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NBS Free-Air Chamber for Measurement of 10 to 60 kV X Rays

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Constructional details of the National Bureau of Standards' new free-air chamber for the measurement of 10 to 60 kV x rays in roentgens are given. The results of the comparisons of the new chamber with the National Bureau of Standards' "low" energy standard in their overlapping range are included. The two standard chambers, on the average, agreed to within 0.3 percent. The maximum uncertainties in the correction factors used for the comparison measurements are examined and their sum is compared with the results obtained for the chamber comparisons. An estimate is also made of the maximum uncertainty, about 1.3 percent, of an exposure rate determination to be expected when using the 10 to 60 kV chamber to measure 10 to 15 kV x rays.

1. Introduction

The National Bureau of Standards has constructed a free-air chamber standard, similar to the one designed by Greening [1960], for the measurement of 10 to 60 kV x rays in roentgens. Greening tested the performance of this chamber by comparing the calibrations obtained with it and those obtained at the U.K. National Physical Laboratory for two types of thimble chambers. The results of the comparisons were in good agreement for x rays generated below 55 kV except for the calibration at 37 kV where the difference between the two calibrations amounted to 2.6 percent.

The present paper gives constructional details of the new NBS chamber. It also gives the values of correction factors which are needed to correct for defects in its realization of the roentgen as well as results of comparative measurements made with the new chamber and with an older one previously described by Ritz [1960]. Uncertainties in the correction factors are examined and their sum is compared with the results obtained for the chamber comparison. In addition an estimate is made of the inaccuracy of a measurement of 10 to 15 kV x rays using the new chamber.

2. Apparatus

Major pieces of equipment used in this investigation included two x-ray sources, two free-air ionization chambers, a radiation monitor, and ionization current measuring systems.

2.1. New Chamber for 10 to 60 kV X Rays

Two cross-sectional views of the new NBS 10 to 60 kV chamber are shown in figures 1A and 1B. Most of the construction of this chamber is straightforward but one needs to take special precautions with the guard and collector plate combination and with tests of the diaphragm and exit apertures. Special care is required with the collector-guard plate system in order to assure that the length of the collecting region is well known. The plate system was machined as a unit until no point on the collector was as far as 0.0001 cm from the plane of the guard plate. According to a previous report [Wyckoff and Attix, 1957] lack of coplanarity of 0.0001 cm could cause an error in the collected ionization of less than 0.05 percent.

To reduce the possibility of differences in contact potential between the collector and guard plate, they were both coated with a thin layer of colloidal graphite. This coating did not change the measured ionization, indicating that this precaution was actually unnecessary.

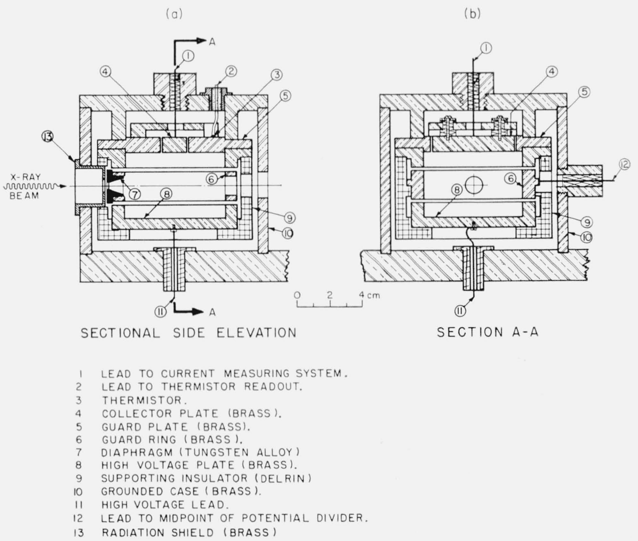

FIGURE 1A and 1B. *Schematic cross-sectional views of 10 to 60 kV free-air chamber.*

To test the influence of the exit and entrance apertures on the collecting field in the region of the collector, x-ray measurements were made with different size apertures. Entrance apertures of 1 and 5 mm and exit apertures of 4.2 and 13.1 mm diam were used. A monitor chamber located in the beam behind the 10 to 60 kV chamber measured the radiation passing through the 10 to 60 kV chamber. The ratio of the ionization obtained in the 10 to 60 kV chamber to that obtained in the monitor was independent of the aperture size, at least to the imprecision of measurement which had a standard deviation of about 0.12 percent. It thus appeared that neither the entrance nor the exit aperture diameter had an influence of as much as 0.12 percent on the field in the collecting region.

2.2. Chamber for 20 to 100 kV X Rays

The NBS chamber for measurement of 20 to 100 kV x rays, already described by Ritz [1960], has 3 different collectors of 1, 3, and 7 cm width, respectively. Ritz reported that the exposure measured with the 1 cm collector differed from that obtained by the 7 cm collector by as much as 0.3 percent at the softer radiation qualities. At the present time the 1 cm collector plate produces too low an ionization current compared to that of the other 2 collectors by as much as 0.9 percent. Subsequent studies appear to indicate that the large opening in the guard strips (2 cm diam) for the beam and the proximity of the guard strips and grounded box causes distortion of the electric field in the vicinity of the 1 cm collector. Therefore, for the present comparisons only the 3 and 7 cm collectors are used. Table 1 gives the important dimensions of the two free-air chambers.

TABLE 1. *Important dimensions of free-air chambers*

Description of dimension	Chamber	
	20–100 kV	10–60 kV
Plate separation cm	9.0	4.0
Plate height cm	9.0	5.0
Collector width cm	7.003_0 3.023_3	1.014_6
Diaphragm aperture diameter cm	0.501_6	0.499_4
Air absorption path length cm	[a] 12.73_9 [b] 7.72_6	3.90_2

[a] Airpath length when using 7 cm wide collector.
[b] Airpath length when using 3 cm wide collector.

2.3. X-Ray Sources

Two x-ray sources, *a* and *b*, were used for the comparison. Each had a constant potential generator, a projected focal spot size of 1.5 mm × 1.5 mm and a beryllium window of 0.25 mm thickness. The radiation from source *b* was highly stabilized, but source *a* was not well stabilized so that a monitor was required with this source. This monitor was located in the beam about 150 cm from the focal spot, that is, after the beam had passed through a free-air chamber. In this position it did not add to the filtration of the measured beam and was not subject to heating by the x-ray tube. However, the area of the beam striking the monitor was dependent upon the size of the entrance aperture of the free-air chamber.

The chambers could be positioned reproducibly in the beam. Each chamber was adjusted for proper alinement in each beam and the alinement was finally checked radiographically. For a comparison, the distance between the x-ray focal spot and the defining plane of the aperture was adjusted so that it was the same for both chambers. This was indicated by a cathetometer capable of indicating differences of ±0.005 cm. Nominal distances of approximately 60 and 100 cm were used with source *a*, 36 and 66 cm with source *b*.

2.4. Monitor Chamber

The monitor chamber used with source *a* was the flat cavity ionization chamber described by Attix, DeLaVergne, and Ritz [1958] with a front and rear wall of 1.6-mm thick carbon and a colloidal-graphite-coated plastic membrane between these walls as a collector. The collecting volume had a larger cross-sectional area than the x-ray beam so its response was proportional to the area of the limiting aperture of the free-air chamber. Thus the ratio of the response of the free-air chamber to that of the monitor was independent of the free-air chamber aperture area.

2.5. Ionization Current Measuring System

All ionization-current measurements were made with a Townsend balance circuit using a capacitor, a potentiometer as a precision potential source, a vibrating reed electrometer as a null indicator, and a precision chronometer to indicate the duration of measurement. With such a technique the current is the product of the capacitance and the rate of voltage buildup.

3. Comparison Procedure

For each comparison, separate ionization measurements were made with one chamber, then with the other and finally again with the first chamber in the beam at the same nominal distance from the source. Two to eight comparisons were made at each quality of radiation listed in table 2. A collecting potential for each chamber was used which would give a lack of saturation of less than 0.03 percent (as indicated by the plots of the type given by Scott and Greening, 1961, 1963) at all exposure rates used.

Air pressures were obtained for each exposure from a barometer believed to have a systematic error of no greater than ±0.1 percent and to have a reading error of less than ±0.02 percent. Temperatures in the chambers were determined with thermometers installed in the 20 to 100 kV chamber and in the monitor chamber and either a thermometer or a thermistor device placed in the collecting volume of the 10 to 60 kV chamber before and after each set

TABLE 2. *Typical factors used in the comparison*

kV	Added filter (mm Al)	HVL (mm Al)	$\frac{(K_a)_R}{(K_a)_G}$	$\frac{(K_a)_R}{(K_a)_G}$	$\frac{(100-K_e+K_{sc})_G}{(100-K_e+K_{sc})_R}$
20	0	[a] 0.07_2	[c, e] 1.112 [d, e] 1.048		0.997
20	0	[b] .068		[c, f] 1.106 [d, f] 1.046	.997
20	0.5	[a] .24	[c, e] 1.027 [d, e] 1.011		.997
20	.5	[b] .25		[c, g] 1.024 [d, g] 1.010	.997
30	0	[a] $.08_6$	[c, e] 1.097 [d, e] 1.042		.997
30	0	[b] $.08_9$		[c, f] 1.084 [d, f] 1.037	.997
30	0.5	[a] .36	[c, e] 1.020 [d, e] 1.009		.998
30	.5	[b] .42		[c, f] 1.017 [d, f] 1.007	.998
50	0	[a] $.09_0$	[c, e] 1.084 [d, e] 1.036		.997
50	0	[b] .12		[c, f] 1.064 [d, f] 1.027	.997
50	0.5	[a] .50	[c, e] 1.016 [d, e] 1.007		.997
50	1.0	[a] .89	[c, e] 1.008 [d, e] 1.003		.997
50	1.0	[b] $.9_4$		[c, g] 1.009 [d, g] 1.004	.997
60	0	[a] $.08_5$	[c, e] 1.081 [d, e] 1.035		.997

[a] Source *a*.
[b] Source *b*.
[c] Using 7 cm wide collector in 20 to 100 kV chamber.
[d] Using 3 cm wide collector in 20 to 100 kV chamber.
[e] Typical values at ambient temperature and pressure, 60 cm from source.
[f] Typical values at ambient temperature and pressure, 66 cm from source.
[g] Typical values at ambient temperature and pressure, 33 cm from source.

of measurements. A separate study showed that these four temperature indicating devices agreed to within 0.04 percent. When compared to a calibrated thermometer, the thermistor had a constant error of −0.11 °C, and the thermometers each had a constant error of −0.2 °C, for which a correction was made.

4. Computations

According to the definition of exposure, one obtains the number of roentgens from the quotient of the ion charge in electrostatic units produced by the electrons that are generated per 0.001293 g of air. However all practical measurements are made under conditions of electronic equilibrium and for a free-air chamber the mass of gas is defined by the area of the defining aperture and the length of the collecting region. In addition, small corrections to the actual measurement are required for: (a) lack of saturation, (b) attenuation of photons between the defining aperture and the collecting region, (c) distortion of the collecting field defining the length of the collection region, (d) loss of electrons which have not dissipated all of their energy in the air, (e) gain of some ionization from the electrons generated by the photons scattered within the air of the chamber, (f) leakage of radiation through the lip of the defining aperture, (g) leakage of radiation through the front face of the chamber, and (h) the presence of water vapor in the air. Equation (1) gives the exposure rate in roentgens per second.

$$\frac{\Delta X}{\Delta t}=\frac{C\frac{\Delta V}{\Delta t}\cdot 2.9979\cdot 10^9}{L\cdot A}\cdot K_a\cdot K_f\cdot K_s\cdot K_l\cdot K_p\cdot K_h \left(\frac{100}{100-K_e+K_{sc}}\right)\left(\frac{T}{273.2}\right)\left(\frac{760}{P}\right), \quad (1)$$

where A is the area of the defining aperture in cm^2,
L is the collector width in cm,
K_{sc} is the correction for ionization produced by scattered photons in percent,
K_e is the correction for loss of ionization from secondary electrons because of inadequate plate separation in percent,
K_s is the correction for lack of saturation,
K_a is the correction for air attenuation between the entrance aperture and the collecting region of the free-air chamber,
K_f is the correction for field distortion,
C is the capacitance in farads of the capacitor used for determining the charge collected from the free-air chamber,
T is the temperature of the collecting volume air in degrees absolute,
P is air pressure in mm of mercury,
$(\Delta V/\Delta t)$ is the rate of change of potential in volt/sec on the capacitor used with the free-air chamber,
K_l is the correction for radiation leaking through the front of the chamber,
K_p is the correction for radiation penetration of the aperture border, and
K_h is the correction for water vapor in the air.

Independent measurements and calculation have indicated that K_l and K_p are equal to one for both chambers for the range of qualities used here. If subscript R refers to the 20 to 100 kV chamber and subscript G to the 10 to 60 kV chamber, then one obtains

$$\frac{\left(\frac{\Delta X}{\Delta t}\right)_R}{\left(\frac{\Delta X}{\Delta t}\right)_G}=\frac{C_R}{C_G}\cdot\frac{L_G\cdot A_G}{L_R\cdot A_R}\cdot\frac{(100-K_e+K_{sc})_G}{(100-K_e+K_{sc})_R}\cdot\frac{(K_s)_R}{(K_s)_G}\cdot\frac{(K_a)_R}{(K_a)_G}\cdot\frac{(K_f)_R}{(K_f)_G}\cdot\frac{(T)_R}{(T)_G}\cdot\frac{(P)_G}{(P)_R}\cdot\frac{\left(\frac{\Delta V}{\Delta t}\right)_R}{\left(\frac{\Delta V}{\Delta t}\right)_G} \quad (2)$$

where K_h is assumed to be the same for both chambers in a given comparison. This equation is applicable to all comparisons with source *b*.

When a monitor is used with source *a*, the ion current in the monitor is proportional to the air pressure in the monitor and to the area of the defining diaphragm for each free-air chamber and inversely proportional to the absolute temperature of the air in the monitor. As the monitor current (corrected to STP) per unit area of the defining diaphragm should be the same for both chambers one obtains

$$1=\frac{(C_m)_G(\Delta V_m/\Delta t)_G\cdot(T_m)_G/(A_G\cdot(P_m)_G)}{(C_m)_R(\Delta V_m/\Delta t)_R\cdot(T_m)_R/(A_R\cdot(P_m)_R)} \tag{3}$$

where P_m and T_m are the pressure and temperature respectively in the monitor chamber, and C_m is the capacitance in the monitor current measuring circuit.

If one multiplies eq (2) by eq (3) one obtains

$$\frac{\left(\frac{\Delta X}{\Delta t}\right)_R}{\left(\frac{\Delta X}{\Delta t}\right)_G}=\frac{C_R}{C_G}\frac{L_G}{L_R}\frac{(100-K_e+K_{sc})_G}{(100-K_e+K_{sc})_R}\frac{(K_s)_R}{(K_s)_G}\frac{(K_a)_R}{(K_a)_G}\frac{(K_f)_R}{(K_f)_G}$$

$$\frac{(T)_R}{(T)_G}\frac{(T_m)_G}{(T_m)_R}\frac{(C_m)_G}{(C_m)_R}\frac{(\Delta V/\Delta V_m)_R}{(\Delta V/\Delta V_m)_G} \tag{4}$$

by assuming that P_G is equal to $(P_m)_G$ and that P_R is equal to $(P_m)_R$ for a given comparison. This equation applies to all comparisons made with source a.

Many of the factors in eqs (2) and (4) were determined in advance of the comparisons. The same capacitor was used for both free-air chambers, and the capacitor used with the monitor chamber was the same for all comparisons made using source a. Therefore, the ratio C_R/C_G in eqs (2) and (4), and the ratio $(C_m)_G/(C_m)_R$ in eq (4) are both equal to one. The ratios of observed effective collector widths and observed aperture areas were obtained from the data in table 1. Values of the corrections for electron loss and scattered photon contribution, K_e and K_{sc}, vary slowly with the quality of the radiation so interpolated values were obtained from the data of Ritz [1959]. Values of the correction for lack of saturation, K_s, for each chamber were determined from experimental data obtained with each chamber and extrapolation according to the method given by Scott and Greening [1961, 1963]. Data for the air attenuation correction, K_a, were obtained by the experimental method used by Day and Taylor [1949]. For the softer qualities of radiation this factor was so large that it was not only a function of distance but also of air pressure and temperature.

Values of the field distortion correction, K_f, might differ from one because of space charge and distortion of the electric collecting field due to the proximity either of other electrodes or of the exit and entrance apertures and because of lack of coplanarity of the guard and collector electrodes. According to Boag [1963], space-charge effects causing a lack of saturation should give differences in the collected current for the two polarities of collecting potential. Differences of as much as 0.12 percent for the 20 to 100 kV chamber and of 0.02 percent for the 10 to 60 kV chamber were noted but the interpretation of the amount of field distortion caused by this difference is difficult. Experimental and theoretical data from Kemp and Barber [1958] indicated that distortion because of the proximity of other electrodes should be negligible for the 10 to 60 kV chamber. Comparative measurements with the 3 cm and 7 cm wide collectors of the 20 to 100 kV chamber indicated that such distortion was also negligible for this chamber. Separate experiments likewise indicated that the apertures had no effect on the collected current except as already noted for the 1 cm wide collector in the 20 to 100 kV chamber. The small lack of coplanarity in the collector-guard plate systems of the two chambers was also assumed to have a negligible effect on the field distortion. Thus $(K_f)_R/(K_f)_G$ was considered to be one for the present comparison. Table 2 gives typical values used for some of the other factors in eqs (2) and (4).

5. Results

The results of the comparisons are summarized in table 3 and are shown as a function of half value layer (mm Al) in figure 2. Table 3 and figure 2 show the average observed ratio of exposure rates determined by each chamber for each quality of radiation and with the two radiation sources. The ratios tabulated include combined results obtained with the 3 cm wide collector and with the 7 cm wide collector in the 20 to 100 kV chamber because there seemed to be no systematic difference between the two sets of results. The deviations shown below each observed ratio (table 3) indicate the maximum deviation from the average. It is seen that the 20 to 100 kV chamber always reads less than the 10 to 60 kV chamber. On the average this difference is about 0.2 or 0.3 percent. It may also be noted that the maximum amount that the observed exposure rate differs from one is about 0.4 percent with either source.

6. Analysis of Uncertainties and Errors

An estimate of the limits of disagreement to be expected in the comparison of the two free-air chambers was made by a detailed analysis of possible inaccuracies associated with all the various factors in eqs (2) and (4) as well as those associated with factors that do not appear explicity in these equations.

The same capacitor was used to measure the ionization current in the two free-air chambers. This capacitor was calibrated before, during, and after the results were obtained for this experiment. The calibration technique was such that a change in the value of the capacitance of less than 0.01 percent could not be observed. The observed value of the capacitance appeared to vary over a range of 0.03 percent for a period of 38 months. In view of this relatively slow change in the observed value of the capacitance and the fact that the ionization current measurements immediately followed one another, it

TABLE 3. *Summary of comparisons of 20 to 100 kV and 10 to 60 kV chambers*

	kV	20	20	30	30	50	50	50	60
Source *a*	Added filtration (mm Al) [a]	0	0.5	0	0.5	0	0.5	1.0	0
Source *a*	Half value layer (mm Al)	.072	.24	.086	.36	.090	.50	0.89	.085
Source *a*	Number of comparisons	7	4	6	4	8	4	4	4
Source *a*	20 to 100 kV chamber exposure rate / 10 to 60 kV chamber exposure rate	0.998 +.003 −.002	0.996 +.001 −.002	0.998 +.004 −.002	0.996 +.000 −.001	0.998 ±.002	0.997 ±.001	0.999 ±.001	0.999 ±.001
Source *b*	Half value layer (mm Al)	0.068	0.25	0.089	0.42	0.12	----------	0.94	----------
Source *b*	Number of comparisons	4	2	4	4	2	----------	2	----------
Source *b*	20 to 100 kV chamber exposure rate / 10 to 60 kV chamber exposure rate	0.998 +.000 −.001	0.998 ±.000	0.997 +.000 −.001	0.998 +.000 −.001	0.996 ±.000	----------	0.999 ±.001	----------

[a] Added to an inherent filtration of 0.25 mm Be.

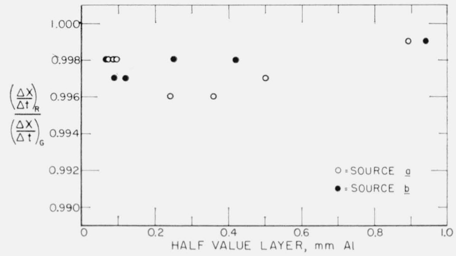

FIGURE 2. *Ratio of exposure rate versus half value layer, in mm of Al.*

seems reasonable to assume that the bias in the observed ratio of capacitances, C_R/C_G, is negligible.

The observed effective widths of the 7 and 3 cm collector plates of the 20 to 100 kV chamber and the 1 cm collector plate of the 10 to 60 kV chamber are calculated from single measurements at three different places along the collector height, at the middle, near the top and near the bottom. The measuring device used for these measurements is claimed to be accurate to within ± 0.02 percent. In the absence of more measurements and in view of past experience with similar measurements, it is estimated that the standard deviation of a measurement is no more than 0.02 percent. Thus, the uncertainty in the ratio of observed effective widths is estimated to be no more than ± 0.11 percent, based on a standard deviation of 0.02 percent and an allowance of ± 0.02 percent for systematic error for each width.

The observed average area of each defining aperture was determined from 24 to 26 measurements of their diameters using devices claimed to be accurate to within 2 parts in 10,000. The apparent variation in the observed diameters of the apertures resulted largely from the irregularities of the aperture surfaces and from out-of-roundness. The standard error of the observed average areas of the apertures, due to imprecision in measuring any given diameter and to the variation in diameter with position, was computed to be 0.004 percent and 0.021 percent for the 20 to 100 kV and 10 to 60 kV free-air chamber apertures respectively. The standard error of the observed ratio of average areas (estimating A_G/A_R), based on the propagation of error formula, is thus 0.021 percent. The uncertainty of the ratio of average areas is taken to be ± 0.063 percent (three times the standard error). The relative areas were also determined ionometrically, on three separate occasions, with one of the free-air chambers. The average value of the ratio of ionizations obtained with this ionometric technique fell within the range of three times the standard error of the observed ratio of average areas computed from measurements of the diameters of the apertures.

Values of the electron loss and scattered photon contribution corrections for each chamber were calculated according to the method described in NBS Handbook 64 [1957] from data of Ritz [1959]. As seen in table 2 the ratio of corrections for each chamber, as they appear in eqs (2) and (4) $(100-K_e+K_{sc})_G/(100-K_e+K_{sc})_R$, differ from 1 by only about 0.3 percent. Of this 0.3 percent, much less than one-third was due to electron loss, K_e. Data for computation of the scattered photon contribution correction, K_{sc}, have also been obtained experimentally by Allisy and Roux [1961]. Differences in the computed ratio due to differences in these two sets of data amounted to a maximum of 0.04 percent. Since the correction for electron loss was so small, the maximum difference of 0.04 percent in the scattered photon correction computed from the two sets of data was used as an estimate of the error in the scattered photon, electron loss correction for each chamber. Thus, the maximum error is the ratio $(100-K_e+K_{sc})_G/(100-K_e+K_{sc})_R$ is about ± 0.03 percent.

As indicated earlier, the correction for lack of saturation in either chamber amounted to not more than 0.03 percent. However, even if the theory used for such extrapolation is not exact (and there is no experimental evidence for this) one would expect the correction for the lack of saturation of the two chambers to be similar because the diaphragm areas and the collecting field strengths are similar. Therefore it is estimated that the error in the ratio of $(K_s)_R/(K_s)_G$ could not be more than ± 0.01 percent.

The observed ratio of the air attenuation correction for each chamber, $(K_a)_R/(K_a)_G$, was determined on 2 to 3 separate occasions for each of the qualities of radiation used in the comparisons for the difference in air absorption path lengths indicated in table 1, and normalized to the same air density. The standard deviation of the average of two to three observed ratios, based on 10 sets of two observations and 14 sets of three observations, is 0.05 percent. The uncertainty in this ratio is taken to be three times the standard deviation of the average, or ± 0.15 percent.

The ratio of the correction for field distortion in each chamber, $(K_f)_R/(K_f)_G$, could be uncertain because of lack of coplanarity of the collector and guard plate for each of the chambers and because of field distortion caused by the proximity of either other electrodes or the entrance and exit apertures. According to Ritz [1960] the guard strips in the 20 to 100 kV chamber would cause an error of less than 0.1 percent in the widths of the collecting region. The width of the collecting region in the 10 to 60 kV chamber should not be influenced by more than a few hundredths of 1 percent by the proximity of other electrodes. However because of possible space charge effects, which are difficult to evaluate at this time, it was assumed that this ratio had a maximum uncertainty of ± 0.20 percent.

The error in the observed ratio of temperatures, T_R/T_G, is due to disagreement between the temperature indicating devices at the same temperature (which includes a possible reading error of no more than 0.02 percent), the temperature indicating device acting as a heat source or sink (important for the 10 to 60 kV chamber only) and a possible temperature gradient between the collecting region air volume and the temperature indicating device (20 to 100 kV chamber only). The devices appeared to agree with one another to within 0.04 percent. In subsequent investigations, it was found that placing the thermometer or thermistor into the 10 to 60 kV chamber collecting region air volume before and after an exposure might lead to an error in the determination of T_G during exposure of as much as ± 0.05 percent. The error in T_R, due to the possible temperature gradient mentioned above, is estimated to be no more than ± 0.03 percent since the rate of change of the temperature of the air volume is small. The total systematic error in the observed ratio T_R/T_G is assumed to be 0.04 percent and the total random error is assumed to be 0.06 percent. The total uncertainty in the observed ratio, T_R/T_G, is therefore ± 0.22 percent.

The same pressure indicating device was used to measure both P_G and P_R during any given comparison. The maximum observed change in pressure during any one set of comparisons was 0.04 percent. The maximum error in reading the pressure was estimated to be no more than ± 0.02 percent. The error in the observed ratio of pressure P_G/P_R was taken to be that due to reading error, ± 0.03 percent.

Since, for comparison measurements made with source b with any given chamber, the value of the change in potential for that chamber, ΔV, is held constant while the time interval, Δt, is observed, the error in the observed ratio of the rate of change of potential depends on constant errors in the ΔV's and Δt's plus random errors in the Δt's. The constant errors in the ΔV's are about ± 0.015 percent. The constant errors in the Δt's are estimated to be about ± 0.02 percent. The standard deviation of the average ratio of Δt's, based on 60 sets of three observations, is as much as 0.04 percent. The total uncertainty in the observed ratio $(\Delta V/\Delta t)_R/(\Delta V/\Delta t)_G$ is assumed to be ± 0.19 percent.

Since the same temperature indicating device was used to determine the observed temperature of the monitor in all comparison measurements, the source of error in the observed ratio $(Tm)_G/(Tm)_R$ is a reading error estimated to be not more than about ± 0.02 percent for each temperature measurement, which results in an estimated error of ± 0.03 percent in the ratio. The total uncertainty of the observed ratio is taken to be ± 0.09 percent.

The same capacitor was used for determining the monitor chamber current for each free-air chamber. This capacitor was also calibrated before, during and after the results were obtained for this experiment. The calibration technique was such that a change in the value of the capacitance of less than 0.01 percent could not be observed. The observed value of the capacitance appeared to vary over a range of 0.02 percent for a period of 38 months. In view of this relatively show change in the observed value of the capacitance and the fact that the ionization current measurements immediately followed one another, it seems reasonable to assume that the bias in the observed ratio of capacitances, $(C_m)_G/(C_m)_R$, is negligible.

The observed ratio of changes of potential $(\Delta V/\Delta V_m)_R/(\Delta V/\Delta V_m)_G$, (source a) has an error that is composed of four possible biases and four random errors due to reading the potentiometers. The biases in each of the ΔV's is about ± 0.015 percent. The random error of the individual ΔV's cannot be determined since the output of the source was not stabilized. However, since the value of the change of potential observed with the free-air chamber relative to that observed with the monitor should be approximately constant for any one comparison measurement, one can obtain an approximate measure of the standard deviation of the observed individual ratios, $(\Delta V/\Delta V_m)_R$ and $(\Delta V/\Delta V_m)_G$, from their ranges. Using the propagation of error formula, the average standard error of the observed ratio $(\Delta V/\Delta V_m)_R/(\Delta V/\Delta V_m)_G$ was computed to be 0.06 percent based on 117 sets of four observations and 23 sets of three observations. Thus the total uncertainty in this ratio is assumed to be ± 0.24 percent.

One must also consider the degree of unreliability of other possible factors not explicitly included in the equations which might influence the uncertainty of a comparison. In this category are the constancy of x-ray output and inaccuracy of positioning of the two chambers.

As indicated earlier, the relative position of each chamber could be adjusted to within 0.005 cm. At the source-to-chamber distances used with source a an error of ± 0.005 cm in positioning either chamber should have caused no error in the comparisons. However, at the shorter source-to-chamber distances used with source b, an error of ± 0.005 cm in positioning either chamber would have led to an error of about ± 0.03 percent in the comparisons.

TABLE 4. *Components of maximum uncertainty in comparison*

Factor	Uncertainty (percent)	
	Source *a*	Source *b*
C_R/C_G		
L_G/L_R	±0.11	±0.11
A_G/A_R		±.06
$(100-K_e+K_{sc})_G/(100-K_e+K_{sc})_R$	±.03	±.03
$(K_s)_R/(K_s)_G$	±.01	±.01
$(K_a)_R/(K_a)_G$	±.15	±.15
$(K_f)_R/(K_f)_G$	±.20	±.20
T_R/T_G	±.22	±.22
P_G/P_R		±.03
$(\Delta V/\Delta t)_R/(\Delta V/\Delta t)_G$		±.19
$(T_m)_G/(T_m)_R$	±.09	
$(C_m)_G/(C_m)_R$		
$(\Delta V/\Delta V_m)_R/(\Delta V/\Delta V_m)_G$	±.24	
Positioning		±.03
Output constancy		
Square root of sum of squares	0.44	0.41
Sum of absolute values	1.05	1.03

A measure of the x-ray output constancy (important only for source *b*) may be obtained from a comparison of the exposure rate obtained with one chamber before and after measurement obtained by the other. The maximum difference obtained for all comparisons with source *b* amounted to 0.1 percent. However, this apparent difference could be due also to the random and possible biases in P, $\Delta V/\Delta t$, T and positioning of the chamber. The square root of the sum of the squares of the errors in these four factors is 0.29 percent. Thus the observed variation in output is less than the random errors and biases in the four separate factors, so no additional uncertainty is attributed to output variation.

The components of the maximum uncertainty of the comparisons are summarized in table 4. The square roots of the sums of squares are seen to be 0.44 percent for source *a* and 0.41 percent for source *b*. If in the worst possible situation it is assumed that all of the uncertainties are in the same direction, then one obtains the maximum uncertainty by adding the absolute values of all the uncertainties associated with the various factors in eqs (2) and (4) plus those due to positioning and to output constancy. For this sum, one obtains 1.05 percent for comparisons with source *a* and 1.03 percent with source *b*.

7. Uncertainty of Exposure Rate Determinations With the 10 to 60 kV Chamber

It is also of interest to estimate the uncertainty of exposure rate measurements with the new chamber and to speculate as to how this can be reduced. It is convienient to consider separately the uncertainties of each of the factors contained in eq (1) and then obtain their sum as an indication of the maximum uncertainty to be expected in the determination of exposure rate. As many of the factors will depend upon the distance of the defining aperture from the x-ray focal spot and upon the quality of radiation, values for these must be assumed before considering numerical uncertainties in the components. This chamber will often be used for the calibration of Grenz-ray chambers. Therefore a distance of about 25 cm together with an x-ray voltage of about 10 or 15 kV will be assumed for the present discussion. The uncertainties of many of the components in eq (1) will be maximized by such a choice, so that the actual uncertainties for harder qualities and at larger distances may be somewhat less.

The calibration report of the capacitance C indicated a maximum uncertainty of ±0.05 percent. During the course of this investigation it was found that the drift in the value of the capacitance amounted to less than 0.01 percent in several months for some capacitors. Therefore it seems reasonable to indicate a maximum uncertainty of ±0.05 percent for the capacitance C.

The uncertainty of the observed ratio $\Delta V/\Delta t$ has been considered in the previous section. There it was indicated that the total uncertainty in the observed ratio is assumed to be ±0.19 percent. This of course assumes that the voltage measuring device has been recently calibrated and that, with the present equipment, Δt is 20 sec or more.

As indicated above, the standard deviation of a measurement of the effective width of the collector is assumed to be no more than 0.02 percent, and an allowance of ±0.02 percent is made for systematic error. Thus the total uncertainty of the observed effective collector width is assumed to be ±0.08 percent. The measurements of the aperture area were indicated previously to have a standard deviation of 0.02 percent. To be conservative, the maximum uncertainty in the area is taken to be three standard deviations, or ±0.06 percent.

At 10 or 15 kV and minimum filtration the value of the air attenuation correction factor is considerably larger than that considered during the comparison of the two chambers. Preliminary data indicates that the value of K_a for the 3.9 cm air absorption path is approximately 1.2. The standard deviation of the average of three observed values of K_a in this quality region, based on 8 sets of three observations and normalized to the same air density, is 0.10 percent. The uncertainty in K_a is taken to be three times the standard deviation of the average, or ±0.30 percent.

It was pointed out earlier that field distortions due to the proximity of other electrodes in this 10 to 60 kV chamber would be minimal. However, because of the possible space charge effects, it is assumed that the inaccuracy of K_f is about ±0.1 percent.

It is also difficult to assign an absolute uncertainty to the value of the correction for lack of saturation, K_s. If one assumes that the theory developed by Scott and Greening is correct, then the actual correction for lack of saturation is only about 0.01 percent for the useful range of this instrument. Thus, if one assumes that the theory is correct, the uncertainty is most likely less than 0.01 percent for this factor.

One can compute the transmission of radiation through the front wall of the new chamber, or one can plug up the aperture and experimentally determine the value of K_l. In either case it can be shown that the contribution due to transmission of radiation through the front wall of this chamber is negligible compared to the total reading.

One may also compute the amount of radiation penetrating the aperture border. It may also be shown that the amount transmitted is negligible compared to that defined by the aperture.

It may be shown that for any reasonable value of temperature, pressure and water vapor in the air, the correction for humidity is not more than about 0.50 percent. The magnitude of this factor of course depends upon our knowledge of the average energy required to produce an ion pair in water vapor compared to air and the relative stopping power for electrons in water vapor and dry air. These errors should not cause an inaccuracy of more than ± 0.05 percent in K_h.

For the chamber and qualities of radiation being considered here, the value of the electron loss correction is estimated to be less than 0.01 percent and the value of the scattered photon contribution correction is the order of 0.4 percent. Ritz (1959) indicated an uncertainty of about ± 0.1 and ± 0.2 percent, respectively, for these two quantities. Therefore the uncertainty of the factor $(100/100-K_e+K_{sc})$ is assumed to be ± 0.03 percent.

The chamber has since been fitted with a thermistor device for indicating the temperature. This has been placed on the guard plate and found to follow quite accurately the temperature of the air inside of the chamber. Therefore, in the future use of this chamber the maximum inaccuracy which could be expected in the temperature is ± 0.03 percent.

The maximum error in reading the observed pressure is estimated to be no more than ± 0.02 percent. It is assumed that a correction will be made to the indicated pressure reading for the systematic error of the device determined from recent calibrations. Therefore, the overall uncertainty of the observed pressure is taken to be three times the standard error of ± 0.02 percent, or ± 0.06 percent.

The position of the chamber can be adjusted to ± 0.005 cm. At a distance of 25 cm, an error of ± 0.005 cm in positioning the chamber could cause an uncertainty of ± 0.05 percent in the exposure rate determination.

We might also consider the uncertainty introduced because of variation in the x-ray tube output. However, as indicated before no extra allowance needs to be made for such an uncertainty. The components of the maximum uncertainty of an exposure rate determination using the 10 to 60 kV chamber are summarized in table 5. The square root of the sum of squares is seen to be 0.50 percent. If in the worst possible situation it is assumed that all of the uncertainties are in the same direction, then one obtains the maximum uncertainty by adding the absolute values of all the uncertainties associated with the various factors in eq (1) plus those due to positioning and output constancy. For this sum one obtains 1.27 percent.

TABLE 5. *Components of maximum uncertainty expected with 10 to 60 kV chamber*

Factor	Uncertainty
	Percent
C	± 0.05
$\Delta V/\Delta t$	$\pm .19$
L	$\pm .08$
A	$\pm .06$
K_a	$\pm .30$
K_f	$\pm .10$
K_s	
K_l	
K_p	
K_h	$\pm .05$
$(100/100-K_e+K_{sc})$	$\pm .30$
T	$\pm .03$
P	$\pm .06$
Constancy of output	
Positioning	$\pm .05$
Square root of sum of squares	0.50
Sum of absolute values	1.27

8. Possible Future Increase in Accuracy of Exposure Rate Determinations With the 10 to 60 kV Chamber

One can see that the major contributors to the inaccuracy of exposure rate determinations with the 10 to 60 kV chamber are the uncertainties associated with the corrections for: (a) electron loss, K_e, (b) scattered photon contribution, K_{sc}, (c) field distortion in the collecting region, K_f, and (d) air attenuation, K_a. The uncertainty in K_a could be reduced somewhat by more measurements. The field distortion uncertainty is a more difficult problem and it would probably require considerable effort in order to make a major reduction in this uncertainty. It might also be worthwhile to determine K_e and K_{sc} more accurately. Here again a major effort would be required in order to appreciably reduce the uncertainty in these factors. Thus it appears that one might reduce the maximum inaccuracy of a measurement of 10 to 15 kV x-rays with this chamber by a few tenths of a percent with some extra effort but reducing it by as much as a factor of two would require a major effort. Such a major effort might be worthwhile to reduce possible disagreement between national standards but there is a real question as to whether the effort is necessary for calibration of clinical x-ray measuring instruments. If there is a medical requirement for greater accuracy in this quality range, x-ray sources of greater stability and clinical instruments capable of better reproducibility than are generally available will be required. In the meantime the new chamber seems adequate for present needs.

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