the limiting diaphragm and center of the collector electrode on the secondary chamber was 22.5 cm, as compared with 7 cm for the corresponding distance on the special chamber. Absorption in the air-path difference of 15.5 cm will, for the same beam, lower the measured current of the secondary chamber relative to that of the special chamber by a corresponding amount. Since this absorption depends upon such factors as voltage wave form, tube characteristic, and tube wall thickness, it must be determined for each set of conditions employed.

At voltages ranging from 40 to 100 kv, where the X rays pass initially through moderately thick tube walls, the radiation is sufficiently hardened so that its quality undergoes no appreciable further change in passing through 50 cm of air. In such case the air absorption is approximately proportional to the length of the air path.[10] But, as shown later, this is not true for the 4 to 12 kv radiation for which the special chamber is designed.

Air-absorption measurements to be applied in the present comparison were made with the large open air standard ionization chamber,[11] using the limiting diaphragm in a fixed position relative to the target so as to define a narrow beam passing between the chamber plates. X-ray intensities, I_1 and I_2, were then measured with the plates at the distances 110.6 and 128.0 cm, respectively, from the target. The ratio $\frac{I_1}{I_2}$, giving the air absorption correction factor for an air path of 17.4 cm, is plotted against applied voltage in curve C of Figure 2. The absorption being practically linear with distance, it is simple to correct it to fit any path length as, for example, 15.5 cm, required in the present set-up and shown by the broken curve.

To insure, in the comparison, proper alignment of the special chamber, measurements were made of the intensity of the X-ray beam over its horizontal cross section in the plane of the diaphragm, N. As shown by curve D in Figure 2, the area of effective uniformity, about 1 cm wide, indicates the range of proper alignment.[12]

Typical results of the comparison of the special with the secondary chambers, with unfiltered radiation from a thin wall, deep therapy Coolidge tube, are given in Table 1.

Table 1.—*Comparisons of special ionization chamber with secondary chamber*

kv	I_g	I_x	Absorption factor $(I_1/I_2)_{15.5}$	$\frac{I_g}{I_x}\left(\frac{I_2}{I_1}\right)_{15.5}$
40	4.63	4.46	1.040	0.998
50	2.30	2.205	1.033	1.008
70	2.88	2.79	1.028	1.003
90	6.08	6.08	1.027	.968

Column 2 gives the intensities I_g in Röntgens per minute as measured with the special chamber; column 3, the intensities, I_x, at the

[10] L. S. Taylor and G. Singer, B. S. Jour. Research, vol. 6 (RP271), p. 219, 1931.
[11] L. S. Taylor, B. S. Jour. Research, vol. 2 (RP56), p. 771, 1929.
[12] L. S. Taylor, B. S. Jour. Research, vol. 3 (RP119), p. 807, 1929.

middle of the collector, as determined with the secondary standard but uncorrected for air absorption in the extra 15.5 cm of path; column 4, the corresponding air-absorption factor as obtained from the broken curve of Figure 3 (*C*), and by which I_x is multiplied in order to obtain the intensity 15.5 cm nearer the diaphragm, at which point the special chamber is used; and the last column gives the ratio of the intensities furnished by the two chambers.

At 90 kv (peak) the small chamber indicates definitely too little ionization. This is attributed to the close spacing (5 cm) of the collector, *C*, and high-potential plate, *A*, which does not permit full utilization of the range of the photoelectrons emitted along the path of the X-ray beam. This sets a definite X-ray voltage limit above which the small chamber should not be used. The safe working range for the present chamber includes, however, the lower part of the diagnostic X-ray region and may be used where, due to "wall effect," measurements with most thimble ionization chambers become inaccurate.

V. MEASUREMENTS OF "GRENZ RAYS"

Having found agreement between the indications of the special and the standard chambers at voltages ranging from 40 to 80 kv (peak), the use of the special chamber may be extended down to any X-ray voltage for which adequate air absorption correction can be made.

For measuring so-called "grenz rays," 4 to 12 kv (peak), the necessary corrections will be indicated and the necessity for accurately measuring the air absorption for each set of experimental conditions under which the radiation is used will be brought out.

Very soft X rays (4 to 12 kv) are absorbed by air to such a degree that the radiation quality changes rapidly even in a distance of only 5 cm. The beam intensity should, therefore, be measured at the exact position, with respect to both tube and filter, where the radiation is to be applied, because it is unsafe to apply the inverse square law for computing intensitites at points other than where measured. Furthermore, it is essential to determine the air absorption between diaphragm and collector, *C*, for an air column having exactly the same position with respect to the target as the column between diaphragm and collector when the chamber is in its working position, if the point of application is taken at the position of the limiting diaphragm.

The requirements are illustrated in Figure 3, which gives a plot of the intensity of an X-ray beam as a function of the distance, *e*, from the target, *T*. At the lower part are indicated several possible positions of an ionization chamber with respect to the tube. Suppose, for example, the intensity, I_b, at the position, *b*, is to be measured. The chamber diaphragm would be placed at position, $n_1 = b$, and the middle of the collector electrode at e_1, a distance, *d*, from n_1, where *d* is the minimum working distance between collector and diaphragm. Owing to air absorption over the path, $b - c$, the intensity measured at e_1 must be corrected to give the value as if at the position, n_1. This correction can not be obtained by simply keeping n_1 fixed, and moving e_1 away an equal distance, *d*, to the position e_1' because, due to the filtering action of the air, the radiation quality at *g* is different from that at *c*.

To obtain the air absorption factor to be applied in the chamber working position, it is necessary to move the chamber, including diaphragm, toward the tube a distance, d, to the position, n_2, and then measure the intensities, I_b and I_c, obtained, respectively, at the two

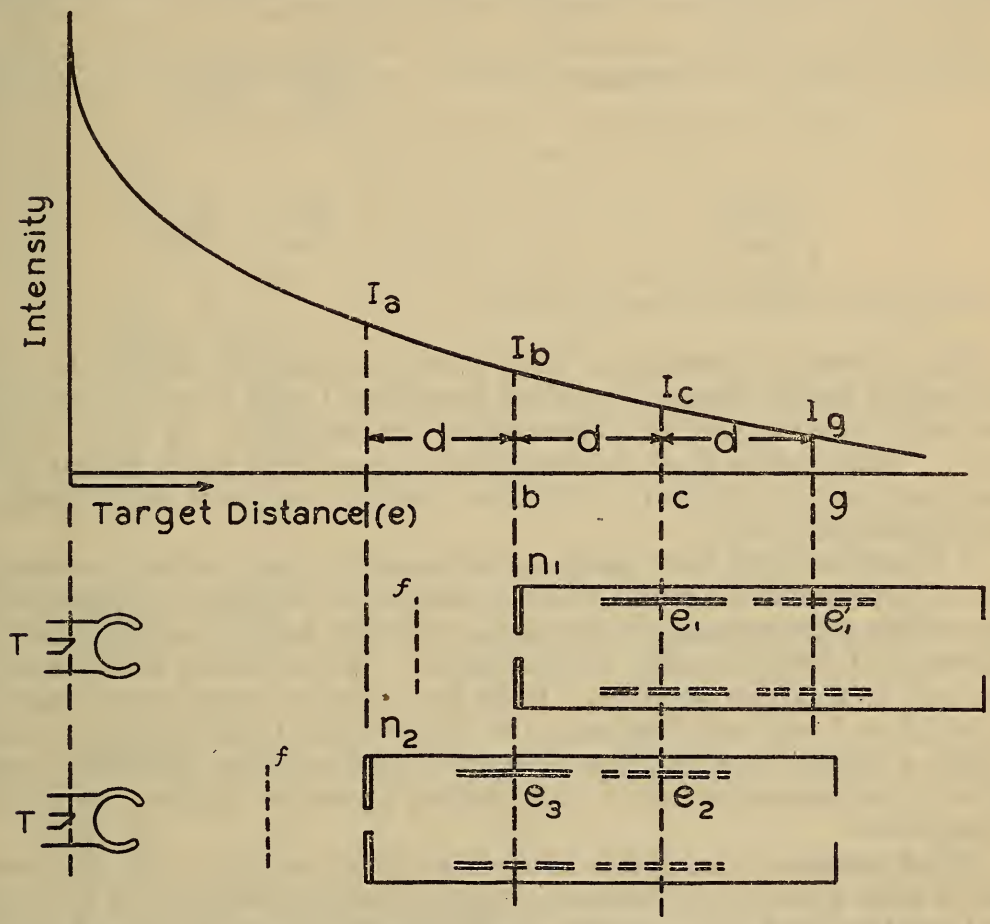

FIGURE 3.—*Diagram of working positions of special ionization chamber in determining air absorption factors*

positions of the collector plate, $e_3 = n_1$, and $e_2 = e_1$. The ratio $\frac{I_b}{I_c}$ gives the air absorption factor to be applied to the readings made with the chamber at the position n_1. Corrections made in this manner are

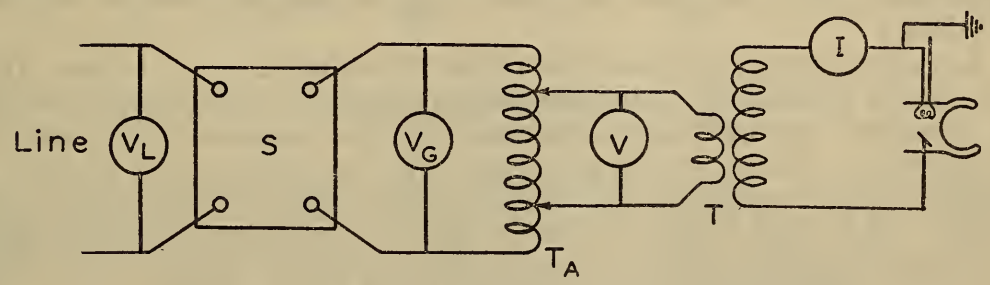

FIGURE 4.—*Power circuit for grenz-ray generator*

limited to distances, d, or greater, from the X-ray tube. The special chamber described, owing to its small size, is particularly well adapted to the problem; an unguarded field type can not be made sufficiently small without introducing too great field distortion.

The observed change in the air absorption factor, as the distance from the tube is changed, is given in Table 2.

TABLE 2.—*Air absorption factors 8 kv (peak) (Slack window, Grenz ray tube)* [1]

Diaphragm position	Absorption path distance from target	Absorption factor
	cm	
1 (*a–b*)	12–18	1.635
2 (*b–c*)	18–24	1.593
3 (*c–d*)	24–30	1.576

[1] C. M. Slack, J. Opt. Soc. Am., vol. 18, p. 123, 1929.

The letters in parentheses refer to the positions in Figure 4. The correction factor changes between positions 1 and 2 by 4.2 per cent; between 2 and 3, due to hardening of the radiation, by only 1.7 per cent. This proves that air-absorption corrections made in one position can not be applied to another position without introducing a corresponding error.

It is also evident from these measurements that, as the distance, d (fig. 3), of the middle of the collector electrode increases, the absorption correction correspondingly increases, and may become so large that its accuracy of determination is insufficient. It is obvious that d should be kept as small as possible. With the chamber used here, d may be as small as 5 cm for radiation up to 80 kv (peak); while, for the same range, a simple parallel plate or cylindrical ionization chamber would have a minimum distance $d=13$ cm and, therefore, at least double the absorption.

Measurements were made using a commercial grenz ray generator and a tube with a thin indrawn-bubble type of window[13] of such size and position that the ionization chamber diaphragm could be brought to about 5 cm of the target. The filament side of the tube was grounded (fig. 4) and the voltage regulated by means of a slide wire auto transformer T_A in the primary circuit of the high-voltage transformer. Peak voltage was determined from the manufacturer's calibration in terms of the voltage, V, on the primary of the transformer. (Since accurate values of the tube voltage were of no great significance in this particular work, the voltage calibration was not checked.)

Air absorption, expressed in terms of an absorption factor, I_b/I_c (see fig. 3) multiplied by the ionization reading, I_c, gives the intensity in Röntgens per minute at the point, b, the position of the limiting diaphragm. The absorption factor, I_b/I_c, for $d=6$ cm is plotted in Figure 5 as a function of the thickness of aluminum filter used in the beam. It is seen that for lightly filtered radiations air absorption correction may be, with 6 kv radiation, as large as 40 per cent. The need for accuracy of this correction is obvious.

Figure 6 gives a series of curves showing the intensity, I_b, in Röntgens per minute at the position $b=12$ cm as a function of the aluminum filtration. The lower curve of each pair gives the measured

[13] See footnote to Table 2.

intensity while the upper curve gives the corresponding calculated value at the diaphragm—obtained by multiplying by the appropriate absorption factor from Figure 6. It is interesting to note in this connection that a lateral shift, corresponding to 0.0055 mm thickness of aluminum, of the first curve of any pair brings the two curves together, within experimental error. This means that the absorption of 6 cm of air is equivalent to 0.00055 cm of aluminum for the range

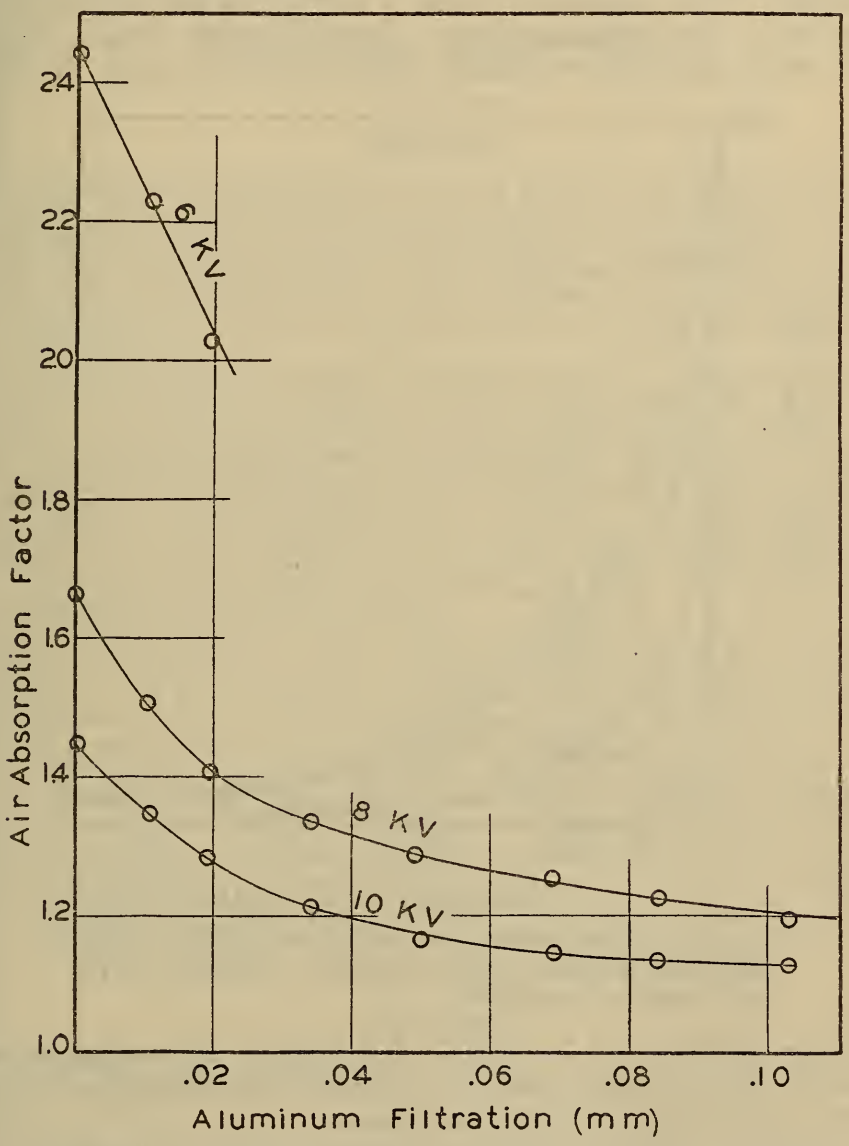

FIGURE 5.—*Air absorption factor for different voltage X rays necessary in the use of special ionization chamber*

of voltages and qualities covered in Figures 5 and 6. The aluminum equivalence of air is from this 9.2×10^{-5} mm Al per mm of air; which agrees favorably with the value 9×10^{-5} reported by Siegbahm.[14] but is appreciably higher than Glasser's value of 7.9×10^{-5} mm.

The logarithm of the intensity plotted against thickness of filter shows a distinct curvature up to 0.1 mm/Al filtration and indicates that there is no "homogeneity filter" [15] beyond which the quality does not change. Typical examples of intensity and absorption

[14] M. Siegbahm, The Spectroscopy of X Rays (Oxford), 1925.
[15] H. Behnken, Zeit. fur. Tech. Phys., vol. 2, p. 153, 1921.

curves for grenz rays have been given by Jacobson [16] and others. Such curves have value only for a particular tube and should be determined separately for each type of generator, as brought out by using the system indicated in Figure 4. Here tube emission was measured for a constant voltage, V, applied to the transformer, T, and constant current, I, through the tube, the input voltage V_G, to the control autotransformer being stabilized in one case and unstabilized in the other.[17] The results in Table 3 show a 50 per cent decrease in emission with the particular type of stabilization used. Since the effect of wave form on emission varies between tubes of different

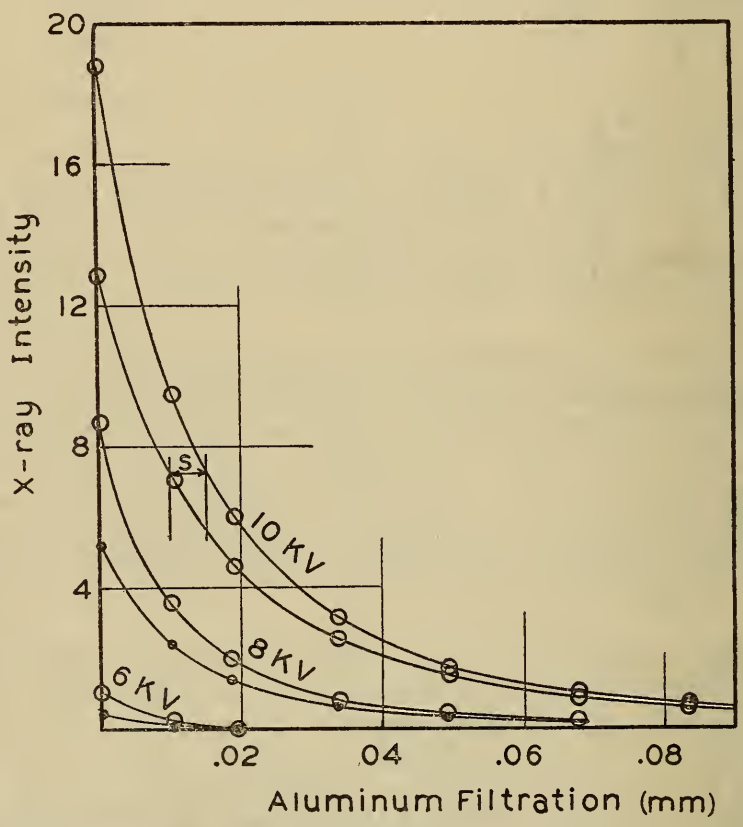

FIGURE 6.—*X-ray intensities measured with the special ionization chamber before and after application of the air absorption correction*

types, there is little to be gained by further investigation of the variation; it simply emphasizes the necessity for individual measurements with each type of generator used.

TABLE 3.—*Grenz-ray emissions for different voltage wave forms*

Line voltage V_L	Stabilizer	Input voltage V_G	Emission
109	Out	109	16.07
104	do	104	16.24
109	In	106.5	8.83
104	do	106.5	8.52

WASHINGTON, August 1, 1932.

[16] L. Jacobson, Am. J. Roent., vol. 22, p. 547, 1929.
[17] All stabilizers of the general type here used produce a distorted wave form depending on the load power factor. This does not affect the usefulness of the instrument for its intended purpose.