Correction Factors for the Calibration of Encapsulated Radium Sources

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Several aspects of the procedure and corrections for the calibration of encapsulated radium sources at NBS have recently been investigated. It was found that a chamber equipped with a guard-ring type electrode system allowing the use of a vibrating reed electrometer as a current detector provides more versatility and precision than the gold-leaf electroscope now in use for routine calibrations. Absorption corrections for the U.S. primary national radium standards have been determined for the NBS chamber: 0.78 percent for standard 5440 and 1.01 percent for standard 5437. The Owen-Naylor integral equation for absorption of rays in the walls of cylindrical radium sources has been evaluated by a power series expansion of the integrand. Absorption coefficients and correction factors for platinum and Monel metal (materials commonly used for source capsules) have been computed for the NBS chamber.

1. Introduction

Encapsulated radium sources are calibrated at the National Bureau of Standards by a comparison, through secondary working standards, with primary national standards prepared by Hönigschmid [1] in 1934. A gold-leaf electroscope with lead and aluminum walls is used for measuring the gamma rays emitted by the sources. The ratio of the measurements with the standard and tested source multiplied by the weight of radium element present in the standard is certified as the "equivalent weight" of the source. A correction factor for the absorption of gamma rays by the wall of the source being calibrated is also given.

Several aspects of the calibration procedure and corrections have recently been investigated. These include the instrument used for comparing sources, absorption corrections for the Hönigschmid standards, and corrections for the wall absorption of the tested source. It was found that a chamber (with walls similar to those used for the gold-leaf electroscope) equipped with a guard-ring type electrode system allowing the use of a vibrating reed electrometer as a current detector provides more versatility and precision. Absorption corrections for the Hönigschmid standards were determined so that the true weight of radium instead of the "equivalent weight" might be determined. The capsule wall absorption corrections were determined through the use of an evaluation of the integral for the absorption of parallel gamma rays by a cylindrical wall. This integral was evaluated by a term-by-term integration of the integrand expanded in a power series. Using the new current detector for the measurements and this evaluation of the integral, an effective absorption coefficient for platinum (commonly used for capsule

walls) and its dependence on several factors was determined. Measurements were also made with Monel metal which is used to a lesser extent for encapsulations.

2. Equipment and Method

The measurements were performed with a lead-walled cubical ionization chamber equipped with a guard-ring type electrode system allowing the use of a vibrating reed electrometer as a current detector. The chamber walls are of the same construction as those used for the gold-leaf electroscope, the instrument used for routine radium calibrations. They consist of 5-mm-thick inner aluminum walls and 10-mm-thick outer lead walls, and are 10 cm on a side. Ionization currents were measured using the capacitance method, with a nulling potentiometer and electronic timer to determine the rate of change of potential with time. Only comparisons of ionization currents resulting from different source conditions are involved in the measurements, so that with capacitance and null voltage constant, only the time need be determined accurately. Saturation curves were plotted and the voltage difference between the electrodes of the chamber was set at an appropriate value.

As in ordinary calibrations, the sources were measured with their axes horizontal and parallel to the front face of the chamber. The source and chamber were at the same height so that the rays could pass horizontally into the chamber. In most cases, the distance between the source and chamber has been made as small as possible since the larger currents can be measured with more precision. The distance cannot be made too small, however, because the correction factors which have been computed depend on the assumption that the gamma rays going from the source to the detector are parallel.

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[1] Figures in brackets indicate the literature references at the end of this paper.

Several experiments, such as the result of one depicted in figure 2, have been performed to determine the minimum distance which may be used for the measurement of a particular quantity.

Long-term changes in measuring conditions such as temperature and pressure were avoided by performing the comparisons over short periods of time and in an ABBA sequence. Where possible, conditions were arranged so that ionization currents were large enough to make background correction unnecessary. If the currents were too small, it was found that the measurements were affected by pulses in the background current. These background pulses were studied by making a continuous recording of the electrometer readings. About 130 of these pulses are observed per hour and their magnitude is approximately 1×10^{-4} statcoulomb. The charge produced in air by the passage of alpha particles from radionuclides such as Rn^{222} is of this order of magnitude.

3. National Standard Correction Factors

3.1. Description of the Standards

The National radium standards used at NBS are two of twenty sources prepared by Hönigschmid in 1934 for use as international and national standards. The sources acquired by the United States were designated as numbers 5437 and 5440 by Hönigschmid, who determined their radium element content by careful weighing to be 38.23 and 20.45 mg respectively as of June 2, 1934. They are also assigned the roman numerals XIV and XV, respectively, by the International Radium Standards Commission as a result of a comparison with the Paris and Vienna 1911 standards. The weights derived from this comparison are 38.13 and 20.38 mg, respectively, as of June 1934. The encapsulation is Thüringen glass tubing of 0.27 mm wall thickness and internal diameter of 3 mm and lengths of 36.7 and 36.3 mm [2] respectively. More information and photographs of the sources are given by Loftus et al. [2] and Davenport et al. [3].

3.2. Corrections Proposed by Other Authors

Although there is no information available on the absorption corrections for the Hönigschmid standards using the NBS type chamber, several values have been proposed for use with other types for the horizontal orientation shown in figure 1. Perry [4] has estimated the correction for the standards in general to be about 0.5 percent for a chamber with a 5-mm wall of lead and no aluminum wall. Weiss [5] lists wall and salt absorption corrections for Hönigschmid standards and a chamber similar to the one used by Perry, but the sources measured are enclosed in an additional tube of glass. The method used for computing the salt absorption is given by Fränz and Weiss [6].

Another analysis of the correction factors is given by Geiger [7] for a chamber with composite walls of 6 mm lead and 6 mm aluminum. The value for
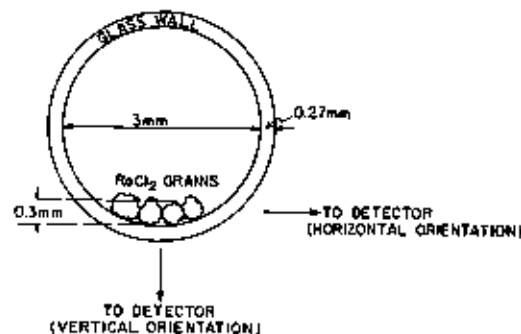
this chamber should be nearly the same as one for the NBS chamber, since the walls are of similar construction. He computed total absorption corrections of 1.13 percent and 1.09 percent for the Hönigschmid standards 5425 (Canadian) and 5440 (U.S.) respectively by a graphical integration. The calculation is based on the assumption that the salt is fine grained and uniformly distributed along the bottom of the glass tube. Examination of enlarged photographs of the standard 5440 indicates, however, that the average grain size is about 0.3 mm, 20 percent of the inner radius of the tube itself. The grains are large enough so that most of them appear to be along the bottom of the tube in a single layer four or five grains across. In order to avoid making this assumption, other methods of determining the correction factors were developed.

3.3. Absorption Correction for Standard 5440

It is considerably easier to compute the correction factors for a vertical orientation, that is, with the axis of the source being parallel to the floor and the rays being directed downward into the chamber. The source geometry in this position is more clearly defined and the absorption corrections are smaller than for the horizontal position which is normally used. Figure 1 shows the vertical and horizontal orientations. By measuring the difference in the ionization current for radiation coming from the primary source placed in the vertical and horizontal orientations, the difference in their absorption corrections can be found. The absorption correction for the horizontal position is, then, the sum of this difference and the absorption correction computed for the vertical position.

The experimental procedure for determining this difference was to compare the primary standard 5440 in both orientations to a radially symmetric source. The percent difference in these comparisons is equal to the percent difference in the absorption corrections. The average of 19 determinations of this quantity is 0.37 percent and the standard error of the mean is 0.06.

The wall absorption for rays passing downward from the source to the chamber was computed from an effective wall thickness of 0.279 mm as determined by a graphical integration assuming that the width of the salt along the axis of the tube is 1.4 mm, as estimated from the enlarged photograph. The mass absorption coefficient for the glass was taken to be 0.032 cm²/g which is the coefficient for elements with Z less than 57, given by Michel [8]. This figure was determined for the Canadian National Research Council chamber, but its construction is similar enough to the NBS chamber that the error incurred in its use should be negligible.[2] The density of the glass, computed from dimensions listed on the source certificate, is 2.39 g/cm³. The linear absorption coefficient is then 0.076 cm⁻¹, and the computed absorption is 0.21 percent.

The computation of the salt absorption as opposed to the wall absorption for the vertical orientation is more uncertain and several different approaches to the problem have been considered. In the computations outlined below, the following quantities are estimated to have an accuracy of better than 5 percent: the density of the individual RaCl₂ grains is 4.9 g/cm³ [9], the volume of the salt with the tube on end is 11.9 mm³ (by actual measurement using a cathetometer), the density as computed from this volume is 2.26 g/cm³ (Michel and Whyte [10] give 2.2 g/cm³), and the mass absorption coefficient[3] for RaCl₂ is 0.047 cm²/g. The percent absorption corrections are based on the formula, $100(1-e^{-\mu x})$, where μ is the product of the mass absorption coefficient and the density of the salt and x is taken to be one-half the length of the salt through which the rays pass.

A value for the salt absorption in the vertical direction may be calculated assuming a uniform distribution of fine grains and a density of 2.26 g/cm³. Such a calculation provides an absorption correction of 0.12 percent for primary 5440. Calculation of the salt absorption using a more realistic description of the salt configuration provides values which are somewhat higher.

An estimate of the depth of the salt grains may be made from the volume measurement with the tube on end and length and width measurements from an enlarged photograph. With the salt evenly distributed through the length of the tube the dimensions are 32.75 and 1.38 mm giving a depth of 0.263 mm. Using this depth, and the density 2.26 g/cm³, the absorption is 0.14 percent.

From the photograph, an average grain diameter of 0.3 mm was estimated. If the effective shape of the grains is assumed to be spherical, the salt absorption calculated from a formula given by Dixon [11] and using 4.9 g/cm³ for the salt density, is 0.26 percent. The average of these two values is 0.20 percent and the estimated error is taken to be ±0.06, one-half the difference between the values.

The total absorption correction using the average value of 0.20 percent ±0.06 for the salt absorption and 0.21 percent (with a negligible error) for the wall absorption, is 0.41 percent ±0.06. Adding this to the measured difference of 0.37 percent ±0.06, the correction for the horizontal orientation is 0.78 percent for national standard 5440 and the estimated error is $(0.06^2+0.06^2)^{1/2}=0.09$.

3.4. Absorption Corrections for Standard 5437

Mann [12] has developed a calorimeter, called a radiation balance, for comparing the energy emission from radioactive sources. Absorption corrections for radium sources in a calorimetric calibration are quite small[4] and in many cases need not be determined for 0.1 percent accuracy. If a source is calibrated with a standard using both the calorimetric and ionization chamber method, a difference in values will result which depends upon the absorption corrections for the standard and source calibrated. By correcting this difference for the absorption of gamma rays in the calibrated source, the remaining discrepancy can be used as a measure of the absorption correction for the standard.

Attix and Ritz [13] give the result of a calibration of a secondary NBS standard N-100 with the primary standard 5437 carried out by W. B. Mann using a Peltier-effect twin microcalorimeter [14] specially designed for the comparison of Hönigschmid standards. The value, 99.6₂ mg ±00.3, was obtained as of October 1956. The result of a recent calibration using the vibrating reed electrometer method described above is 100.63 mg (corrected for absorption in the secondary standard and for decay since October 1956) with a 0.05 percent standard error of the mean. The difference between the two determinations is then 1.01 percent which represents the absorption correction for the standard 5437.

3.5. Summary

The corrections derived from the two methods described above are 0.78 percent for the 5440 and 1.01 percent for the 5437. This difference in absorption corrections of 0.23 percent occurs because standard 5440 contains 20 mg of radium element and the 5437 contains 38 mg, making the geometries different. Loftus et al. [2] compared several of the Hönigschmid standards with both the calorimeter and the electroscope. Table 1 lists the pertinent data. The differences in the ratio obtained by the two methods should be a measure of the differences in gamma ray absorption since the calorimetric method is independent of corrections. The difference in weight for the 5440 and 5437 standards is 18 mg which corresponds to a percent difference of about 0.25, in good agreement with the difference of 0.23 percent for the two methods.

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[2] This is assumed since the absorption coefficient for Monel metal (composed of elements with Z less than 57) reported in this paper is 0.0335 cm²/g, only 5 percent different from Michel's value. In this paper and also in Keyser [16] it is shown that the absorption coefficient for platinum is also approximately the same for both chambers.
[3] This value is given by Geiger [7]. It was measured with the Canadian chamber and its use here is discussed in footnote 2.

[4] The size of the absorption corrections depends upon the amount of energy which is not absorbed in the calorimeter, usually several percent. If, for example, it is 5 percent, then absorption corrections for the calorimetric method will be 5 percent of those for the ionization chamber method.

4. Evaluation of the Owen-Naylor Integral

Owen and Naylor [15] have derived an integral equation for the absorption of gamma rays in a cylindrical capsule having its axis at right angles to a line drawn between the source and the detector. It is assumed that the rays leaving the source are parallel and that the capsule is completely filled with radium salt. That integral is:

$$I/I_0 = \frac{4}{\pi} \int_0^{\pi/2} \cos^2 x \cdot e^{-\mu a(\sqrt{(b/a)^2 - \sin^2 x} - \cos x)} \, dx$$

where a=internal radius
b=external radius
μ=linear absorption coefficient
x=an angle
I_0=intensity of unattenuated radiation
I=intensity after wall absorption

Using a planimeter, Owen and Naylor evaluated this integral for specific wall thicknesses and external diameters. To gain more accuracy and flexibility in its application, it was decided to integrate the equation by expanding the exponential in a power series. The exponent is usually of the order of 0.1 or less so that three terms in the expansion is sufficient, the contribution of the fourth term being of the order of 0.01 percent. The result of the expansion is seven terms which may be integrated term by term. The integration of one of these terms was performed by another expansion (in four terms). The result is:

$$I/I_0 = 1 + \mu[5a^5/1024b^5 + a^4/64b^3 + a^2/8b + 8a/3\pi - b]$$
$$+ \mu^2[b^2/2 + a^2/4 + (b^2/\pi)(b^2/2a^2 - 2) \text{ arcsin } (a/b)$$
$$- 1/\pi \sqrt{(b/a)^2 - 1}(b^2/2 + a^2)] + \cdots \quad (1)$$

It may be noticed that eq (1) is of the form:

$$I/I_0 = A(a,b)\mu^2 + B(a,b)\mu + 1. \quad (2)$$

The result was checked to better than 0.1 percent for specific cases using Simpson's rule and by comparison with Owen and Naylor's graphical evaluation.

5. Linear Absorption Coefficient for Platinum and Monel Metal

5.1. Previous Measurements

It is important to note that the effective absorption coefficients determined are highly dependent upon the thickness and composition of the walls of the chamber used for the measurement. Platinum (actually 90 percent platinum and 10 percent iridium) is most widely used for the capsules of radium sources which are submitted for calibration, but there have been few measurements of the platinum absorption coefficient for the type of chamber used at NBS. Keyser [16] has made measurements using the same type of chamber, but flat absorbers were used to measure the absorption coefficient of platinum, instead of cylindrical sleeves which more nearly approximate the condition under which the coefficient will be used. The determinations for three different flat absorber thicknesses are 1.000 ± 0.050, 0.960 ± 0.050, and 0.960 ± 0.060 cm^{-1}, averaging 0.973 cm^{-1}. The value 0.93 cm^{-1} was given to Attix and Ritz [11] in a private communication from G. N. Whyte, but no details on the type of absorbers used were given.

5.2. Procedure

The linear absorption coefficients were computed from measurements using right cylindrical sleeves of the material in question and two secondary standard sources, nominally 50 and 100 mg, which fit snugly in and were the same length as the sleeves. The wall thickness of the sleeves, the critical value, was computed indirectly from their density, weight, length, and external diameter, quantities which could be measured very accurately. This method has an advantage over more direct means because it accounts for irregularities in the internal diameter and gives an average wall thickness for the whole length and circumference of the tube. An average sleeve thickness is important since many measurements are taken using random orientations of source and sleeve. Errors in the sleeve wall thicknesses are estimated to be no greater than a few tenths of a percent. The dimensions used for the sources are certified by the manufacturer to be correct to 1 percent.

The ratio, R, of the electrometer measurements with the sleeve on the source to those with the sleeve off was found experimentally as described above. Using the internal radius, a, and the external radius, b, of the source, the coefficients, A and B in eq (2),

$$I/I_0 = A(a,b)\mu^2 + B(a,b)\mu + 1,$$

could be computed. For the combination of the sleeve and source, a new eq (2) may be determined, using the internal radius of the source for a, and the sum of the external radius of the source and the wall thickness of the sleeve for b:

$$I'/I_0 = A(a,b')\mu^2 + B(a,b')\mu + 1.$$

Since the ratio of I' to I is R, μ may be computed from

$$R = \frac{A(a,b')\mu^2 + B(a,b')\mu + 1}{A(a,b)\mu^2 + B(a,b)\mu + 1}. \qquad (3)$$

5.3. Dependence of μ on Several Factors

The linear absorption coefficient, μ, for platinum was measured under various conditions to obtain information on its constancy.

It was assumed in deriving the integral for wall absorption that the rays coming from the source were parallel. The effect of having nonparallel rays was determined by measuring the sleeve wall absorption for different distances between the source and the front of the detector (a 10-cm square) and making the computation for the linear absorption coefficient. Figure 2 shows the range of constancy for μ as a function of distance for a sleeve of wall thickness 0.934 mm. The graph shows that μ remains reasonably constant for distances greater than 20 cm.

Four sleeves having different wall thicknesses were used for the determination of μ, and the average values for several determinations with each sleeve are listed in table 2. The table indicates that there is a slight downward trend in μ with decreasing wall thickness. The magnitude of this trend makes it reasonable to assume that it is caused by such factors as the error in eq (1) due to the omission of the remaining terms in the expansion and the change in energy due to the absorption of softer gamma rays by the sleeve wall. These factors would all become negligible if a sleeve of very small thickness were used so that the best estimate of μ would be given by an extrapolation of μ to zero sleeve thickness. The use of a secondary standard source nominally 50 mg or one nominally 100 mg (having the same dimensions) had negligible effect on the data. The fact that these measurements were in such good agreement indicates that μ is independent of wall thickness in the range used, that there was good precision in the dimensions, and that errors due to a looseness of fit of the source in the sleeve (this varied appreciably among the different combinations of sources and sleeves) were negligible.

Several different geometries were used in the measurements and it was noted that the effects of scattering objects on the ratio, R, were not appreciable except if located near the axis of the source so that rays passing out through the ends are scattered and detected.

Table 2. *Linear absorption coefficient for platinum measured with different sleeve wall thicknesses*

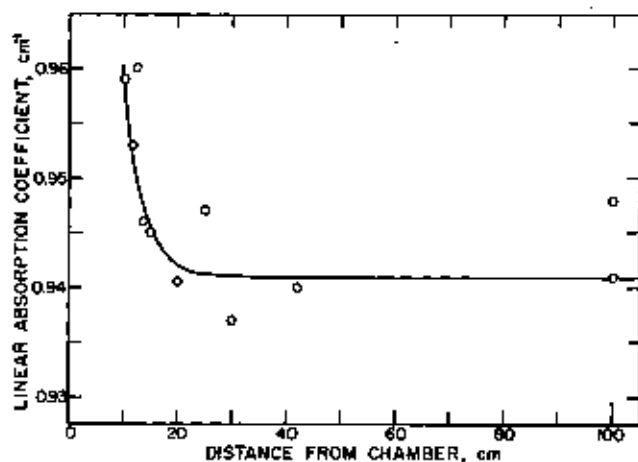| Sleeve wall thickness	Linear absorption coefficient
mm	cm⁻¹
1.592	0.944
1.343	.940
0.934	.941
.439	.939

FIGURE 2. *Dependence of the linear absorption coefficient of platinum on the distance between source and chamber.*

5.4. Final Result

Twenty-one values, measured under various conditions (except where the divergence of the beam was considered to have an appreciable effect), were averaged in the determination of μ with the four platinum sleeves listed in table 2. It was pointed out above that the best estimate of μ is given by an extrapolation of μ to zero sleeve thickness. The result of this extrapolation is $\mu = 0.939$ cm⁻¹ and the estimated error is 0.2 percent, one-half the range of values. Since the source used for the measurements had a 0.5-mm platinum wall, this value of μ is applicable to gamma rays from radium filtered by 0.5 mm platinum, 10 mm lead and 5 mm aluminum. Table 2 shows that μ remains reasonably constant for wall thicknesses up to approximately 1.5 mm so that it can be used in that range. A check on this value was performed using the gold-leaf electroscope. The mean of six measurements was 0.95 cm⁻¹ with a 1 percent standard error of the mean.

In different laboratories, ionization chambers having varying wall thicknesses are used for calibrations. So that comparisons may be made, μ for platinum was measured as a function of chamber wall thickness by replacing the outer wall with lead filters of different thickness. Table 3 lists these values and figure 3 shows the shape of the curve. These measurements were performed with a source having a 0.5-mm platinum wall to which was added a cylindrical sleeve having a 0.934-mm platinum wall so that the values listed are for these filtrations.

The linear absorption coefficient for Monel metal was also measured using three sleeves and a value of 0.296 cm⁻¹ with a 0.8 percent standard error of the mean. Correction factors for filled capsules of various wall thickness and external diameter were computed for Monel metal and platinum using eq (1), the result of the evaluation of the Owen-Naylor integral. Tables 4 and 5 list these correction factors and figure 4 shows the shape of some representative curves.

TABLE 3. *Linear absorption coefficient of platinum for chambers having 5-mm inner aluminum walls and different thicknesses of lead outer walls*

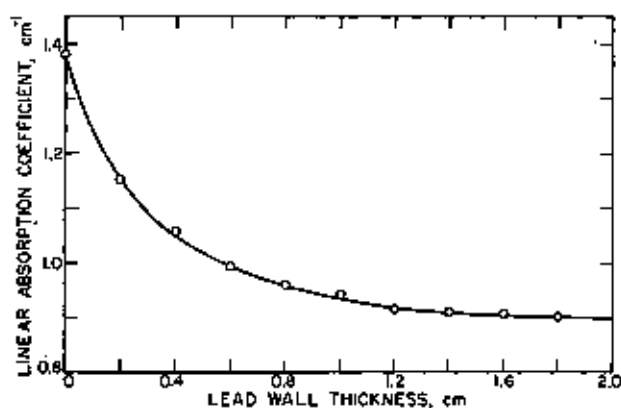| Lead wall thickness	Linear absorption coefficient
mm	cm⁻¹
00	1.381
02	1.152
04	1.056
06	0.993
08	.965
10	.941
12	.914
14	.910
16	.909
18	.901
20	.873

FIGURE 3. *Dependence of the linear absorption coefficient of platinum on the lead wall thickness of the ionization chamber.*

The ionization chamber has 5-mm inner walls of aluminum to which varying thicknesses of lead were added. A 1.0-cm lead wall is used at NBS.

TABLE 4.—*Platinum wall correction factors for filled cylindrical radium sources*

Wall thickness	Outside diameter, mm						
	1	2	3	4	5	6	7
mm							
0.1	1.0108	1.0114	1.0118	1.0119			
.2	1.0207	1.0220	1.0229	1.0234			
.3	1.0299	1.0323	1.0337	1.0346			
.4	1.0391	1.0423	1.0441	1.0450			
.5	1.0481	1.0522	1.0541	1.0552	1.0561		
.6		1.0615	1.0640	1.0652	1.0658		
.7		1.0710	1.0744	1.0764	1.0778		
.8		1.0806	1.0848	1.0872	1.0891		
.9		1.0885	1.0941	1.0971	1.0993		
1.0		1.0965	1.1038	1.1073	1.1095	1.1114	
1.1			1.1135	1.1172	1.1197	1.1218	
1.2			1.1229	1.1271	1.1300	1.1322	
1.3			1.1324	1.1373	1.1408	1.1488	
1.4			1.1417	1.1473	1.1509	1.1541	1.1670
1.5			1.1512	1.1572	1.1614	1.1645	1.1674

TABLE 5.—*Monel wall correction factors for filled cylindrical radium sources*

| Wall thickness	Outside diameter, mm						
	1	2	3	4	5	6	7
mm							
0.1	1.0034	1.0037	1.0038	1.0039			
.2	1.0065	1.0069	1.0071	1.0073			
.3	1.0094	1.0101	1.0106	1.0106			
.4	1.0122	1.0132	1.0139	1.0143			
.5	1.0149	1.0163	1.0166	1.0172	1.0174		
.6		1.0192	1.0199	1.0201	1.0205		
.7		1.0220	1.0230	1.0235	1.0238		
.8		1.0248	1.0260	1.0267	1.0271		
.9		1.0274	1.0289	1.0298	1.0303		
1.0		1.0300	1.0317	1.0327	1.0335	1.0339	
1.1			1.0344	1.0356	1.0364	1.0370	
1.2			1.0372	1.0386	1.0395	1.0401	
1.3			1.0401	1.0416	1.0429	1.0432	
1.4			1.0427	1.0444	1.0456	1.0408	1.0469
1.5			1.0454	1.0473	1.0486	1.0494	1.0501
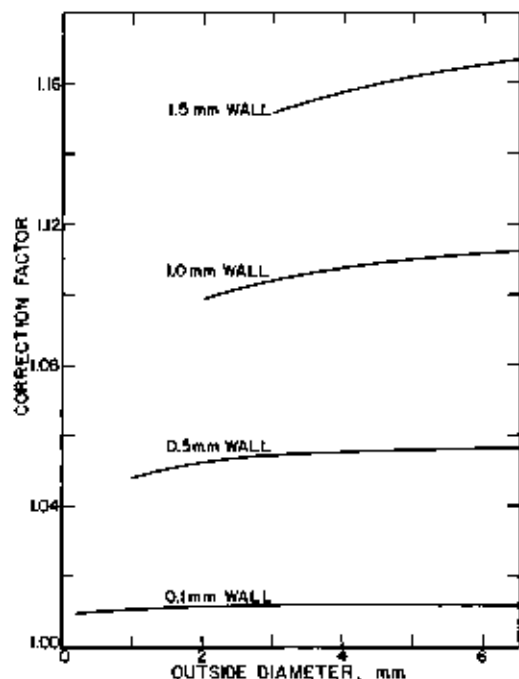
FIGURE 4. *Correction factors for gamma ray absorption in cylindrical platinum walls.*

Four representative curves for wall thicknesses of 0.1, 0.5, 1.0, and 1.5 mm are shown. The factors were computed from an absorption coefficient of 0.989 cm⁻¹ using the evaluation of the Owen-Naylor integral given in this paper. They are applicable only for measurements with an NBS type chamber.

6. Discussion

As a result of an investigation of the radium calibration procedure, measurements can be performed with greater precision, more accurate wall absorption corrections have been developed, and through the use of absorption corrections determined for the primary standards, the "true weight" of radium element in a source can be specified. If the current reading for the source being calibrated is I_x (which is increased by a factor A_x for wall and salt absorption in the source), the current reading for the standard is I_s (with corresponding factor A_s),

and the weight of radium element in the standard is M_s, then the "true weight" of radium element in the source being calibrated is:

$$M_x = \frac{I_x A_x}{I_s A_s} M_s \qquad (4)$$

In this equation, $M_s\, I_x/I_s$ is the "equivalent weight."

In table 6, the accuracy with which each quantity in eq (4) can be determined is listed. The total estimated error is the square root of the sum of the individual errors squared and is equal to 0.17 percent.

TABLE 6. *Accuracy with which a typical radium source can be calibrated at NBS*

see eq (4)

Quantity	Estimated error	Range for error	Source of quantity
I_x/I_s	% 0. 07	10 to 250 mg RaEl	Experimentally determined by the new method with four readings on each source.
A_s	. 09	All sources	Determined in this paper. 0.78% for standard 5440 and 1.01% for standard 5437.
A_x: wall	. 06	Less than 1.5-mm wall thickness.	Determined in this paper. $\mu = 0.939$ cm^{-1} for Pt-Ir.
salt	. 05	Less than 2 mm ID	From the equation for μ_s given by Michel [8]* and the method of Paterson et al. [17]
M_s	. 1	All sources	"Best estimates" determined by Connor (Report of ICRU 1959 [18]).

Combined error = 0.17%

*The use of this equation for the computation of absorption coefficients for radium salts is discussed in footnote 2.

7. References

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