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Standard Free-Air Chamber for the Measurement of Low Energy X-rays (20 to 100 Kilovolts-Constant-Potential)[1]

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A description of the new National Bureau of Standards "low" energy free-air chamber is given. The standard chamber is designed to measure the exposure dose in roentgens for X-ray beams generated at potentials from 20 to 100 kilovolts-constant-potential (kvcp) with filtrations ranging from 2 millimeters of beryllium to 2 millimeters of beryllium plus 4 millimeters of aluminum. The chamber has been compared with the National Bureau of Standards "medium" energy standard at 60, 75, and 100 kvcp with filtrations of 3, 3, and 4 millimeters of aluminum, respectively. The two standard chambers agreed to within 0.3 percent.

1. Introduction

The roentgen has been recommended [1] [2] by the International Commission on Radiological Units and Measurements as the unit of exposure dose. A measurement with a free-air ionization chamber is the most convenient way to accurately determine the exposure dose in the low energy X-ray region. Design criteria for standard free-air chambers have been summarized by Wyckoff and Attix [2] in National Bureau of Standards Handbook 64 for moderately and heavily filtered X-rays generated at potentials from 50 to 500 kilovolts-constant-potential (kvcp).[3] Agreement to about 0.5 percent has been reached in international intercomparisons of the roentgen in this energy region. However, differences of 1 percent or more have been observed [3, 4] in intercomparisons involving lightly filtered low energy X-rays. Design criteria have recently been obtained [5] for 20 to 100 kvcp X-rays with filtrations ranging from 2 mm of beryllium to 2 mm of beryllium plus 4 mm of aluminum. The present paper will discuss the application of these criteria to the design of a "low" energy standard free-air chamber. The reader is referred to Handbook 64 and reference [5] for background information on the correction factors that are applied to free-air chamber measurements.

A schematic of a parallel plate free air chamber, viewed from above, is given in figure 1. The design of a standard chamber involves many compromises. The factors involved include the air attenuation, electric field distortion, electronic equilibrium, electron ionization loss and scattered photon contribution. The largest correction in the "low" energy X-ray region is for the attenuation of the X-ray beam by the air between the chamber diaphragm and the collecting plate. This may be reduced by decreasing the distance between diaphragm and collector. However, the resultant decrease in the distance between the guard strips and collector plate increases the field distortion in the collecting region [5]. In practice the field distortion limits the decrease in the length of the air path. The distance from the inside of the guard strips to the front edge of the collector must be large enough to achieve electronic equilibrium along the X-ray beam.[4] The resultant larger diaphragm to collector distances at the higher voltages and filtrations are partially offset by the decrease in the air attenuation coefficients at higher energies. The collimated beam of X-rays within the chamber interacts with the air to produce high speed electrons and secondary scattered photons. These scattered photons may in turn produce high speed electrons within the collecting volume. A measurement in roentgens requires a determination of the ionization from the high speed electrons produced by the collimated photons alone. The separation of the collecting and high voltage plates and the height of the collecting plate must be sufficiently large to allow the electrons from the collimated beam to expend most (>99 percent) of their energy in the air before striking the plates or guard strips. An excessively large plate separation will result in an unnecessary increase in the scattered photon contribution. The plate separation and height should be made as small as possible, consistent with the consideration of keeping the electron ionization losses smaller than 1 percent [5].

2. Description of the Low Energy Standard

The chamber is designed for 20 to 100 kvcp. X-rays with filtrations ranging from 2 mm of beryllium to 2 mm of beryllium plus 4 mm of aluminum.

[1] A portion of this work was supported by the U.S. Atomic Energy Commission.
[2] Figures in brackets indicate the literature references at the end of this paper.
[3] Kilovolts-constant-potential applied to the X-ray tube.

[4] Handbook 64 [2] recommends that the distance between the diaphragm and the front edge of the collector be adequate for electronic equilibrium. This assumes that none of the electrons generated between the diaphragm and guard strips are intercepted by the guard strips before reaching the collecting region. The distance from the inside of the guard strips to the front of the collector is the critical one in the chamber described here because its closely spaced guard strips intercept most of the electrons generated between the diaphragm and guard strips.

Various views of the chamber are shown in figures 1 to 4 and a list of important dimensions is given in table 1. The plate system is housed in a lead-lined steel box. All connections passing through the box are vacuum tight so that the box can be evacuated and filled with gases other than air if desired. The design of the diaphragm holder is such that the defining plane of the tungsten alloy diaphragm is inside the box. This reduces the air attenuation correction by decreasing the diaphragm to collector distance.

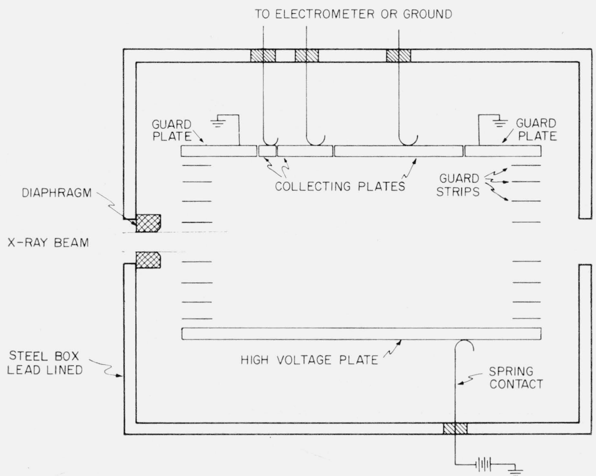

FIGURE 1. *Schematic of a parallel plate free air chamber, viewed from above.*

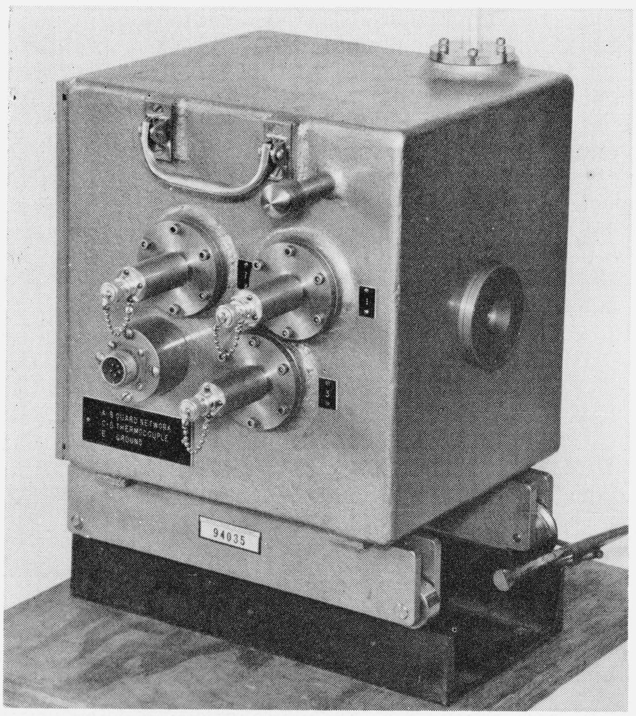

FIGURE 2. *Front, exterior view of the lead lined steel box (27 cm long × 22 cm wide × 27 cm high) housing the plate system.*

Connectors for the collecting plates, guard network monitor, thermocouple and an inlet for gas filling are visible on the side. The diaphragm and thermometer holders are seen on the front and top of the box, respectively.

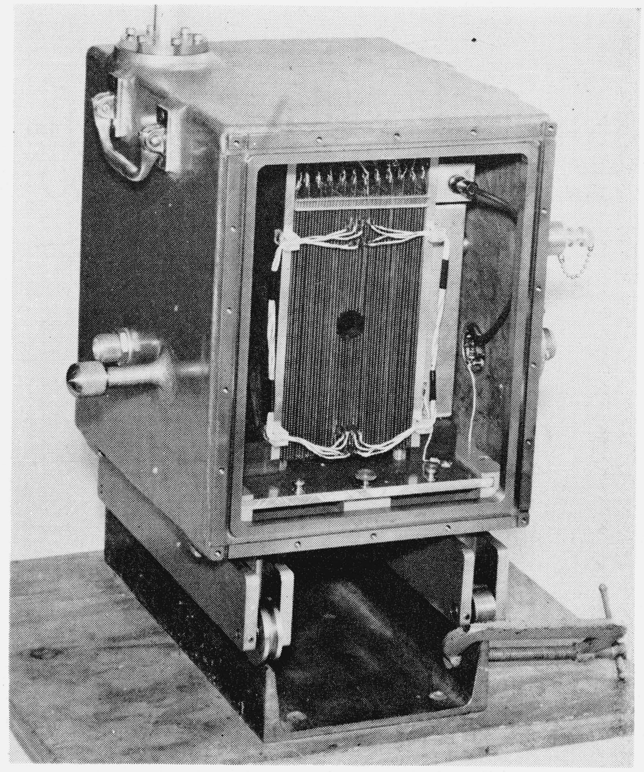

FIGURE 3. *View of the chamber with the rear cover plate removed, showing the plate system in its normal position.*

The high voltage plate is at the left, the collector with its dust cover is at the right.

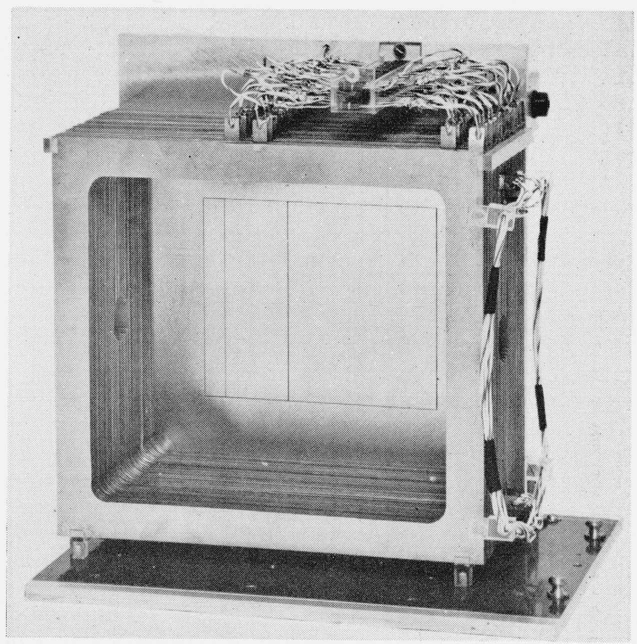

FIGURE 4. *Closeup of the collecting plate assembly and guard strips.*

The high voltage plate has been removed.

TABLE 1. *Important dimensions of "low" energy standard chamber*

Plate separation	9 cm
Collector lengths	1, 3, and 7 cm
Collector height	9 cm
Guard plate width	4 cm
Guard strips:	
Centerline to centerline spacing	0.2 cm [a]
Thickness	0.05 cm
Depth	1.5 cm
Air path from diaphragm to centerline of 1-cm collector	5.7 cm
Air path from diaphragm to centerline of 3-cm collector	7.7 cm
Air path from diaphragm to centerline of 7-cm collector	12.7 cm
Distance from inside of guard strips to closest edge of collector	2.5 cm

[a] Except strips immediately adjacent to the high voltage and collector plates which have a spacing of 0.1 cm.

Three aluminum collecting plates are provided: a 1-cm long collector closest to the diaphragm for use with the lowest energy X-rays; a 3-cm collector further away from the diaphragm for intermediate energy X-rays; and a 7-cm collector at the rear of the chamber for the highest energy X-rays. This arrangement minimizes the air attenuation corrections and provides the distances necessary for electronic equilibrium. Field distortion may be caused by a lack of coplanarity of the collectors with their guards [2]. The collectors and guards in this chamber were machined as a unit until they were coplanar to 0.00025 cm. A similar collecting plate assembly has maintained its planarity since its construction 13 months ago. The details of the collector construction are shown in figure 5. The 1-cm thick collectors are held on a yoke by screws which pass through Kel-F bushings. The collectors are insulated from each other and the guard plate by narrow air gaps ($\approx$0.018 cm wide) and from the yoke by a narrow strip of 0.025-cm-thick polyethylene. The backs of the collectors are shielded from dust by an aluminum cover. Spring-loaded contacts passing through the box and dust cover make contact with the collecting plates. Commercial cable connectors

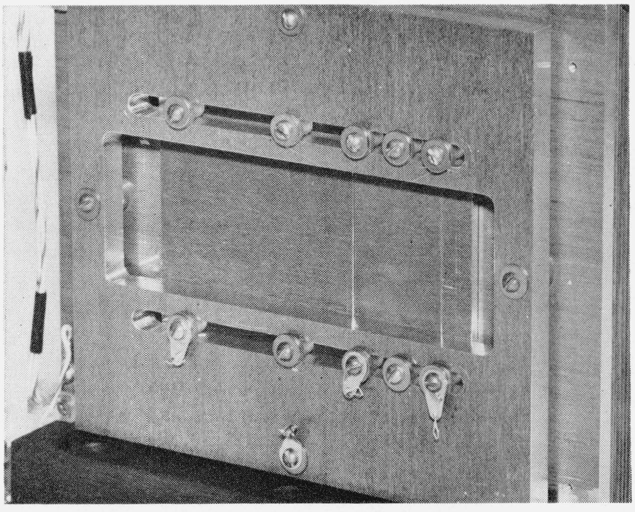

FIGURE 5. *Closeup of the back of the collecting plate assembly with the dust cover removed.*

and low noise cable join the spring loaded contacts to the electrometer. Shorting caps on the connectors ground those collectors that are not in use.

The guard strips were milled from brass sheets and spaced by slotted Lucite bars which were made as small as possible to avoid field distortion effects from exposed insulators [5]. No change in the ionization current was observed when duplicate Lucite bars were added to the guard strip assembly. The potentials of the guard strips are determined by a network of megohm resistors which grades the potential linearly from the high voltage to the collector plate. The current through the network can be monitored by measuring the potential drop across a 50-K resistor in series with resistor chain. This permits easy detection of a shorted guard strip or an open resistor. Field distortion can also be caused by the presence of the grounded box or by the guard strips themselves [5]. The chamber was designed so that distortion from the guard strips was less than 0.1 percent. Distortion caused by the box was determined experimentally by measuring an exposure dose rate with the box alternately at the potential of the high voltage plate and at ground [2]. No change was observed for the 3-cm and 7-cm collectors. The box caused a 0.09-percent distortion at the 1-cm collector. This is not surprising since this plate probably "sees" the box through the entrance hole (2 cm in diam) cut in the guard strips for the X-ray beam.

The ionization measured by the various collectors is compared in table 2. The readings have been normalized so that the reading of the 7 cm collector is unity at each voltage and filtration. The data have been corrected for air attenuation, distortion of the electric field by the box and differences in the collector lengths. An inspection of the data taken for X-rays between 20 kvcp, inherent filtration, and 60 kvcp, inherent +0.5 mm Al filtration, reveals differences of $\pm$0.2 percent in the ionization measured by the collectors. This reflects uncertainties in the collecting volume caused by field distortion and difficulties in measuring the ionization currents and lengths of the collectors. These uncertainties are of the same order as those observed in a previous experiment [5]. The drop in the ionization measured by the 1 cm collector at 60 kvcp inherent +1 mm Al filtration was attributed to a lack of electronic equilibrium caused by an inadequate distance between

TABLE 2. *Ionization measured by the various collectors* [a]

Collector	Tube potential and filtration [b]					
	20 kvcp none	60 kvcp none	60 kvcp 0.5 mm Al	60 kvcp 1.0 mm Al	75 kvcp 3.0 mm Al	100 kvcp 4.0 mm Al
1 cm	0.999	0.998	0.998	[c] 0.994	[c] 0.994	[c] 0.990
3 cm	1.003	1.003	1.003	1.002	[c] 1.000	[c] .998
7 cm	1.000	1.000	1.000	1.000	1.000	1.000

[a] In addition to the inherent filtration of 2 mm of beryllium.
[b] The readings have been normalized so that the reading of the 7-cm collector is unity at each kilovoltage and filtration. The data have been corrected for air attenuation, distortion of the electric field by the box and differences in the collector lengths.
[c] See the text for a discussion of the influence of electronic equilibrium on the entries marked.

the inside of the guard strips and the front edge of the collector. The distance necessary for equilibrium at a particular energy may be taken to be approximately half the plate separation required at that energy [2]. Figures 7 to 10 of reference [5] may be used to determine the plate separation at which the electron ionization losses will be 0.05 percent. A good working criterion is to take half of this plate separation as the required equilibrium distance. Combinations in table 2 marked with "c" do not satisfy this criterion. It is seen that the relative readings of the various collectors is independent of the energy of the X-ray beam within the experimental error if electronic equilibrium has been achieved.

Some typical correction factors for the chamber are listed in table 3. The plate separation had to be adequate for 100-kvcp X-rays filtered by 4 mm of aluminum. This resulted in a chamber that was somewhat oversized for lower energy X-rays. For example, a free-air chamber designed for X-rays generated at or below 50-kvcp, 0.5-mm aluminum filtration, might have a 3-cm plate separation. The electron and scattered photon corrections would be about 0.7 percent and 0.15 percent, respectively, for such a chamber. The same chamber would have electron and photon corrections of <0.01 percent and 0.2 percent, respectively for 20 kvcp inherent filtration X-rays. Thus such a standard would have much smaller correction factors at "low" energies than the one described in this paper. Some accuracy at "low" energies was sacrificed in the present chamber to enable it to overlap the X-ray energy range covered by the NBS "medium" energy free air standard. A description of a comparison between the two chambers is given in the next section.

TABLE 3. *Typical corrections for the "low" energy standard chamber, in percent*

	Tube potential and filtration [a]					
	20 kvcp none	100 kvcp none	50 kvcp 0.5 mm Al	60 kvcp 3 mm Al	75 kvcp 3 mm Al	100 kvcp 4 mm Al
Collector used	1 cm	3 cm	1 cm	7 cm	7 cm	7 cm
Air attenuation	4.5	4.5	0.9	0.6	0.5	0.4
Photon contribution	0.70	0.70	0.54	0.41	0.38	0.30
Electron loss	<0.01	0.02	<0.01	0.02	0.11	0.71

[a] In addition to the inherent filtration of 2 mm of beryllium.

3. Intercomparison of NBS "Low" and "Medium" Energy Free-Air Chambers [4]

Details of the NBS "medium" energy standard instrument have been published elsewhere [6, 7]. The chamber, designed for X-rays generated at potentials up to 250 kvcp, has a 20-cm plate separation and a 30.8-cm air path between the diaphragm and the center of the collector. The "low" and "medium" energy chambers were mounted on carriages that rolled on a track perpendicular to the roentgen beam. Each standard chamber could be brought into the beam in turn. A 1.3-cm diam diaphragm on the tube housing, 17.5 cm away from the target, was used to collimate the beam. The ratio of the two standards was unchanged when the 1.3-cm diaphragm was replaced by one 2.5 cm in diam. The defining planes of the chamber diaphragms (1-cm diam) were 153 cm from the X-ray tube target. The chambers were alined optically and radiographically [2]. The focal spot lay within the "tunnel" formed by the extension of the sides of the chamber diaphragm. Aitken [8] indicates that there will be no alinement error in such a case. Separate charge measuring systems and chamber diaphragms were used in the intercomparison. A field gradient of 250 v/cm was used on both chambers. The inherent filtration of the X-ray tube used for the intercomparison was determined by a comparison of the measured half-value-layers, in mm of aluminium, with those obtained previously with a beryllium window tube [5]. Aluminum was added to the inherent filtration of 1.7 mm of Al to produce the different filtrations used in the intercomparison. The tube potentials, equivalent filtrations and half-value-layers used in the intercomparison are listed in table 4.

Measurements of the exposure dose rate in roentgens per minute were made alternately with each chamber. Corrections for air attenuation, electron losses and the scattered photon contributions were taken from Handbook 64. The ratios of the dose rates measured by the "low" energy standard chamber to those measured by the "medium" energy standard chamber are listed in table 4. The multiple entries at a given energy reflect day to day fluctuations in the ratio of the two chambers. The collecting

[4] April 1 to 9, 1959.

TABLE 4. *Results of the intercomparison*

Tube potential	Equivalent filtration	Half-value layer	"Low" energy chamber / "Medium" energy chamber		"Low" energy chamber / "Medium" energy chamber [a]
100 kvcp	2 mm Be+ 4 mm Al	3.9 mm Al	$.999_7$ $.997_7$ $.998_4$	$.998_6$ average	$.997_1$
75 kvcp	2 mm Be+ 3 mm Al	2.5 mm Al	$.998_5$ $.998_1$	$.998_3$ average	$.996_8$
60 kvcp	2 mm Be+ 3 mm Al	2.1 mm Al	1.000_8 $.999_8$	1.000_3 average	$.998_8$

[a] Corrected for collector plate warp.

plate of the "medium" energy standard chamber has warped and is no longer coplanar with its guards. It is estimated [2] that this causes it to read 0.15 percent too low. Application of this correction to the average ratios of the two chambers yields the results listed in the last column of table 4. Agreement between the two standard instruments is excellent, well within the ± 0.5 percent expected for such an intercomparison [2].

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