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*Part of Bureau of Standards Journal of Research, vol. 12, April 1934*STANDARD ABSORPTION CURVES FOR SPECIFYING THE QUALITY OF X-RADIATION¹

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ABSTRACT

In the measurement of X-rays there is a proportionality between the energy in the beam and its strength in roentgens, only for radiation of the same effective spectral distribution. In previous work comparison with the copper and aluminum absorption curves produced by constant potential has been established as a means of equating the qualities of X-ray beams excited by various voltage wave forms. Therefore a set of standard absorption curves is set up for copper up to 180 kv (constant) and aluminum up to 110 kv (constant). Accurate evaluation of the wall absorption of the tubes used permits the establishment of basic absorption curves. Similar curves are given for potentials from 250 to 550 kv (constant) using a tube having 6 mm of copper filtration. The effect of wall absorption on the relative position of the absorption curves is discussed, and it is shown how for any given excitation voltage a single curve may be used for a complete and adequate specification of X-ray quality. This may be contrasted with all other quality specifications, none of which is adequate without auxiliary information.

CONTENTS

	Page
I. Introduction.....	401
II. Experimental procedure and correlation of absorption curves.....	403
III. Equivalent thickness of tube walls.....	411
IV. Copper absorption curves above 250 kv excitation potential.....	418

I. INTRODUCTION

Numerous investigations during the past years have stressed the need for a more adequate filtration method of determining the quality of X-ray beams that are excited by different potential wave forms. It is not that the methods in use—such as the half-value layer—are theoretically unsound, but rather that, given alone, they are insufficient to give satisfactory correlation between radiations excited by potentials of different wave form. Furthermore, the several different methods in vogue do not express the quality of radiation in comparable terms.

It is, of course, well recognized that while the quality of an X-ray beam is given accurately only by the spectral energy distribution of the radiation, it is unfortunately impractical for common use. Accordingly, various indirect methods of quality description have been based upon the absorption properties of some metal such as copper or aluminum for the radiation in question. Since an X-ray spectrum is a function of the potential, these methods are frequently complicated by the fact that the potential used for exciting the X-rays is periodically fluctuating. The "simple spectrum" is one produced by, and a function of, the instantaneous or sustained value of the exciting voltage, and the target material.

¹ Presented at First American Congress of Radiology, Chicago, Ill., Sept. 25, 1933.

On the other hand, a "composite spectrum" is the resultant of the succession of instantaneous spectra produced by a periodically fluctuating potential and is, therefore, also a function of the wave form. Since the voltage wave forms applied to X-ray tubes are exceedingly varied and complicated, it is obvious that there is no direct simple relationship between the resultant composite spectra and the peak value of the exciting voltage. The absorption curve for radiation having a composite spectrum will be referred to as a "composite absorption curve" to distinguish it from the "simple absorption" curve characteristic of X-rays produced by constant potential.

Prime requisites for a satisfactory quality specification are, therefore: (1) A sound theoretical relationship between observed magnitudes and the spectral distribution of the radiation, and (2) a simple method of quality correlation which is reasonably independent of the exciting voltage wave form, i.e., a correlation between the quality of some one simple spectral distribution and that of the given composite spectral distribution. Simplicity and convenience of operation naturally dictate the choice of method only after these two requirements are satisfied.

Of the customary quality specifications: (1) Complete absorption curve,^{2,3} (2) half-value layer,⁴ (3) effective wave length,^{5,6} and (4) average wave length⁷—Duane's effective wave-length method, requiring but two measurements, is the most convenient. This simplicity is offset, however, by the indefiniteness of the final result.⁸ The half-value layer method has a slight advantage in simplicity over the remaining methods in that it requires fewer auxiliary computations. A theoretically definite conclusion, however, is obtained only from the complete absorption curve, the others requiring further information which can only be obtained from the complete absorption curve. That the complete absorption-curve method is not only adequate but has advantages not possessed by any of the others has been shown by a number of workers.⁹ For example, Silberstein has shown¹⁰ theoretically that a given X-ray spectral distribution will yield a particular copper absorption curve; and conversely, a spectral distribution which is sufficiently accurate for practical purposes may be derived from the complete copper absorption curve.

Until recently the complete absorption-curve method has had the disadvantage of not being expressible by a single numerical magnitude. This has been removed, however, by finding that,¹¹ within reasonably satisfactory limits, the complete composite absorption curve of radiation excited by any particular one of the different potential wave forms in use, may be matched by the simple absorption curve of the same material for radiation excited by some definite constant potential. It is further found¹² that such beams having equivalent absorption curves are, over a considerable range of initial filtration, closely alike as regards their intensity distribution in a large body of low atomic number material such as a water phantom. Since the

² E. A. Pohle and C. S. Wright, *Radiology*, vol. 14, p. 17, 1930.

³ R. B. Wilsey, *Radiology*, vol. 17, p. 700, 1930.

⁴ H. Holthausen and R. Braun, *Strahlentherapie*, vol. 47, p. 263, 1933.

⁵ W. Duane, *Proc. Nat. Acad.*, vol. 13, p. 668, 1927.

⁶ L. S. Taylor, *B.S. Jour. Research*, vol. 5 (RP-212), p. 517, 1930.

⁷ A. Mutscheller, *Radiology*, vol. 12, p. 283, 1929.

⁸ E. Quimby, *Am. Jour. Roent.*, vol. 21, p. 64, 1929. See also footnote 6.

⁹ L. S. Taylor, G. Singer, and C. F. Stoneburner, *B.S. Jour. Research*, vol. 11 (RP-592), p. 293, 1933. See also footnotes 2 and 3.

¹⁰ L. Silberstein, *Phil. Mag.*, ser. 7, vol. 15, p. 375, 1933.

¹¹ See footnote 9.

¹² L. S. Taylor and K. L. Tucker, *B.S. Jour. Research*, vol. 9 (RP-475), p. 333, 1932.

spectral distribution of radiation excited by constant potential is perfectly reproducible, a family of simple absorption curves of constant voltage radiation should constitute a very convenient and adequate standard of reference for inferring the constant potential equivalent¹³ of any given radiation.

It is of course obvious that two equivalent X-ray beams might be produced by voltages of very different peak values and hence one beam have shorter wave lengths not present at all in the other. However, the proved equivalence, where the peak voltages are very different, signifies that while there are some shorter wave lengths in one spectrum than in the other, they are present to a negligible extent.¹⁴ As the equivalent constant voltage approaches the peak voltage, it signifies that the energy in the shorter wave lengths becomes relatively greater. This, however, is taken care of in the specification of quality by the fact that for a given peak voltage, if the shorter wave lengths gain in importance, the equivalent voltage is correspondingly increased. For example, with X-rays produced respectively by mechanical, full-wave, or Villard rectifiers operated at the same peak values, the equivalent voltage approaches nearer the peak value, indicating an increasing relative intensity of the shorter wave lengths. Correspondingly it is found that the absorption curves indicate, respectively, harder composite radiations after the same initial filtration.

It is also to be expected that two beams which yield like absorption curves with a low or moderate initial filtration (up to 1.5 mm Cu at 150 kv (constant)), may after a higher initial filtration furnish somewhat divergent curves—the curve for the radiation having the higher peak voltage falling above the other. By matching the curves above the point corresponding to the initial filtration, however, a new equivalent voltage may be found which specifies the radiation more closely. This is perfectly justifiable, since the radiation not passing through the filter is lost.

This specification of X-ray quality, by using the complete absorption curve, has been recommended by the X-ray standardization committee of the Radiological Society of North America.¹⁵

The main purpose, then, of the present investigation was to lay a general foundation and develop a procedure for deriving the two parameters of any absorption curve, namely, the equivalent constant potential excitation, together with the equivalent initial absorption.

II. EXPERIMENTAL PROCEDURE AND CORRELATION OF ABSORPTION CURVES

The standard absorption curves shown here were obtained under conditions believed to be adequate for the purpose at the present time. The irradiation¹⁶ was measured in roentgens per minute by

¹³ By "constant potential equivalent" is meant the constant potential necessary to apply to an X-ray tube to yield a simple absorption curve of the same form as the composite absorption curve in the same material for the unknown radiation in question.

¹⁴ L. S. Taylor, G. Singer, and C. F. Stoneburner, B.S. Jour. Research, vol. 11 (RP-592), p. 293, 1933. In particular see curves in figs. 8 and 9 of this paper.

¹⁵ Quotation from par. 7, 1933 committee report, "For most practical purposes the quality of the X-radiation may be satisfactorily specified in terms of the copper or aluminum absorption curve combined with a statement of the initial filtration. In lieu of an absorption curve, the equivalent constant potential applied to the tube terminals to yield the same curve may be stated as a single numerical magnitude. Up to 100 kv (constant) aluminum absorption curves and above 100 kv (constant) copper absorption curves shall be used to establish the equivalent potential."

¹⁶ The term "irradiation" is used to emphasize the fact that these measurements were made in terms of the ionization produced in air. The ionization measurements can be used for "intensity" only when dealing with X-ray beams of exactly the same spectral distribution, but not with beams of different distribution.

means of a standard guarded field ionization chamber. The ionization current was measured by a null method¹⁷ using an electrometer and compensating system previously described. The readings were accurate within ± 0.3 percent. Voltages applied to the tube were supplied by a kenotron rectifier of the Hull-Webster type, in which at the tube currents used the ripple did not exceed 1 percent.

The average tube voltage was measured by means of a shielded high-resistance voltmeter connected directly across the tube terminals.¹⁸ The voltages given are all average values and hence peak values are about 0.3 to 0.5 percent higher. Since the average voltage has been shown to provide a better indication than peak voltage of the tube output on voltages of different ripple,¹⁹ the uncertainty of 0.2 percent in the peak value is of no consequence. During observations the tube voltage was measured and kept constant within limits of about 0.15 percent.

The X-ray tubes employed were housed in a lead box 4 by 4 by 7 feet. To provide steadiness of operation the filament was heated by a storage battery, and the high-voltage source supplied through a power stabilizer. Fluctuation in voltage was very slow, corresponding to, and caused by, the change in power line frequency; and, since it was seldom greater than about ± 0.3 percent, was easily compensated manually.

The filters were located for convenience about 50 cm from the target and 60 cm from the entrant diaphragm on the chamber. This precluded the possibility of a measurable amount of scattered radiation entering the chamber. To further insure this, the beam was diaphragmed down to a diameter of about 4 cm at the filters.

Two types of tungsten target tube were used for the measurements—a hard glass thick-walled type for the higher excitation potentials and a soft glass thin-walled type for the lower—corresponding approximately to the voltage ranges in which such tubes are used in practice. Since absorption of radiation by the walls is very different between such tubes, it is necessary that it be taken into consideration. Of a number of thick pyrex tubes available we chose for the final measurements one 4.8 mm thick, about the average of the group.

Table 1 gives the copper absorption values for radiation from a thin tube (in which the wall absorption is about the same as for 0.02 mm of copper). In the first column are given filter thicknesses at selected intervals. In the other double columns headed by the applied tube voltage are given respectively the percent transmission of the filter and its corresponding logarithm to the base 10. Where, in making the measurements, the filter thickness or applied voltage deviated appreciably from the given rounded values, corrections were applied to obtain the desired values.

Similar data for the thick pyrex tube (having a wall absorption about the same as 0.1 mm of copper) is given in table 2.

¹⁷ L. S. Taylor, B.S.Jour. Research, vol. 6 (RP306), p. 807, 1931.

¹⁸ L. S. Taylor, B.S.Jour. Research, vol. 5 (RP 217), p. 609, 1930.

¹⁹ L. S. Taylor, G. Singer, and C. F. Stoneburner, B.S.Jour. Research, vol. 9 (RP 491), p. 561, 1932.

TABLE 1.—Absorption of general X-radiation in copper

Tube wall, 1.29 mm cerium glass

I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	100 kv		110 kv		120 kv		130 kv		140 kv		150 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
mm												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
0.14	20.4 ₀	1.310	22.0 ₈	1.344	23.8 ₀	1.377	25.8 ₂	1.412	27.6 ₅	1.442	30.3 ₅	1.482
.20	15.3 ₉	1.187	17.8 ₄	1.251	19.9 ₂	1.299	21.8 ₁	1.339	23.4 ₂	1.370	25.6 ₈	1.410
.25	12.8 ₉	1.110	15.1 ₈	1.181	17.3 ₇	1.240	19.1 ₉	1.283	20.8 ₅	1.319	22.8 ₅	1.359
.30	11.1 ₅	1.047	13.1 ₇	1.120	15.2 ₃	1.183	17.0 ₉	1.230	18.7 ₁	1.267	20.5 ₅	1.313
.40	8.78	.943	10.2 ₈	1.012	12.1 ₂	1.084	13.7 ₅	1.138	15.3 ₇	1.187	16.9 ₈	1.230
.50	7.15	.854	8.50	.924	10.0 ₅	1.002	11.5 ₇	1.063	13.0 ₆	1.116	14.4 ₂	1.159
.75	4.53	.656	5.77	.761	7.04	.848	8.32	.920	9.55	.980	10.6 ₈	1.029
1.00	3.08	.489	4.13	.616	5.18	.714	6.35	.803	7.41	.870	8.43	.926
1.50	1.77	.248	2.42	.384	3.13	.496	4.00	.602	4.86	.687	5.75	.760
2.00	1.03	.013	1.60	.210	2.06	.314	2.73	.436	3.38	.529	4.13	.616
2.50	-----	-----	1.02	.009	1.46	.164	2.00	.301	2.50	.398	3.12	.494
3.00	-----	-----	-----	-----	1.09	.037	1.48	.170	1.93	.286	2.49	.396

TABLE 2.—*Absorption of general X-radiation in copper*

Tube wall, 4.78 mm pyrex glass

 I_0 = Incident radiation. I = Transmitted radiation. $100 I/I_0$ = Percent transmission.

Copper filter	100 kv		110 kv		120 kv		130 kv		140 kv		150 kv		160 kv		170 kv		180 kv	
	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$	$100 I/I_0$	$\text{Log } 100 I/I_0$
<i>mm</i>																		
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
.14	44.3 ₀	1.646	46.2 ₈	1.665	49.6 ₀	1.695	52.1 ₅	1.717	54.2 ₀	1.734	55.6 ₅	1.745	56.6 ₃	1.753	57.9 ₆	1.763	59.5 ₆	1.775
.20	34.5 ₆	1.539	37.0 ₆	1.568	40.7 ₂	1.610	43.9 ₀	1.642	45.2 ₆	1.656	47.2 ₀	1.674	49.0 ₆	1.690	51.1 ₀	1.708	52.8 ₅	1.723
.25	29.8 ₈	1.475	32.3 ₀	1.510	36.0 ₆	1.558	39.0 ₈	1.592	40.5 ₆	1.607	42.7 ₀	1.630	44.4 ₅	1.648	46.7 ₅	1.670	48.1 ₈	1.683
.30	25.8 ₀	1.411	28.6 ₂	1.457	32.3 ₅	1.510	34.0 ₆	1.531	36.9 ₂	1.567	38.6 ₃	1.587	40.6 ₀	1.609	42.8 ₈	1.632	43.9 ₈	1.643
.40	20.3 ₈	1.309	23.1 ₈	1.365	26.5 ₆	1.424	29.2 ₀	1.465	31.5 ₅	1.499	33.2 ₃	1.522	34.9 ₅	1.543	36.7 ₅	1.565	38.8 ₇	1.590
.50	16.3 ₇	1.214	18.9 ₅	1.278	21.8 ₂	1.339	24.3 ₅	1.387	26.7 ₇	1.428	29.3 ₀	1.467	30.1 ₇	1.480	32.1 ₅	1.507	33.8 ₈	1.530
.75	11.6 ₀	1.064	13.9 ₂	1.144	15.8 ₂	1.199	18.2 ₈	1.262	20.4 ₁	1.310	22.4 ₀	1.350	24.5 ₅	1.381	26.0 ₄	1.416	27.7 ₂	1.443
1.00	8.2 ₇	.918	10.2 ₇	1.012	11.9 ₈	1.078	14.0 ₆	1.148	16.0 ₂	1.205	17.8 ₈	1.252	19.5 ₅	1.291	21.2 ₂	1.327	22.7 ₈	1.358
1.50	4.4 ₄	.647	6.0 ₂	.780	7.68	.885	9.28	.968	10.8 ₂	1.034	12.2 ₈	1.089	13.8 ₅	1.141	15.2 ₂	1.182	16.4 ₉	1.217
2.00	2.6 ₀	.415	3.8 ₉	.590	5.1 ₇	.714	6.5 ₃	.815	7.78	.891	9.02	.955	10.1 ₈	1.008	11.4 ₃	1.058	12.6 ₈	1.103
2.50	-----	-----	-----	-----	3.5 ₅	.550	4.6 ₇	.669	5.8 ₇	.769	6.84	.835	7.88	.897	8.83	.946	9.9 ₅	.997
3.00	-----	-----	-----	-----	2.5 ₇	.410	3.6 ₁	.558	4.64	.667	5.84	.744	6.48	.812	7.36	.867	8.3 ₅	.921

TABLE 3.—Absorption of general X-radiation in aluminum

Tube wall, 1.29 mm cerium glass

 I_0 ≡Incident radiation. I ≡Transmitted radiation. 100 I/I_0 =Percent transmission.

Copper filter	60 kv		70 kv		80 kv		90 kv		100 kv		110 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
mm												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
1	32.1	1.507	33.8 ₈	1.530	36.0 ₄	1.557	38.9 ₀	1.590	40.3 ₉	1.606	42.4 ₂	1.628
2	19.0	1.279	20.8 ₁	1.318	22.9 ₂	1.360	25.2 ₈	1.403	27.2 ₀	1.435	29.4 ₀	1.468
3	12.8 ₈	1.109	14.4 ₀	1.158	16.5 ₂	1.218	18.4 ₂	1.265	20.3 ₈	1.309	22.3 ₅	1.349
4	9.3 ₄	.970	10.7 ₈	1.033	12.6 ₄	1.102	14.4 ₁	1.159	16.2 ₀	1.210	18.0 ₂	1.156
5	7.0 ₀	.845	8.44	.926	10.0 ₈	1.003	11.6 ₀	1.064	13.4 ₀	1.127	15.0 ₂	1.177
6	5.41	.733	6.79	.832	8.25	.916	9.69	.986	11.3 ₂	1.054	12.8 ₈	1.110
7	4.35	.639	5.53	.743	6.88	.838	8.33	.921	9.80	.991	11.2 ₂	1.050
8	3.55	.550	4.61	.664	5.84	.766	7.21	.858	8.58	.934	9.92	.997
10	2.44	.387	3.42	.534	4.38	.642	5.44	.736	6.63	.822	7.85	.895
15	1.16	.065	1.79	.253	2.40	.380	3.17	.501	4.06	.609	4.80	.681
20	-----	-----	1.00	.000	1.40	.147	2.01	.303	2.60	.415	3.17	.501

FIGURE 1.—Copper absorption curves for thin glass tube.

Below 100 kv (constant), absorption in aluminum has been recommended as a standard, hence table 3 gives aluminum absorption data. In making these measurements the same thin glass tube as for table 1 was used.

FIGURE 2.—Copper absorption curves for thick glass tube.

FIGURE 3.—Aluminum absorption curves for thin glass tube.

Figures 1, 2, and 3 give, respectively, for various constant potential excitations, the semilogarithmic absorption curves for copper and aluminum as plotted from tables 1, 2, or 3, respectively. If it is assumed that, for the same excitation potential, the spectral distribution of the radiation emitted by the anticathodes of the 2 tubes is the same, then the difference between the copper absorption curves corresponding to the same potential in figures 1 and 2 arises entirely from the difference in the absorption of the 2-tube walls—1.3-mm cerium glass, and 4.8-mm pyrex glass.

To bring out the general information to be inferred from the absorption curves of figures 1 to 3, and from this to correlate the curves of figure 2 with those of figure 1, we will take a hypothetical absorp-

FIGURE 4.—Hypothetical absorption curve showing the shift of coordinates due to initial filtration.

tion curve AB (fig. 4) in which x gives the thickness of copper filter, and

$$y = \log (100 I/I_0) \quad (1)$$

gives the corresponding values of log percent transmission. Here we will also assume that the incident radiation I_0 is obtained from an ideal X-ray tube of zero wall thickness. In that case, AB is the basic absorption curve corresponding to the given excitation potential.

As a first case, we wish to show how, from this basic curve, the absorption curve is obtained for the same radiation after it has been modified in quality by traversing a given thickness, d , of the filter. In this case, I_d , the number of roentgens emerging from the thickness,

d , becomes the incident radiation for the new curve. Against new thickness values,

$$x' = x - d \quad (2)$$

of the filter, are plotted new log percent transmissions,

$$\begin{aligned} y' &= \log \left(100 \frac{I}{I_d} \right) \\ &= \log \left(100 \frac{100 \frac{I}{I_o}}{100 \frac{I_d}{I_o}} \right) \\ &= \log \left(100 \frac{I}{I_o} \right) + \log \left(\frac{100}{100 \frac{I_d}{I_o}} \right) \\ &= y + 2 - \log \left(100 \frac{I_d}{I_o} \right) \\ &= y + \text{constant.} \end{aligned} \quad (3)$$

Thus all points on the new curve differ in position from corresponding ones on the basic curve by the same amount; that is, the new curve is obtained from the basic curve by merely shifting the origin of coordinates to the point $x=d$ and $y = -\left(2 - \log 100 \frac{I_d}{I_o}\right)$. That this conclusion is true may be shown by the following analysis. The 100 percent transmission point ($y'=2$) of the new curve must lie directly above the point $x=d$ on the basic curve; this is C in figure 4. By assigning y' this value in eq. 3

$$y = \log 100 \frac{I_d}{I_o}$$

which is, compared with eq. 1, the log percent transmission on the basic curve for a thickness $x=d$ of the filter. This is consistent with the imposed condition that I_d should be considered the incident radiation for this particular case. If, then, we have the data for the basic absorption curve—no initial filtration—corresponding data for the radiation, after being subjected to any given initial filtration, is readily obtained by reducing the observed filter thicknesses by the initial thickness d , and by increasing all observed log percent trans-

missions by $2 - \log \left(100 \frac{I_d}{I_o} \right)$.

The second case deals with the converse problem: given two absorption curves of the same radiation, but subjected to different amounts of filtration; to find the difference in thickness of the initial filters. Here we are supposed to have two separate absorption curves of figure 4—AB on the xy axes; and CB plotted (on transparent paper) on the $x'y'$ axes. The second is laid over the first and shifted to that position where it is found to fit the first. The difference, d , in the two filter thicknesses, for corresponding points on the two curves, is

given by the difference $(x-x')$ for the point C and is the magnitude sought.

Having outlined the general procedure we shall next inquire if like excitation potentials in the two tubes of figures 1 and 2 produce absorption curves which are subject to the same correlation as curves CB and AB (fig. 4) just treated. In other words: is the radiation from the thick-wall pyrex tube (of fig. 2) of the same quality as that from the thin-wall tube (of fig. 1) after passing through some unknown thickness of copper?

By taking curves of figure 2 and fitting them, as just described, to the curves of like excitation potential in figure 1, a very satisfactory correlation is obtained. The curves of figure 5 are those of figure 1

FIGURE 5.—Copper absorption curves for thin tube (line) and thick tube (circles) superposed to show matching.

reproduced; the plotted points on these curves are from the corresponding curves of figure 2—each point on the extreme left indicating the thickness of copper (about 0.1 mm) which would make up the difference in effect of the walls of the two tubes. As may be expected, this thickness varies somewhat with the excitation potential, because the spectral absorption in glass is not the same as in copper.

From the consistency of this correlation—in which it is obvious that absorption curves corresponding to different excitation potentials do not fit—it is to be concluded that the shape of the absorption curve is characteristic of the excitation potential. On the other hand, the coordinate displacement of the given curve from that of the basic

curve is characteristic of the filtration between the target and the point of measurement. Having a family of such curves (as in fig. 1), in which the constant excitation potential varies by steps of practicable magnitude, it is clear that instead of using the complete absorption curve to specify the quality of the radiation, we may use the more convenient magnitudes: excitation potential (constant) and initial filtration. Since, as shown in an earlier publication, the radiation from various wave forms of excitation potential may be simply and adequately equated to that of some equivalent constant potential excitation, the quality of any given radiation may be specified by its equivalent constant excitation potential and the initial filtration. This initial filtration is desirably expressed in terms of the equivalent copper or aluminum.

III. EQUIVALENT THICKNESS OF TUBE WALLS

This section is for the two-fold purpose of revealing the degree of consistency obtainable from the foregoing conclusion and of providing data from which an operator may evaluate the absorption in the wall of his own X-ray tube.

It should, of course, be borne in mind that because of the difference in atomic numbers of glass, aluminum, and copper, the equivalent thickness of one in terms of any other varies with the excitation potential of the radiation. By equivalent thickness of the tube wall, therefore, is meant the thickness of copper or aluminum which will reduce the given incident radiation by the same fraction of its initial value as does the tube wall.

As will be seen, the equivalent thickness is not proportional to the thickness of the material. Then, too, two different materials of the same equivalent thickness do not necessarily change the quality of the beam to the same degree; the change in quality varies with the exciting potential and the thickness of the absorber. However, for conditions ordinarily encountered in practice the quality change produced by equivalent thicknesses of glass, aluminum, and copper is not very different and therefore, as we shall do below, may usually be neglected. Thus tube wall absorption may be considered as a special example of the general case set forth in figure 4 where the wall absorption corresponds to the initial filtration, d , for the curve CB. Upon

the experimental determination of $\log \left(100 \frac{I_d}{I_o} \right)$ it is thus possible by the methods already discussed to set up the basic absorption curve for filter thickness greater than d —but not less.

Tables 4 to 10, inclusive, give absorption data for various tube walls, together with the commonly used filters of copper and aluminum.

TABLE 4.—*Absorption of general X-radiation in copper*

Initial filtration: Tube wall, 1.29 mm cerium glass and 0.25 mm copper

 I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	100 kv		110 kv		120 kv		130 kv		140 kv		150 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
<i>mm</i>												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
.15	66.5	1.823	67.3	1.828	69.8	1.844	71.8	1.856	73.5	1.866	74.5	1.872
.25	53.7	1.730	56.2	1.750	58.5	1.767	61.0	1.785	62.4	1.795	63.8	1.805
.5	34.2	1.534	38.0	1.580	40.7	1.609	43.7	1.640	45.7	1.660	47.1	1.673
.75	23.9	1.378	27.2	1.435	29.8	1.475	33.1	1.520	35.5	1.551	36.9	1.567
1.25	13.7	1.138	15.9	1.203	18.0	1.256	20.9	1.319	23.3	1.368	25.2	1.401
1.75	8.00	.903	10.1	1.005	11.9	1.074	14.2	1.154	16.2	1.210	18.1	1.257
2.25	-----	-----	6.70	.826	8.40	.924	10.4	1.018	12.00	1.078	13.7	1.136
2.75	-----	-----	-----	-----	6.11	.786	7.72	.887	9.25	.966	10.9	1.037

TABLE 5.—*Absorption of general X-radiation in copper*

Initial filtration: Tube wall, 1.29 mm cerium glass, and 0.5 mm copper

 I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	100 kv		110 kv		120 kv		130 kv		140 kv		150 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
<i>mm</i>												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
.25	63.8	1.805	67.6	1.830	70.2	1.846	71.8	1.856	73.3	1.865	74.6	1.873
.50	44.3	1.646	48.7	1.688	51.6	1.712	54.9	1.739	56.8	1.754	58.5	1.767
1.0	24.4	1.387	28.5	1.455	31.2	1.494	34.6	1.539	37.2	1.571	39.9	1.601
1.5	14.6	1.165	18.1	1.257	20.5	1.312	23.6	1.373	25.9	1.413	28.6	1.457
2.0	9.29	.968	12.0	1.080	14.5	1.162	17.3	1.238	19.1	1.280	21.6	1.335
2.5	-----	-----	-----	-----	10.9	1.035	12.8	1.107	14.8	1.170	17.3	1.237

TABLE 8.—*Absorption of general X-radiation in aluminum*

[Initial filtration: Tube wall, 1.29 mm cerium glass, and 1.0 mm aluminum]

 I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	60 kv		70 kv		80 kv		90 kv		100 kv		110 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
<i>mm</i>												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
1	59.2	1.772	61.5	1.789	63.6	1.803	64.9	1.813	67.4	1.829	69.3	1.841
2	40.0	1.602	42.5	1.629	45.8	1.661	47.3	1.675	50.4	1.703	52.6	1.721
3	29.1	1.464	31.8	1.503	35.1	1.545	37.0	1.569	40.1	1.603	42.5	1.628
4	21.8	1.338	24.9	1.397	28.0	1.447	29.8	1.475	33.2	1.521	35.4	1.549
5	16.8	1.226	20.4	1.310	22.9	1.360	24.9	1.397	28.0	1.448	30.3	1.482
6	13.5	1.131	16.3	1.213	19.1	1.281	21.4	1.331	24.3	1.385	26.4	1.422
7	11.1	1.043	13.6	1.134	16.2	1.210	18.5	1.268	21.2	1.327	23.4	1.369
9	7.59	.880	10.1	1.004	12.2	1.085	14.0	1.146	16.4	1.215	18.5	1.267
14	3.61	.557	5.28	.723	6.66	.824	8.15	.911	10.0	1.001	11.3	1.054
19	1.86	.271	2.95	.470	3.89	.590	5.16	.713	6.44	.809	7.47	.873

TABLE 9.—*Absorption of general X-radiation in aluminum*

[Initial filtration: Tube wall, 1.29 mm cerium glass, and 2.0 mm aluminum]

 I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	60 kv		70 kv		80 kv		90 kv		100 kv		110 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
<i>mm</i>												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
1	67.5	1.829	69.2	1.840	72.0	1.858	72.9	1.863	74.9	1.875	76.0	1.881
2	49.1	1.691	51.8	1.714	55.1	1.741	57.0	1.756	59.6	1.775	61.3	1.787
3	36.8	1.566	40.5	1.608	43.9	1.263	45.9	1.661	49.3	1.693	51.1	1.708
4	28.4	1.454	32.6	1.514	36.0	1.556	38.3	1.584	41.6	1.619	43.8	1.642
5	22.9	1.360	26.6	1.424	30.0	1.477	33.0	1.518	36.0	1.557	38.2	1.582
6	18.7	1.271	22.2	1.345	25.5	1.406	28.5	1.455	31.5	1.499	33.7	1.528
8	12.8	1.103	16.4	1.216	19.1	1.281	21.5	1.333	24.8	1.394	26.7	1.427
13	6.10	.785	8.60	.935	10.5	1.020	12.6	1.099	14.9	1.174	16.3	1.213
18	3.15	.498	4.80	.681	6.12	.787	7.96	.901	9.56	.981	10.8	1.033

TABLE 10.—*Absorption of general X-radiation in aluminum*

[Initial filtration: Tube wall, 1.29 mm cerium glass, and 4.0 mm aluminum]

 I_0 ≡Incident radiation. I ≡Transmitted radiation. $100 I/I_0$ =Percent transmission.

Copper filter	60 kv		70 kv		80 kv		90 kv		100 kv		110 kv	
	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0	100 I/I_0	Log 100 I/I_0
<i>mm</i>												
0	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00	100	2.00
1	75.0	1.875	78.3	1.894	79.8	1.902	80.4	1.905	82.6	1.917	83.3	1.921
2	57.9	1.763	63.0	1.799	65.3	1.815	67.2	1.828	69.8	1.839	71.4	1.854
3	46.6	1.668	51.3	1.710	54.4	1.736	57.8	1.762	60.5	1.782	62.2	1.794
4	38.0	1.580	42.8	1.631	46.2	1.665	50.0	1.699	53.0	1.724	55.0	1.741
6	26.1	1.417	31.7	1.501	34.7	1.540	37.7	1.577	40.9	1.612	43.6	1.639
11	12.4	1.094	16.6	1.220	19.0	1.279	22.0	1.342	25.1	1.399	26.6	1.425
16	6.42	.807	9.28	.968	11.1	1.046	14.0	1.145	16.5	1.218	17.6	1.245

Samples used for obtaining absorption data (tables 11 and 12) of tube walls were in part cut from old tubes and in part from unused plane plates of lime and pyrex glass. The thickness of the curved pieces was measured by a spherical micrometer. The wall thickness, D , of the X-ray tubes used was also measured—by the customary micrometer microscope method—focussing first on the outer surface markings, then on the inner surface markings, and observing the displacement, s , of the microscope between these two positions.²⁰ This displacement multiplied by the refractive index, n , of the glass gives its thickness. The index of refraction used for lime glass was 1.52 and that for pyrex 1.48.²¹ These refractive indices were checked by thickness measurements, D , and displacement measurements, s , on pieces of the same kind from broken tubes, n being equal to D/s .

TABLE 11.—Copper and aluminum equivalents of pyrex glass for radiations excited by various constant potentials and filtered by 1.3 mm of cerium glass (copper equivalence, about 0.02 mm)

Thick- ness of pyrex	100 kv			110 kv			120 kv			130 kv		150 kv	
	Log % trans- mis- sion	Cu thick- ness	Al thick- ness	Log % trans- mis- sion	Cu thick- ness	Al thick- ness	Log % trans- mis- sion	Cu thick- ness	Al thick- ness	Log % trans- mis- sion	Cu thick- ness	Log % trans- mis- sion	Cu thick- ness
mm		mm	mm		mm	mm		mm	mm		mm		mm
0-----	2.00	0	0	2.00	0	0	2.00	0	2.00	0	2.00	0	2.00
2-----	1.657	.02	.80	1.667	.025	.95	1.720	.025	1.05	1.756	.023	1.804	.024
4-----	1.477	.067	2.10	1.508	.064	2.15	1.539	.066	2.22	1.604	.065	1.640	.070
6-----	1.354	.115	3.52	1.382	.117	3.70	1.405	.125	3.80	1.459	.125	1.512	.124
8-----	1.265	.157	5.00	1.301	.167	4.70	1.330	.175	5.25	1.362	.180	1.428	.180
10-----	1.176	.205	5.95	1.225	.22	6.15	1.258	.23	6.6	1.292	.237	1.356	.245
12-----	1.079	.260	7.25	1.146	.28	7.40	1.182	.30	7.9	1.225	.30	1.288	.32

For determining the copper and aluminum absorption equivalents of pyrex glass above 100 kv, table 11, the radiation from the cerium glass tube of figure 1 was used, being taken without wall correction as representing the unaltered anticathode radiation. This was considered permissible in that the copper equivalent of its wall could not be more than 0.02 mm—one sixth that found for the difference between this thin tube and the pyrex tube of figure 2.

For determining the aluminum equivalents of lime glass, table 12, a lime glass tube, 0.45 mm thick, was used as source of radiation. The nearly linear relation between the thicknesses of glass and of aluminum which have the same absorption at the lower thicknesses permits a fairly accurate aluminum equivalent to be assigned to this tube wall.²²

An examination of tables 11 and 12 will show that the variation with exciting voltage of the equivalent copper or aluminum filtration of glass is not large and may be assumed as constant except for the most accurate work.

The consistency of these data on tube wall equivalents is strikingly illustrated in figure 6 by the accuracy of the correlation which they furnish for the copper absorption curves of the radiation from 5 tubes differing both in construction and wall thickness, all excited by 150 kv (constant).

²⁰ The surface markings are best seen under tangential illumination.

²¹ Their respective densities were 2.54 and 2.24.

²² There may be some question as to the validity of this assumption since the measurements were all made on a radiation initially filtered with 0.45 mm of lime glass. If present at all, the error is small.

TABLE 12.—Aluminum equivalents of lime glass for radiations excited by various constant potentials and filtered by 0.45 mm of lime glass

Thick- ness of lime glass	60 kv		80 kv		100 kv	
	Log % trans- mission	Al thick- ness	Log % trans- mission	Al thick- ness	Log % trans- mission	Al thick- ness
mm		mm		mm		mm
0	2.00	0	2.00	0	2.00	0
.5	1.607	.42	1.690	.47	1.751	.48
1.0	1.516	.84	1.558	.86	1.605	.88
1.5	1.403	1.26	1.461	1.30	1.526	1.33
2.0	1.295	1.72	1.373	1.76	1.459	1.78
2.5	1.185	2.16	1.286	2.23	1.395	2.24
3.0	1.072	2.56	1.199	2.74	1.322	2.77

FIGURE 6.—Absorption curves showing the correction for wall effect.

To be properly related, the data for these curves should be plotted each on its proper coordinates as fixed by the wall filtration. To avoid this multiplicity of coordinate systems, the data for the pyrex tubes (dash lines) and the cerium tube (solid line) are plotted in the usual manner taking as 100 percent transmission, the radiation filtered only by the tube wall in each case. Finally, the data for all pyrex tubes are correlated with that of the cerium glass tube, following the procedure indicated by equations 2 and 3 and taking into account here the copper equivalent of the cerium tube wall. All copper filtration values for the pyrex tube data are increased by the difference in the copper equivalents of the two tube walls—that of the cerium tube being estimated as .02 mm of Cu. All log percent transmissions

for the radiation from the pyrex tube are accordingly decreased by the difference in the log percent transmission of the corresponding copper equivalents of the walls—as given in table 11. This operation should bring the absorption curve for the given pyrex tube into coincidence with that of the cerium tube. This correlation is indicated by the plotted points on the full line curve for the cerium tube of figure 6.

The fit is very good, and shows with what assurance the quality of constant potential radiation from a tube of given wall thickness can be evaluated in terms of the constant potential excitation and equivalent filtration. In other words, the equivalent thickness of the tube wall constitutes a unique and adequate specification of the quality of radiation furnished by a given X-ray tube.

IV. COPPER ABSORPTION CURVES ABOVE 250 KV EXCITATION POTENTIAL

The need for specifying the quality of X-rays excited by the so-called “ultra-high voltages”—250 kv and above—is particularly accentuated at present when such radiations are fast coming into use. In case of such radiation in which the wave form of the excitation potential varying as it does from the extreme furnished by the induction coil up to that of very nearly constant magnitude, it is essential that their equivalence be fixed—perhaps most suitably in terms of constant potential. The first step is to obtain the absorption curves of radiation excited by the corresponding range of constant potentials. These data were obtained through the courtesy of Dr. Roscoe L. Smith, of Lincoln, Nebr., who placed for this purpose his 800-kv constant-potential set at our disposal.²³ With this set, in which the X-ray tube with a tungsten target had a wall of 6.4-mm steel plus 13 mm of water—this initial filtration being equivalent to about 6 mm of copper—the determination of copper absorption curves in the range between 250 and 550 kv (constant) was carried out under as nearly standard conditions as the facilities permitted.²⁴

Since, as pointed out by Lauritsen,²⁵ the international definition of the roentgen permits disturbing conditions to enter at these high potentials, our measurements were made according to the revised definition of the roentgen recommended by the R.S.N.A. standardization committee.²⁶ Here all forms of scattered radiation are eliminated from the measuring volume of the ionization chamber.

The end of the tube containing the target and its water jacket was surrounded by a lead shield 1 inch thick, in which a hole about $\frac{3}{4}$ inch in diameter was drilled to serve as a window for passing the radiation. The filters were inserted in the beam immediately adjacent to the lead cap; and the limiting diaphragm for the ionization chamber placed 35 cm from these. This diaphragm consisted of a 2.5-cm square hole half way out on the radius of a large circular lead disk 2.54 cm thick. Following the technique described by Lauritsen the beam was cut off, without altering the amount of extraneous radiation entering the ionization chamber, by rotating this lead disk on its geometrical axis. The difference in reading of the ionization chamber magnitude

²³ We are greatly indebted to him and to Mr. T. R. Folsom for their cordial cooperation and assistance.

²⁴ Only a brief description of these is given here, as others will undoubtedly publish a more adequate one.

²⁵ C. C. Lauritsen, *Am. Jour. Roentgenology*, vol. 6, p. 321, 1933.

²⁶ “The roentgen is the quantity of X-radiation which, when the secondary electrons are fully utilized and the effects of all scattered radiation avoided, produces in 1 cubic centimeter of atmospheric air at 0°C and 76-cm mercury pressure, such a degree of conductivity that one esu of charge is measured under saturation conditions.”

with the limiting diaphragm open and closed eliminated the effect of radiation scattered from the room.

The ionization chamber was of the parallel aluminum plate type, having a 28-cm spacing between the plates. That this separation was probably sufficient, at the voltages used, is concluded from cloud expansion photographs²⁷ which show that at a considerably higher peak voltage the bulk of the ion tracks are confined within 10 cm of the sides of the beam.

The ionization current was measured by a high sensitivity galvanometer, and voltages by the spark gap between 50-cm spheres placed

FIGURE 7.—Copper absorption curves above 225 kv; voltages are peak values which are the same as the effective values within the limits of error of measurement.

in accordance with 1928 AIEE standards and corrected to normal pressure. These potential measurements were in reasonably close agreement with the sum of the potentials measured individually on each of the cascaded units by the manufacturer.

The resulting semilogarithmic copper absorption curves, for the indicated excitation potentials and an initial filtration equivalent to about 6 mm of copper, are plotted in figure 7. Along with these is also plotted the curve for radiation excited by 180 kv (constant) and

²⁷ C. C. Lauritsen, personal communication.

initially filtered by 4.8 mm of pyrex glass—equivalent to 0.1 mm of copper—that obtained by Mayneord²⁸ for 370 kv (constant), but an unstated initial filtration; and, of radiation from a sample of Ra (B + C) after “a heavy” initial filtration (also from Mayneord). The half-value layer line is also inscribed at $\log_{10} 50 = 1.70$.

Owing to the very different excitation potentials and initial filtrations involved in radiations of figure 7, as compared with those of figures 1 and 2, no attempt is made to correlate the absorption curves of figure 6 with the basic curves of figure 1.

For the 370-kv (constant) curve of Mayneord the initial filtration was confined to the tube wall and hence was of much smaller copper value than that (about 6 mm) in our measurements. In this respect Mayneord's curve agrees with our 374-kv curve at the lower copper filtrations in that his drops the more rapidly as it should; but at the highest filtrations somewhat greater slope of our curve denies the agreement. Since his measurements were made with a thimble chamber of unknown wall effect, it seems rather gratifying that the results are not even more divergent.

Inasmuch as our curves of figure 7 were obtained with nearly constant potential—2 percent ripple—they may serve as standard for specifying radiation quality within the range of excitation potentials covered and for the initial filtration of about 6 mm of copper. Absorption curves obtained with a greater initial filtration can be correlated with these curves of figure 7 just as those of figure 2 with figure 1; but not so with curves for radiation of lower initial filtration because of the uncertainty with which the magnitudes can be extrapolated toward the higher transmissions. In other words, although these curves can be of value as standards, they do not have the range of application reserved to basic curves—i.e., of radiation subjected to zero initial filtration.

We would suggest, therefore, that in specifying the radiation in this high potential range the peak of the excitation voltage be stated when possible along with the equivalent constant voltage until further studies have been made.

Recognition is due to C. F. Stoneburner of this laboratory for his valuable assistance in obtaining much of the data.

WASHINGTON, February 10, 1934.

²⁸ W. V. Mayneord, *Brit. Jour. Radiology*, N.S. vol. 6, p. 321, 1933.