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INTERCOMPARISON OF NATIONAL ROENTGEN AND GAMMA RAY EXPOSURE-DOSE STANDARDS

by

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Many national laboratories maintain free-air ionization chambers for the measurement of exposure dose in roentgens. In the past, accurate comparison of these chambers was not possible without the transport of one of the standards to another laboratory where a direct comparison of the instruments was made. Because of the considerable cost and time involved, such intercomparisons have not been frequent. On the other hand, intercomparisons between national laboratories are necessary to assure worldwide agreement. A more readily portable instrument of sufficient calibration stability for use as a transfer instrument is therefore desirable. This instrument should also be usable in the higher energy regions, for example, with cobalt 60 and cesium 137 gamma rays.

At the 1956 meeting of the International Commission on Radiological Units and Measurements (ICRU) the U. S. National Bureau of Standards agreed to construct and calibrate a small cavity chamber, a defining diaphragm, and a charge-compensating capacitor for such indirect intercomparisons. A similar kit has been constructed for the United Nations

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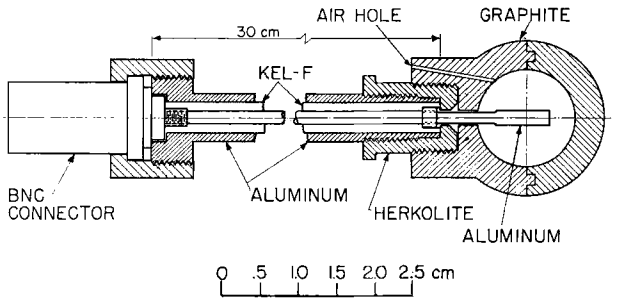

Fig. 1. Cross-sectional view of cavity chamber used on these intercomparisons.

Educational, Scientific, and Cultural Organization. These kits are made available to the various national laboratories for intercomparison purposes.

The present paper reports the results of the calibration of the ionization chamber instruments by four national laboratories. (The results of the diaphragm and capacitor intercomparison are reported elsewhere.) These laboratories were chosen for the first calibration because there has been a direct intercomparison between two (U. K. National Physical Laboratory-NPL and U. S. National Bureau of Standards-NBS) of the national standards (ASTON and ATTIX 1956) and indirect intercomparisons between two (French Laboratoire de Dosimétrie-LD and U. S. National Bureau of Standards) of these laboratories (ALLISY et coll. 1957) and the fourth laboratory (German Physikalisch-Technische Bundesanstalt-PTB) is in the same geographical region. It was hoped that a comparison of the data obtained with the small cavity chambers with that previously reported, might indicate the adequacy of the cavity chambers for such intercomparisons. The calibration data are reported in some detail. By the comparison of data taken at different times by the same laboratory with the same quality of radiation one may obtain some idea about the reproducibility of calibration. One may also examine the data to see if there is a trend in the calibration with the geometrical arrangement which is somewhat different in the various laboratories.

Experimental arrangements

A cross-sectional view of one of the cavity chambers is shown in Fig. 1. It is a three-terminal chamber so that the same current-measuring system can be used for it as for the standard instrument. The wall is about 4 mm thick so that electronic equilibrium will exist even for cobalt 60 gamma rays. The diameter of the aluminum center electrode is adjusted empirically so as to reduce the energy dependence as far as possible. (Subsequent work

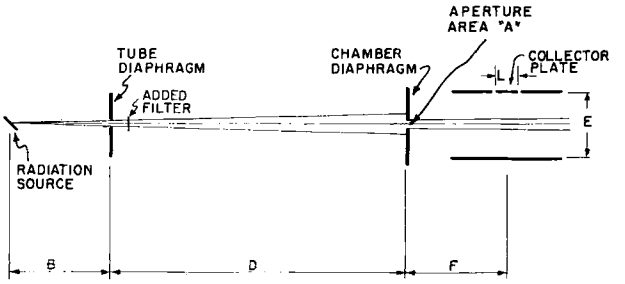

Fig. 2. Schematic view of experimental arrangement at each of the national laboratories during the X-ray calibrations. The principal dimensions are labeled. The plate height of the parallel-plate free-air chamber is dimension G. (See Table 1 for numerical values for each of these dimensions. The principal dimensions of the cylindrical standard at PTB are given in fig. 3.)

with the plastic mixture suggested by SHONKA et coll. 1958 indicates a similar energy dependence with the plastic.) The ionization collecting potential is applied between the graphite shell and the aluminum tubing. Tests of saturation indicate that the lack of saturation is only about 0.1 per cent for dose rates of the order of a few roentgens per minute when 300 volts are used as the collector potential. All calibrations are therefore made with a 300 volt collecting potential and saturation corrections for this chamber are neglected.

Ionization currents are determined for each polarity of collecting potential. The average of these two currents is reported. In this way extracameral effects are eliminated and the effect of leakage from strained insulators is reduced.

The schematic arrangement for the measurement of the roentgen beam with a free-air chamber, at each of the national laboratories, is indicated in

Table 1

Principal parameters for free-air standard measurements at the laboratories in France, Germany, U. K. and the U. S.

Parameters*:	A (cm^2)	B (cm)	D (cm)	F (cm)	L (cm)	E (cm)	G** (cm)	Field strength v/cm	Field distorsion (K_f)
France.....	0.7758	14.5	119.5	22.5	6.003	16	20	125	1.000
Germany....	0.7879	36	100.2	48.1	25.122	***	***	***	1.004
U. K.	0.8139	25	50	52.4	10.043	30	30	100	1.0006
U. S.	0.7855	20	130	30.8	10.08	20	26.8	240	1.000

* See Fig. 2 for interpretation of the letters.
** G is the collector plate height.
*** See Fig. 3.

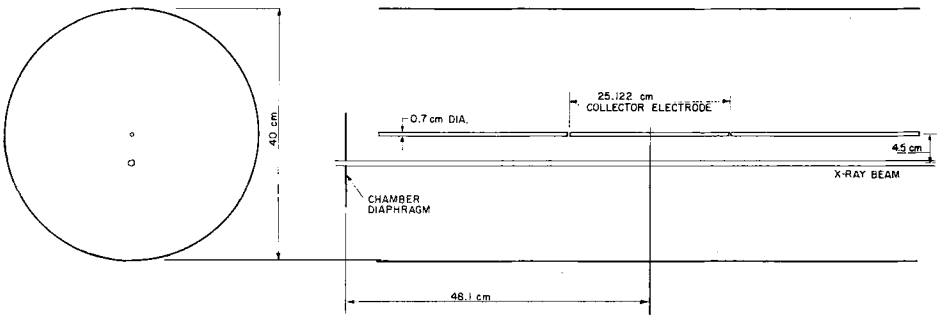

Fig. 3. Schematic view of experimental arrangement at PTB for X-ray calibration. A collecting potential of 3 kV is used and the field strength at radius, r, is given by

$$\frac{3000}{r \ln\left(\frac{40}{0.7}\right)} \text{ v.cm}^{-1}$$

Fig. 2. The important dimensions are indicated by letters. The numerical values for each of the dimensions at each national laboratory are indicated in Table 1. The important dimensions for the cylindrical standard at the PTB are indicated in Fig. 3. Two of the laboratories (PTB and NPL) use a monitoring instrument. This is inserted between the source and the chamber diaphragm. The filtration of this chamber is included when obtaining the indicated half-value layer in Tables 4 and 5.

At LD, NBS and PTB the roentgen tubes are operated with a constant potential high voltage generator. At NPL two roentgen tubes cover the 80 to 290 kV range but the generators for each tube at the time of the measurement provided a pulsating potential.

A substitution method is used for the calibration of the cavity chamber at each of the laboratories. The dose rate is first determined by the national standard. The standard is then moved out of the way and the cavity chamber is accurately centered at the position previously occupied by the aperture of the free-air-chamber diaphragm. After determination of the ionization current in the cavity chamber, it is removed and the free-air chamber repositioned and the dose rate is determined again.

The dose rate for the 2 MV roentgen beam and for the cobalt 60 and cesium 137 gamma ray beams is determined by means of cavity chambers. The cavity chambers and the corrections used for the 2 MV roentgen beam calibration are described by BARNARD et coll. (1956, 1959a, 1959b). The graphite cavity chamber used for the cobalt 60 and cesium 137 gamma ray beam calibrations is described by ATTIX and RITZ (1957) and the corrections are discussed by WYCKOFF (1960). (The stopping power corrections used for these calibrations are those labeled 'Bakker and Segré' in the paper mentioned here.)

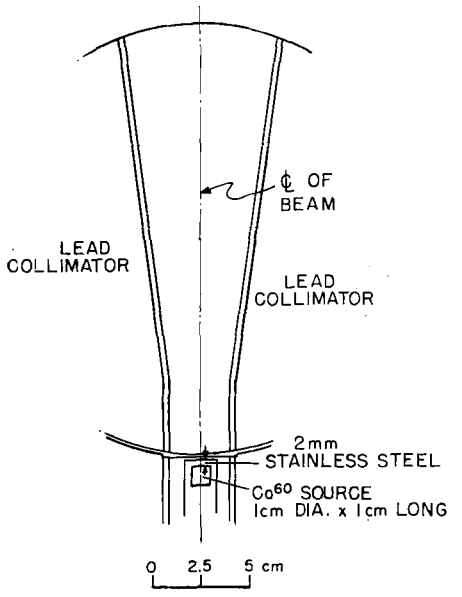

Fig. 4. Cross-sectional view of 100 curie cobalt 60 source and collimator used for gamma-ray calibration. The graphite chamber is positioned on the center line of the beam at a distance of approximately 1 meter from the source.

The geometrical arrangement of the source and collimation for these calibrations are shown in Figs 4 and 5. Calibration of the gamma ray beams is obtained with the radiation incident at about 45 degrees to the axis of the cylindrical chamber. This is necessary in order to reduce the end-wall attenuation discussed by ATTIX and RITZ.

The 2 MV roentgen beam is produced by electrons accelerated by a Van de Graaff generator. The transmission target is of 2.3 mm thick tungsten and the focal spot is about 0.3 mm diameter. A conical aperture in a tungsten alloy collimator gives a beam of half angle about 43′. The HVL of the radiation is 11.9 mm Cu. Calibrations are performed at 180 cm from the target.

Results

For the calibrations obtained with free-air chambers the calibration factor, M, of the cavity chamber is obtained from

$$M = \frac{1.7986 \cdot 10^{11}}{A \cdot L} K_a \cdot K_f \cdot K_s \cdot K_{sh} \cdot K_l \cdot K_p \cdot K_h \left(\frac{1}{1 - K_e + K_{sc}}\right) \left(\frac{T_s}{T_c}\right) \left(\frac{C_s}{C_c}\right) \frac{\left(\frac{\Delta v}{\Delta t}\right)_s}{\left(\frac{\Delta v}{\Delta t}\right)_c} \text{ r/amp.min,} \quad (1)$$

where A is the area of the diaphragm in cm²,
L is the length of the collecting electrode in cm,
K_a is the correction for air attenuation in a distance F (see Fig. 2),
K_f is the correction for field distortion (see Table 1),
K_s is the correction for lack of saturation,
K_e is the correction for loss of ionization from secondary electrons because of inadequate plate separation,
K_{sc} is the correction for ionization produced by scattered photons,
K_{sh} is the correction (WEHRHEIM 1938) for shadowing of the collector and is applicable only to the PTB chamber,
K_l is the correction for radiation leaking into the free air chamber,
K_p is the correction for radiation penetration of the aperture border,
K_h is the correction for humidity,
T is the absolute temperature in the free-air chamber,

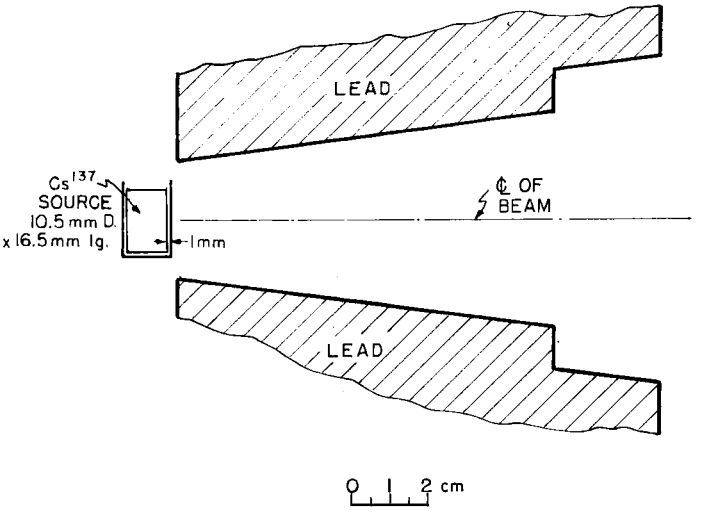

Fig. 5. Cross-sectional view of 120 curie cesium 137 source and collimator used for gamma ray calibration. The graphite chamber is positioned on the center line of the beam at a distance of approximately 83 cm from the source.

T_c is the absolute temperature in the cavity chamber (assumed to be the same as in the room),

C_s is the capacitance in farads of the capacitor used for determining the charge collected from the free-air chamber,

C_c is the capacitance in farads of the capacitor used for determining the charge collected from the cavity chamber,

$\left(\frac{\Delta v}{\Delta t}\right)_s$ is the rate of change of potential in volt/sec on the capacitor used with the free-air chamber, and

$\left(\frac{\Delta v}{\Delta t}\right)_c$ is the rate of change of potential in volt/sec on the capacitor used with the cavity chamber.

Values for K_f are obtained by the methods outlined by WYCKOFF and ATTIX (1957). Values of K_e are obtained from the same reference. Values of K_s used at PTB are obtained from the paper by HÜBNER (1958). Each of the other three laboratories determined the values experimentally. Values of K_a and K_{sc} are obtained either from measurements in the particular laboratory (NPL, NBS) or from the data reported by WYCKOFF and ATTIX. The data for K_{sc} in this reference are corrected in accordance with the more precise values obtained by RITZ (1959) and HENRY (1961). (See correction sheet added to the WYCKOFF and ATTIX reference in 1961.) Values of K_h are obtained from the report by BARNARD, ASTON and MARSH (1961). The value of K_l is obtained experimentally by noting the charge collected when the diaphragm is replaced with a solid plug or by measurements with a thicker diaphragm (NPL). The value of K_p is determined by computing the ratio of the radiation transmitted by the border of the aperture to that passed by the aperture.

The data obtained at NBS before cavity chambers II and IX were shipped to the other laboratories are indicated in Table 2. Data obtained after they were returned to NBS are indicated in italics in the same table. The data obtained at LD, PTB and NPL, respectively, are given in Tables 3, 4 and 5. No humidity data are available for some of the calibrations. However, from the recorded temperature and the usual relative humidity encountered during the time of these measurements the estimated correction probably is not more than 0.05 to 0.02 per cent for Table 2 and about twice this for Table 3. When these data were not available these corrections have been neglected in computing the value of M.

At NBS, the exposure time, Δt, is usually the same for both the free-air and the cavity chambers. At LD the value of the capacitor potential was the same for both instruments.

At NPL, experience has indicated no difference in the temperature of the interior of the free-air chamber and the room. For this laboratory the value of T_s/T_c is 1.000.

An additional correction, K_c, is applied at NBS because of the lack of coplanarity of the guard plates and the collector plate. Earlier measurements (RITZ 1960) indicated that $K_c = 1.0015$. Measurements made after the calibrations reported here indicated that the correction is still the same.

For the gamma ray and 2 MV roentgen calibrations the calibration factor is given by

$$M = \dot{R}/C_c \left(\frac{\Delta v}{\Delta t}\right)_c \left(\frac{T_c}{273.2}\right) \left(\frac{760}{P}\right) K_h \qquad (2)$$

where

$\dot{R}$ is the exposure dose rate at the calibration point in r/min,

P is the atmospheric pressure in mm of mercury, and the other symbols having the meaning previously described.

Results of such calibrations are given in Table 6.

One of the investigators (G. P. BARNARD) noted a $\pm$ 0.2 per cent variation of response with direction of incident 2 MV radiation on chamber II but none on chamber IX. No investigation for such a possible orientation dependence was conducted before the chambers left NBS but an attempt was made to verify the NPL results after the chambers were returned. In agreement with NPL no orientation dependence greater than the reproducibility (about 0.1 per cent) was observed for chamber IX with cobalt 60 gamma rays. The results for chamber II are less certain. Shortly after the chambers were returned to NBS, chamber II developed an intermittent electrical short between the center electrode and the grounded aluminum tube. Radiograms indicated that the collecting electrode was not positioned on a diameter of the cavity. Forced rotation of the center pin of the BNC connector, which connects directly to the collecting electrode, moves the center electrode on the surface

Table 2

Data from National Bureau of Standards at the start and end of intercomparison (The values from the end of the intercomparison are in italics)

kV	Total filtration mm Al	Total filtration mm Cu	HVL (mm Cu)	Approx. dose rate (r/min)	Free-air chamber corrections [a] K_a	K_s	K_l	K_p
60	4.4	0	0.089	0.67	1.013_1	1.000_7	1.000	1.000
75	4.4	0	0.11	1.12	1.011_2	1.000_8	1.000	1.000
100	5.4	0	0.20	1.69	1.009_7	1.000_9	1.000	1.000
150	5.4	0.25	0.66	2.3	1.006_8	1.001_0	1.000	1.000

Table 2 *(cont.)*

K_e	K_{sc}	Chamber	Date	$\frac{\left(\frac{\Delta v}{\Delta t}\right)_s}{\left(\frac{\Delta v}{\Delta t}\right)_c}$	$\frac{T_s}{T_c}$	K_h	M·10^{-11} (r/amp.min)
0.000_0	0.007_0	II	2/6/59	0.7526	1.000_7		1.806
			2/13/59	0.7509	1.000_3		1.801
			5/9/60	*0.7900*	*1.000_4*	*1.000_9**	*1.802*
			1/10/61	*7.756*	*1.000_3*	*1.000_4*	*1.801*
		IX	1/18/59	0.7179	1.001_3		1.724
			2/14/59	0.7174	1.001_0		1.722
			5/5/60	*0.7541*	*1.000_6*	*1.000_9*	*1.721*
			5/9/60	*0.7542*	*1.001_6*	*1.000_9***	*1.722*
			1/10/61	*7.459*	*1.000_0*	*1.000_4*	*1.731*
0.000_0	0.007_0	II	2/6/59	0.7427	1.000_7		1.779
			2/13/59	0.7413	1.000_4		1.775
			5/10/60	*0.7784*	*1.000_3*	*1.000_9*	*1.772*
			1/10/61	*0.7330*	*1.001_0*	*1.000_4*	*1.772*
		IX	1/18/59	0.7089	1.002_0		1.700
			2/13/59	0.7061	1.001_7		1.693
			2/14/59	0.7076	1.001_3		1.696
			5/5/60	*0.7442*	*1.000_7*	*1.000_8*	*1.695*
			1/10/61	*0.7032*	*1.001_0*	*1.000_4*	*1.700*
0.000_0	0.006_0	II	2/6/59	0.7264	1.001_3		1.740
			2/13/59	0.7258	1.000_7		1.738
			5/10/60	*0.7613*	*1.001_0*	*1.000_7*	*1.734*
			1/10/61	*0.7182*	*1.002_3*	*1.000_4*	*1.738*
		IX	1/18/59	0.6932	1.002_0		1.662
			2/13/59	0.6907	1.001_0		1.654
			2/14/59	0.6926	1.001_0		1.659
			5/5/60	*0.7263*	*1.001_0*	*1.000_7*	*1.654*
			1/10/61	*0.6846*	*1.002_7*	*1.000_4*	*1.657*
0.001_5	0.004_0	II	2/6/59	0.7161	1.001_7		1.717
			2/14/59	0.7151	1.002_4		1.716
			5/10/60	*0.7523*	*1.001_3*	*1.000_6*	*1.715*
			1/10/61	*0.7119*	*0.999_7*	*1.000_2*	*1.719*
		IX	1/18/59	0.6787	1.002_4		1.629
			2/14/59	0.6784	1.001_3		1.626
			5/6/60	*0.7112*	*1.000_0*	*1.000_6*	*1.619*
			1/10/61	*0.6710*	*0.999_3*	*1.000_3*	*1.619*

Table 2 *(cont.)*

kV	Total filtration mm Al	Total filtration mm Cu	HVL (mm Cu)	Approx. dose rate (r/min)	Free-air chamber corrections[a]* K_a	K_s	K_l	K_p
200	5.4	0.52	1.26	3.6	1.005_9	1.001_2	1.000	1.000
250	5.4	1.02	2.17	4.7	1.005_2	1.001_3	1.000	1.000
250	5.4	3.15	3.2	2.4	1.004_5	1.001_0	1.000	1.000

* In eq. 1 the value of $\frac{1.7986 \cdot 10^{11}}{A \cdot L} \cdot K_f \cdot K_c = 0.22750 \cdot 10^{11}$; for the 1959 data $\frac{C_s}{C_c} = 10.469$; for the 1960 data $\frac{C_s}{C_c} = 9.9475$; for the 1961 data at 60 kV $\frac{C_s}{C_c} = 1.0132$; and for the remainder of the 1961 data $\frac{C_s}{C_c} = 10.558$.

of an imaginary small cone. Apparently the axis of the collecting electrode and its connection are not the same.

Measurements on the radiograms of this chamber also indicated no large differences in wall thickness such as might exist if the outer and inner sphere did not have the same center. The uncertainty (0.1 to 0.2 mm) in such measurement, however, is large enough so that this reason for orientation de-

Table 2 *(cont.)*

K_e	K_{sc}	Chamber	Date	$\frac{\left(\frac{\Delta v}{\Delta t}\right)_s}{\left(\frac{\Delta v}{\Delta t}\right)_c}$	$\frac{T_s}{T_c}$	K_h	M·10^{-11} (r/amp.min)
0.004_0	0.004_0	II	2/6/59	0.7200	1.001_7		1.731
			2/14/59	0.7193	1.002_4		1.730
			5/10/60	*0.7583*	*1.001_7*	*1.000_4*	*1.732*
			1/10/61	*0.7138*	*1.000_7*	*1.000_2*	*1.728*
		IX	1/18/59	0.6796	1.003_0		1.636
			2/14/59	0.6788	1.001_7		1.632
			5/6/60	*0.7118*	*1.000_3*	*1.000_5*	*1.624*
			1/10/61	*0.6716*	*1.000_7*	*1.000_2*	*1.626*
0.005_0	0.003_5	II	2/6/59	0.7254	1.001_3		1.744
			2/14/59	0.7254	1.002_4		1.746
			5/10/60	*0.7620*	*1.001_7*	*1.000_3*	*1.742*
			1/10/61	*0.7214*	*1.002_7*	*1.000_2*	*1.752*
		IX	1/18/59	0.6818	1.004_1		1.644
			2/14/59	0.6825	1.001_7		1.642
			5/6/60	*0.7155*	*1.001_0*	*1.000_3*	*1.635*
			1/10/61	*0.6761*	*1.001_7*	*1.000_2*	*1.640*
0.005_0	0.003_5	II	2/6/59	0.7303	1.001_7		1.754
			2/14/59	0.7321	1.002_0		1.759
			5/10/60	*0.7713*	*1.001_0*	*1.000_2*	*1.760*
			1/10/61	*0.7278*	*1.002_7*	*1.000_2*	*1.765*
		IX	1/18/59	0.6852	1.004_1		1.650
			2/14/59	0.6860	1.002_0		1.649
			5/6/60	*0.7189*	*1.000_7*	*1.000_2*	*1.640*
			1/10/61	*0.6788*	*1.003_0*	*1.000_2*	*1.647*

** Estimated.

pendence of calibration cannot be ruled out. Calibrations of chamber II at NBS indicated that the orientation dependence may be as large as reported by NPL but the reproducibility is of the same order (about 0.1 per cent). Such calibrations included determinations with cobalt 60 gamma rays and with 100 kV roentgen rays. The latter determinations also included different orientations of the collecting electrode.

Table 3

Data from Laboratoire de Dosimétrie

kV	Added filter (mm)		HVL (mm Cu)	Approx. dose rate (r/min)	Free-air chamber corrections**			
	Al	Cu			K_a	K_s	K_l	K_p
60	1.2	—	0.08_9*	0.36	1.009	1.001	1.000	1.000
100	1.8	—	0.2	0.98	1.007	1.001	1.000	1.000
150	1	0.25	0.65	1.35	1.005	1.001	1.000	1.000
200	1	0.5	1.2	2.12	1.004	1.001	1.000	1.000

* The HVL in copper at 60 kV was not measured at the Laboratoire de Dosimétrie but the HVL in aluminum was determined to be 2.85 mm. As this agrees very well with the HVL in aluminum (2.9 mm) determined at NBS it is assumed that the HVL in copper for 60 kV X-rays is the same as that obtained at NBS.

The reason for the orientation dependence has not been definitely established at this time but care should be taken to minimize the probability of its happening in the future. Radiograms of the chamber after construction will check the centering of the collector electrode. The chamber could be calibrated always in the same orientation. This is now the standard practice at NBS. While the magnitude of the orientation dependence is probably not large it is suggested that these two precautions be observed for future intercomparisons.

Comparison of results

An examination of the results listed in Table 2 permits an evaluation of the reproducibility of the cavity chamber calibration. In order to eliminate possible changes of these calibrations between the two sets, it is necessary to examine separately the data taken before and after shipment. The maximum deviation of any calibration from the mean value obtained for either chamber at any one quality varies from about 0.03 to 0.3 per cent. The mean value of these

Table 3 *(cont.)*

K_e	K_{sc}	Chamber	$\frac{\Delta v_s}{\Delta v_c}$	Date	$\frac{T_s}{T_c}$	$M \cdot 10^{-11}$ (r/amp.min)
0.000	0.006_0	II	1.000	4/21/59	0.9953	1.794
0.000	0.004_7	II	1.000	4/13/59	0.9983	1.741
				4/14/59	0.9971	1.737
				4/15/59	0.9958	1.735
				4/17/59	0.9980	1.737
				4/21/59	0.9932	1.741
0.003_6	0.003_4	II	1.000	4/10/59	0.9976	1.715
				4/14/59	0.9969	1.714
				4/16/59	0.9986	1.712
				4/20/59	0.9986	1.718
0.007_1	0.003_2	II	1.000	4/14/59	0.9970	1.728
				4/15/59	0.9974	1.727
				4/17/59	0.9969	1.725
				4/21/59	0.9988	1.730

** In eq. 1 the value of $\frac{1.7986 \cdot 10^{11}}{A \cdot L} \cdot K_f = 0.38621 \cdot 10^{11}$; $\frac{C_s}{C_c} = 9.762_6$

deviations for all qualities for either chamber is about 0.1 per cent. Similar ranges and mean values are obtained from the data in the other tables where there are sufficient data for analysis.

A comparison of the two sets of data from NBS permits a determination of the long-term stability of the calibration. The ratio of the mean calibration factor in the first set to that in the second set for the same quality is taken as a measure of the long-term stability. For chamber II this ratio varies from about 0.997 to 1.003 for the different qualities and the mean value for all qualities is 1.000. For chamber IX the ratio varies from about 0.999 to 1.006 with a mean value of 1.003.

Thus there appears to be a reproducibility uncertainty of as much as 0.3 per cent for either chamber when only a small number of measurements are available. In addition there appears to be a possible orientation dependence of up to 0.2 per cent for chamber II and a drift of calibration of up to 0.3 per cent for chamber IX. These factors set the maximum uncertainty of the calibration at about 0.5 per cent. Thus one might expect that the lack of reproducibility

Table 4

Data from the Physikalisch-Technische Bundesanstalt

kV	Added filter * (mm) Al	Cu	HVL (mm Cu)	Approx. dose rate (r/min)	Free-air chamber corrections** K_a	K_s	K_{sh}	K_l
60	—	—	0.083	0.28	1.021_8	1.000_2	1.001_2	1.000
75	—	—	0.110	0.58	1.018_1	1.000_3	1.001_2	1.000
100	1.0	—	0.197	1.02	1.014_4	1.000_5	1.001_2	1.000
150	1.0	0.13	0.64_7	1.15	1.011_1	1.000_6	1.001_2	1.000
200	1.0	0.26	1.20_5	1.00	1.010_0	1.000_5	1.001_2	1.000
200	1.0	0.26	1.20_5	1.00	1.010_0	1.000_5	1.001_2	1.000
250	1.0	0.72	2.11	1.18	1.009_3	1.000_6	1.001_2	1.000
250	1.0	3.0	3.13	1.12	1.008_8	1.000_6	1.001_2	1.000
250	1.0	3.0	3.13	1.12	1.008_8	1.000_6	1.001_2	1.000
300	1.0	4.0	3.95	1.10	1.008_5	1.000_6	1.001_2	1.000
350	1.0	6.0	4.74	1.10	1.008_3	1.000_6	1.001_2	0.9918_8

* Inherent filtration about 4 mm Al.

** In eq. 1 the value of $\frac{1.7986 \cdot 10^{11}}{A \cdot L} \cdot K_f = 0.091231 \cdot 10^{11}$

of the calibration of either chamber at any laboratory for any quality should not exceed about 0.5 per cent.

As the data from the four laboratories are not all obtained for the same qualities, it is necessary to interpolate in order to compare the results. The calibration factor obtained for the two chambers at the four laboratories are plotted against the half-value layer (HVL) of the radiation in Figs 6 and 7. The vertical line for each NBS calibration indicates the range of values obtained while the circle indicates the mean value. For clarity only the mean values are plotted for the other laboratories. A smooth curve is drawn through the

Table 4 *(cont.)*

K_p	$\frac{1}{1-K_e+K_{sc}}$	Chamber	Date	$\left(\frac{C_s}{C_e}\right)\frac{\left(\frac{\Delta v}{\Delta t}\right)_s}{\left(\frac{\Delta v}{\Delta t}\right)_c}$	$\frac{T_s}{T_c}$	K_h	M·10^{-11} (r/amp. min)
1.000	0.9896	II	6/8/59	19.499	1.001_6	1.0017	1.808
		IX	6/8/59	18.685	1.001_6		1.732
1.000	0.9899	II	6/1/59	19.248	$0.9\,99_4$	1.0013	1.773
		IX	6/1/59	18.418	0.998_8		1.696
1.000	0.9913	II	5/28/59	18.930	1.000_5	1.0011	1.743
		IX	5/28/59	18.016	1.001_7		1.660
1.000	0.9933	II	6/3/59	18.629	1.000_8	1.0012***	1.713
		IX	6/3/59	17.726	1.001_2		1.630
1.000	0.9943	II	6/2/59	18.716	1.002_2	1.0011	1.723
		IX	6/2/59	17.654	1.002_1		1.625
1.000	0.9943	II	6/11/59	18.756	1.002_4	1.0011	1.727
		IX	6/11/59	17.698	1.001_7		1.628
1.000	0.9954	II	5/29/59	18.918	1.001_0	1.0008***	1.740
		IX	5/29/59	17.735	1.001_3		1.632
1.000	0.9940	II	6/4/59	19.051	1.000_8	1.0005***	1.748
		IX	6/4/59	17.826	1.001_8		1.637
1.000	0.9940	II	10/15/59	19.027	1.002_3	1.0004	1.748
		IX	10/15/59	17.888	0.999_7		1.638
1.000	0.9963	II	10/13/59	19.079	0.999_8	1.0003	1.752
		IX	10/13/59	17.931	1.000_4		1.647
0.9983	0.9973	II	10/14/59	19.368	0.999_8	1.0003	1.763
		IX	10/14/59	18.113	1.001_1		1.650

*** Estimated.

NBS roentgen data points. The large value for the softer qualities results from the large wall attenuation which decreases for the harder radiations. The rise beyond the minimum is due to the decrease of the photoelectric effect in the aluminum center electrode.

The deviation of the calibration factors obtained at LD, NPL, and PTB from the smooth curve through the NBS results are listed in Table 7. Column 3 of that table gives the deviations for chamber II, column 4 for chamber IX, and column 5 the mean value for the two chambers at each of the qualities. The maximum difference between columns 3 and 4 is 0.9 per cent for one

Table 5

Data from National Physical Laboratory

kV	Added filter * (mm) Al	Cu	HVL (mm Cu)	Approx. dose rate (r/min)	Free-air chamber corrections K_a	K_s	K_p	K_l
80	—	—	0.103	2.1	1.023_3	1.002_1	1.000	1.000_0
125	1.0	—	0.200	4.3	1.015_6	1.004_3	1.000	1.000_0
125	1.0	0.05	0.250	3.4	1.014_4	1.003_4	1.000	1.000_0
145	1.0	0.25	0.50	2.7	1.011_5	1.002_7	1.000	1.000_0
180	—	—	1.02	3.4	1.010_2	1.003_4	1.000	1.000_0
250	1.0	0.1	1.53	5.7	1.009_1	1.005_7	1.000	0.999_7
290	1.0	0.63	2.19	6.4	1.008_4	1.006_3	1.000	0.998_8
250	1.0	1.9	2.55	2.6	1.008_2	1.002_6	1.000	0.998_8
290	1.0	4.0	3.40	2.5	1.007_9	1.002_5	1.000	0.995_8

* From 80 to 145 kV the tube had an inherent filtration equivalent to about 0.095 mm Cu and at higher voltages to about 1.1 mm Cu. The monitor provided a permanent additional filtration of 8 mm perspex.

quality but the next highest difference is 0.6 per cent and the remainder are 0.4 per cent or less. These differences are consistent with the expected reproducibility noted above.

Table 5 *(cont.)*

K_6	K_{sc}	Cavity chamber number	Date of measurements	P**	K_h	M·10^{-11} (r/amp.min)
0.000_0	0.006_9	II	12/8/59	1.7602	1.001_1	1.796
		II	12/14/59	1.7693	1.001_2	1.805
		IX	1/16/60	1.6774	1.001_0	1.711
		IX	1/8/60	1.6811	1.000_9	1.715
0.000_0	0.006_7	IX	1/7/60	1.6394	1.000_7	1.663
		IX	1/8/60	1.6445	1.000_8	1.669
0.000_0	0.006_6	II	12/9/59	1.7066	1.000_9	1.728
		II	12/15/59	1.7050	1.001_0	1.727
0.000_2	0.006_1	II	12/9/59	1.6846	1.000_7	1.701
		II	12/14/59	1.6989	1.000_7	1.715
		II	12/15/59	1.6962	1.000_7	1.713
		IX	1/7/60	1.6104	1.000_6	1.626
		IX	1/11/60	1.6138	1.000_6	1.629
0.000_8	0.005_6	II	12/9/59	1.7007	1.000_5	1.718
		II	12/11/59	1.7036	1.000_5	1.721
		IX	12/31/59	1.6124	1.000_4	1.628
		IX	1/11/60	1.6109	1.000_4	1.627
0.001_5	0.005_1	II	1/27/60	1.7291	1.000_4	1.750
		II	1/28/60	1.7293	1.000_4	1.750
0.002_2	0.004_7	II	12/22/59	1.7466	1.000_4	1.768
		II	1/25/60	1.7376	1.000_4	1.758
		IX	1/4/60	1.6341	1.000_3	1.654
		IX	1/18/60	1.6338	1.000_3	1.653
0.002_2	0.004_6	II	12/10/59	1.7431	1.000_3	1.757
		II	12/16/59	1.7421	1.000_3	1.756
0.001_7	0.004_3	II	12/10/59	1.7498	1.000_3	1.758
		II	12/11/59	1.7565	1.000_3	1.764
		IX	1/20/60	1.6553	1.000_2	1.663
		IX	1/21/60	1.6531	1.000_2	1.660

** $P = \dfrac{1.7986 \cdot 10^{11}}{A \cdot L} \left(\dfrac{C_s}{C_c}\right) \dfrac{\left(\dfrac{\Delta v}{\Delta t}\right)_s}{\left(\dfrac{\Delta v}{\Delta t}\right)_c}$

It is noted that the average calibration factors obtained at NPL tend to be larger than those obtained at NBS and those at PTB seem to be lower especially at the harder qualities. Those at LD are in close agreement but

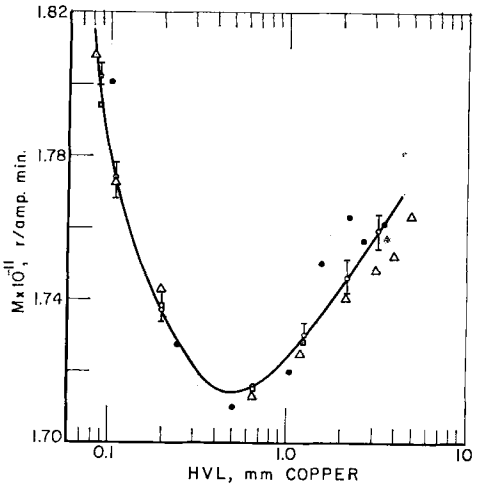

Fig. 6. Average calibration factors for chamber II obtained at the four laboratories for the various qualities. ⊡ = LD, ⊙ = NBS, ● = NPL, △ = PTB. The vertical line through each NBS point gives the range of values obtained.

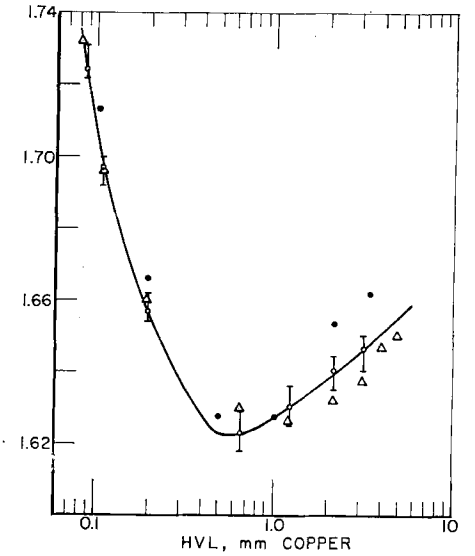

Fig. 7. Average calibration factors for chamber IX obtained at three laboratories for the various qualities. ⊙ = NBS, ● = NPL, △ = PTB. The vertical line through each NBS point gives the range of values obtained.

cover only a limited range of qualities. There has been no previous intercomparison between NBS and PTB but the previous indirect intercomparison between LD and NBS and the previous direct intercomparisons between NPL and NBS gave results similar to the present ones. The last column of Table 7 indicates the deviations previously obtained (ALLISY et coll. 1957, and ASTON and ATTIX 1956) for approximately the indicated qualities. It is seen that these values differ from those obtained in the present intercomparisons by not more than the expected amount (0.5 per cent). While the previous NBS-NPL intercomparisons were obtained with a d. c. generator for the roentgen tube, the present results are obtained with a pulsating potential at NPL and a d. c. generator at NBS. The good agreement between columns 5 and 6 indicate that the effect of this different wave form is not greater than the possible lack of reproducibility, 0.5 per cent.

For the previous NBS-NPL intercomparison the dose rates and target-diaphragm distances were the same for both chambers, and determinations were made at the same collecting field strengths. During the present measurements, the dose rates, target-diaphragm distances, and field strengths, were all different at the two laboratories. The saturation corrections, K_s, were

Table 6

High energy calibrations

Source	HVL (mm Cu)	Chamber	Date	$M \cdot 10^{-11}$ (r/amp.min)
Co^{60} (NBS)	14.7	II	2/9/59	1.780
		IX	2/9/59	1.663
Cs^{137} (NBS)	10.5	II	2/10/59	1.788
		IX	2/11/59	1.680
2 MV roentgen rays (NPL)	11.9	II	2/16/60	1.774
			2/19/60	1.771
			3/4/60	1.770
		IX	2/16/60	1.650
			3/3/60	1.648
			3/4/60	1.649
Co^{60} (NBS)	14.7	II	5/19/60	1.793
			5/19/60	1.774
			5/20/60	1.773
			1/6/61	1.775
		IX	5/19/60	1.650
			5/30/60	1.655
			1/6/61	1.659
Cs^{137} (NBS)	10.5	II	5/19/60	1.794
			5/29/60	1.799
		IX	5/16/60	1.666
			5/20/60	1.667
			5/29/60	1.673

determined at each laboratory under the conditions used at that laboratory. Further investigations are needed to assure that these are consistent.

As noted earlier the NPL results tend to be higher than NBS and PTB lower for the harder qualities. Moreover, the present results for NPL are in moderately good agreement with those obtained earlier. Good agreement in the area of diaphragms and in the value of the capacitance used for current measurement (ICRU Report 1959) seem to rule out these factors as contributing to these differences. In any case, because both the NPL and PTB chambers are larger than the NBS chamber the differences cannot be attributed to a simple function of chamber size. Perhaps detailed redetermination of the correction factors will be necessary in order to obtain a reason for these differences.

The measurements with gamma rays and 2 MV roentgen rays give less useful intercomparison. The large spread in the NBS calibration factors and the large difference in the spectra of the roentgen and gamma ray sources make a comparison difficult. In view of these difficulties the intercomparisons seem reasonable.

Table 7

Comparison of calibration factors—deviation of calibration factor from NBS (per cent)

HVL (mm Cu)	Lab	Chamber II	Chamber IX	Av.	Previous**
0.083	PTB	— 0.1	— 0.1	— 0.1	
0.089	LD	— 0.4	—	— 0.4	0.0
0.103	NPL	+ 0.8	+ 0.4	+ 0.6	+ 0.5
0.11	PTB	0.0	0.0	0.0	
0.197	PTB	+ 0.3	+ 0.2	+ 0.3	
0.20	LD	+ 0.1	—	+ 0.1	+ 0.1
0.20	NPL	—	+ 0.6	+ 0.6	+ 0.4
0.25	NPL	0.0	—	0.0	+ 0.4
0.50	NPL	— 0.2	+ 0.2	0.0	+ 0.3
0.64_7	PTB	— 0.2	+ 0.4	+ 0.1	
0.65	LD	0.0	—	0.0	+ 0.4
1.02	NPL	— 0.3	+ 0.0	— 0.2	+ 0.3
1.2	LD	— 0.1	—	— 0.1	— 0.1
1.20_5	PTB	— 0.2	— 0.2	— 0.2	
1.53	NPL	+ 0.8	—	+ 0.8	+ 0.4
2.11	PTB	— 0.3	— 0.4	— 0.4	
2.19	NPL	+ 1.0	+ 0.8	+ 0.9	+ 0.5
2.55	NPL	+ 0.2	—	+ 0.2	
3.13	PTB	— 0.6	— 0.5	— 0.6	
3.4	NPL	0.0	+ 0.9	+ 0.5	
3.95*	PTB	— 0.8	— 0.2	— 0.5	
4.74*	PTB	— 0.6	— 0.3	— 0.5	

* Deviations uncertain at this quality as an extrapolation of NBS data is involved.
** For approximately the indicated HVL.

Conclusions

Indirect intercomparisons of calibrations of ionization chambers for exposure dose measurements in roentgens have been completed between the national standards of France, Germany, U. K., and U. S. A., with an estimated maximum uncertainty of about 0.5 per cent. This is somewhat larger than that assigned to direct comparisons (ASTON and ATTIX 1957). This large uncertainty can probably be reduced by a factor of about 2 by (1) assuring that there is no drift in calibration before the intercomparison is attempted, (2) radiography of the chambers before use to see that they are as symmetrical as possible, and (3) always calibrating the instrument in a fixed orientation. Under these conditions such indirect intercomparisons should be almost as accurate as the direct ones.

The present calibrations agree with those obtained earlier between three of the laboratories to within the expected uncertainty, 0.5 per cent; also the

calibrations at PTB agree with those at NBS to within 0.6 per cent. However the results from NPL and PTB disagree by slightly more than one per cent for nearly the same quality of the harder radiations. A detailed redetermination of some of the correction factors may be needed to remove this discrepancy.

Acknowledgement

The measurements at NPL were mostly made by Mr A. R. S. Marsh and Mr J. E. Woodall. Many of the measurements at NBS were made by Mr L. DeLaVergne and Mr J. T. Weaver. The work described above has been carried out as part of the research programs of the several laboratories and this paper is published by permission of their directors.

SUMMARY

A pair of cavity ionization chambers has been circulated to the national laboratories of France, Germany, U. K., and U. S. A. for calibration with roentgen and gamma rays. The difference of their calibrations with a given quality of radiation is taken as a measure of the disagreement of the national standards. The results obtained agree with some earlier direct comparisons to within the expected uncertainty of these measurements — about 0.5 per cent.

ZUSAMMENFASSUNG

Ein Paar Hohlraumsionisationskammern haben zum Zweck der Kalibrierung in den staatlichen Laboratorien von Frankreich, Deutschland, U. K., und U. S. A. zirkuliert. Die Differenz der Kalibrierungsfaktoren bei einer gegebenen Strahlenqualität wird als Mass für die Abweichungen zwischen den nationalen Standardmethoden angenommen. Die erhaltenen Resultate stimmen mit einigen früheren direkten Vergleichen innerhalb einer Fehlergrenze von ca. 0.5 % überein.

RÉSUMÉ

Les auteurs ont envoyé aux laboratoires nationaux d'Allemagne, de France, du Royaume Uni et des U.S.A. deux chambres d'ionisation à cavité pour étalonnage avec les rayons roentgen et gamma. La différence d'étalonnage avec une qualité donnée de rayonnement est considérée comme une mesure de la discordance des étalons nationaux. Les résultats obtenus concordent avec certaines comparaisons directes préalables, dans l'intervalle d'incertitude prévisible de ces mesures, environ 0.5 pour cent.

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