United States Department of Commerce, Bureau of Standards

RESEARCH PAPER RP595

Part of Bureau of Standards Journal of Research, Vol. 11, September 1933

COMPARISON OF HIGH VOLTAGE X-RAY TUBES

By Lauriston S. Taylor, George Singer, and C. F. Stoneburner

ABSTRACT

A comparison of the X-ray output as a function of the applied voltage has been made for 2 thin glass X-ray tubes, 5 thick glass tubes, and 1 metal-centered tube on several generators of different voltage wave form. Thin glass tubes show about 15 percent greater output than thick glass tubes on constant potential, while the metal-centered tube gave about 15 percent less output. At any given effective (rms) voltage, the outputs of all glass tubes on all generators were nearly the same, and equal to the output on a constant potential of the same value. Likewise, at a given effective voltage, the quality (full absorption curve) was the same for all tubes on all generators.

Outputs of all tubes at a given peak voltage varied over a range of 25 percent between tubes and between different generators. The metal-centered tube output varied widely between half and full wave rectification at equal peak voltages. The same tube, however, gave the same output at any given effective voltage supplied by any generator.

CONTENTS

	Page
I. Introduction	341
II. Experimental results	342
1. Tubes and generators employed	342
2. Output on constant potential	344
3. X-ray output per average milliampere	344
4. X-ray output per effective milliampere	345
5. Measurements on metal-centered tube (T5)	349
6. Relationship of X-ray quality to voltage measurements	350

I. INTRODUCTION

Previous papers from the Bureau of Standards X-ray laboratory[1 2 3 4] have dealt with the relationship between the applied X-ray tube voltage and the intensity and quality of the emitted radiation measured under given filtrations and other conditions. These showed for a wide variety of applied voltage wave forms that, regardless of the peak voltage, the resultant X-ray qualities as given by a full absorption curve are alike for any given effective voltage; also the outputs per effective milliampere [5] for a given tube operated on

[1] L. S. Taylor and K. L. Tucker, B.S.Jour. Research, vol. 9, p. 333, 1932. Also Amer. Jour. Roent.
[2] L. S. Taylor, G. Singer, and C. F. Stoneburner, B.S.Jour. Research, vol. 9, p. 561, 1932.
[3] L. S. Taylor, Strahlentherapie.
[4] L. S. Taylor, G. Singer, and C. F. Stoneburner, B.S.Jour. Research, vol. 11, p. 293, 1933.
[5] See footnote no. 2.

the various voltage wave forms are nearly the same at any given effective voltage. As a consequence, the quality (and intensity, to a certain extent) of all radiations is expressible in terms of two readily measured quantities, the effective tube voltage and effective tube current.

This previous work was carried out, using thin-walled glass Coolidge tubes which are free from certain inherent disadvantages present in other tubes. In order that the relationship between quantity, quality, and effective tube voltage might be more completely generalized, however, it is, of course, necessary to investigate the effect with the other types of tubes and generators.

Most prominent among the newer tubes are the several American makes of thick-walled pyrex tubes, and the foreign tubes of the metal-centered type. In operating the thick-walled tubes on a fluctuating voltage, it is found that the output changes (usually decreased) some 20 percent during the first few minutes of operation, even though the average tube current and transformer primary (rms) voltage are held constant.[6] [7] This is caused by current and voltage wave-form change arising from the interaction of the transformer and tube, which change in turn is caused by a high electrostatic charge on the tube walls acting as a charged grid when the tube is cold but which is dissipated as the glass heated up. It was then found [7] that by maintaining the effective tube voltage and current constant during the transition period, a change in output no longer occurred. That is, output readings for any effective voltage and current are characteristic of the tube, irrespective of accumulated charge on the glass walls. On the other hand, using the customary peak voltage and average current measurements, sufficient time must also be allowed to permit the tube to reach a steady state before making output measurements.

While this grid action is not present in the metal-centered type of tube another difficulty in arriving at an adequate comparison of tubes is introduced through the elimination of stem radiation from the ionization readings. With the common glass tube, stem radiation may amount to 10 to 20 percent of the total, and this, in general, [8] is of a considerably softer quality than the focal spot radiation.[9] [10]

In view of the above described tube differences, the principal purpose of this investigation was to further compare the operation of several typical X-ray tubes on a group of typical X-ray generators.

II. EXPERIMENTAL RESULTS

1. TUBES AND GENERATORS EMPLOYED

The arrangement of the equipment is the same as in our recent studies of generators.[11] The tube was in a lead box 4 by 4 by 7 feet, lined with one fourth inch of lead (fig. 1), with a fixed insulating support insuring a uniform distance from the center of the target to the ionization chamber. In addition to the box being well ventilated, a strong blast of air could be directed against the tube walls.

[6] M. J. Gross, Radiology, vol. 20, p. 14, 1933.
[7] L. S. Taylor and C. F. Stoneburner, B.S.Jour. Research, vol. 10, p. 233, 1933.
[8] W. D. Coolidge and C. N. Moore, G. E. Rev., p. 272, April 1917.
[9] E. Lorenz, Proc. Nat. Acad. Sci., vol. 14, p. 582, 1928.
[10] L. S. Taylor and G. Singer, B.S.Jour. Research, vol. 6, p. 219, 1931.
[11] See footnote no. 4, p. 341.

Simultaneous measurements were made of the effective (rms) tube voltage and current, peak voltage, average voltage and average current in the high tension circuit. The average and effective voltage were measured by means of a 150-megohm coronaless shielded resistor [12] used as a voltmeter multiplier. As before, to avoid possible uncertainties in the comparison of tubes, the aerial system was kept the same for all generators. Tubes and generators could be changed within a minute's time. The results have been checked repeatedly over a period of several months.

Radiation emerged from the box through a 10-cm aperture forming a beam about 14.5 cm in diameter at the ionization chamber, thus giving similar to conditions used clinically. A fixed filter of 0.557 mm Cu + 1.0 mm Al was placed over the aperture with the copper toward

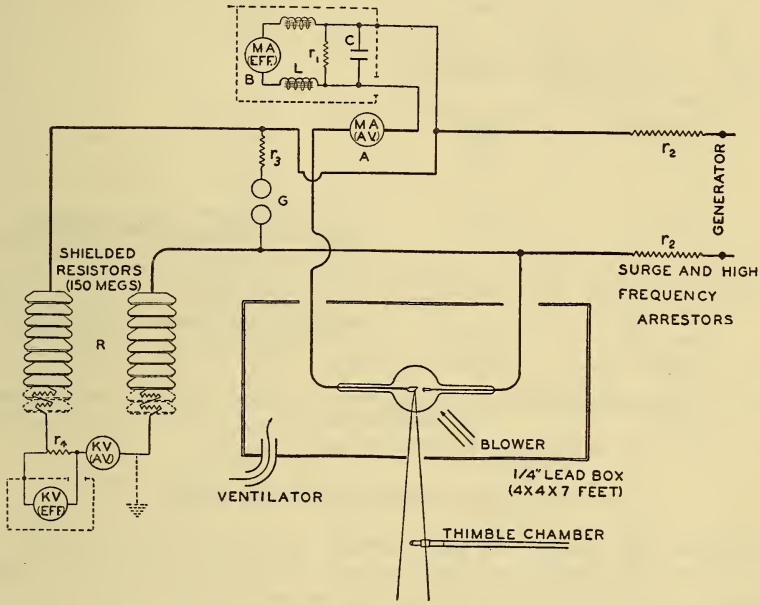

FIGURE 1.—*Diagram showing arrangement of apparatus used in the comparison of X-ray tubes.*

the tube. Ionization measurements were made in air with a calibrated thimble chamber at a distance of 50 cm from the target center, particular care being taken to avoid the inclusion of any spurious (scattered) radiation, particularly back-scattering and scattering from the diaphragm. The only difference between this arrangement and the one previously used in our generator comparisons is in the diameter of the beam at the point of measurement. In the earlier work (with thin-walled tubes) the beam diameter was 5.5 cm, as compared with 14.5 cm in this work. The resulting difference in measured ionization was 9 ± 0.4 percent at all voltages and is attributable to the inclusion of more stem radiation in the larger beam. The measurements given here for thin-walled tubes are our earlier values increased by 9 percent which change renders the results in this paper directly comparable with our earlier work. The following high

[12] L. S. Taylor, B.S.Jour. Research, vol. 5, p. 609, 1930.

voltage generators, as previously designated, were used: (B) Mechanical rectifier, double high-tension transformer in single tank, rectifies 20 electrical degrees of each half cycle; (C) Constant potential, commercial, 2 percent ripple per ma; (D) Half-wave kenotron rectifier; (E) Full-wave kenotron rectifier; (F) Constant potential (B.S. Standard), 0.2 percent ripple per ma.

The following X-ray tubes (fig. 2) were used: *T1*, (2 tubes) thin glass, massive target; *T2*, (2 tubes) thick glass, massive target; *T3*, (2 tubes) thick glass, disc target; *T4*, (1 tube) thick glass, disc target; *T5*, (1 tube) metal centered, line focus, water cooled.

It may be stated here that all tubes of the same make and type gave practically the same output on any one generator so the results obtained with one tube only of each type are given.

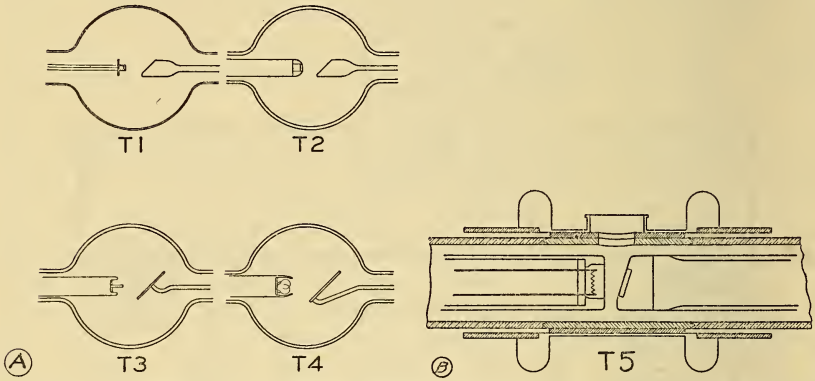

FIGURE 2.—*Schematic diagram of X-ray tubes employed, showing essential details of construction.*

[A, glass tubes. B, metal-centered tube]

2. OUTPUT ON CONSTANT POTENTIAL

In figure 3 is plotted on two curves the output in roentgens per minute per milliampere of the various tubes operated on constant potential. The data happened to be taken on generator C, but as pointed out previously there is no appreciable difference between the outputs using generators (C) and (F), although the ripplage of (F) is only about a tenth that of (C). The lower curve for the thick-walled tubes (*T2*, *T3*, and *T4*) clearly shows no appreciable difference between the outputs per ma at any given voltage. The upper curve for the thin-walled tube (*T1*) shows a considerably higher output than the thick-walled at all voltages—ranging from about 17 percent at 105 kv to 14 percent at 145 kv. A decrease in relative output with increased voltage is to be expected, since at the higher voltages, the radiation being harder, the absorption in the thick glass walls becomes relatively less.

3. X-RAY OUTPUT PER AVERAGE MILLIAMPERE

As in our previous study of X-ray generators, output curves obtained under the more common criteria of control, are given first to show the limitations therein. In comparing the tubes operated on different generators, it is least confusing to group on one graph the

outputs of all the tubes on one particular generator. Figures 4, 5, and 6 show the output per average ma, for the full-wave (E), half-wave (D), and mechanical rectifier (B), respectively, as a function of the peak voltage. The upper curve in all three figures is for tube *T3* on the constant potential generator (C).

It is evident from the curves that there is a considerable difference between the outputs of individual tubes when operated on the same generator. At 180 kv (peak) the maximum difference on the full-wave rectifier is about 28 percent; on the half-wave rectifier about 32 percent, and on the mechanical rectifier about 35 percent. Part of the difference is attributable to differences in the transformer design, but earlier studies have shown that there is not necessarily any similarity between the outputs produced by half-wave and full-wave rectifiers operating on the same transformer.[13]

Differences between tubes appear to be for the most part random. However, in all of the curves the output per average ma of tube *T3* is predominantly higher than the others at any given peak voltage.

It is also seen that while occasionally there is no difference in output per average ma for a given tube when the magnitude of the tube current is changed, this appears to be largely accidental and dependent upon the particular circuit conditions for which the measurements were made.

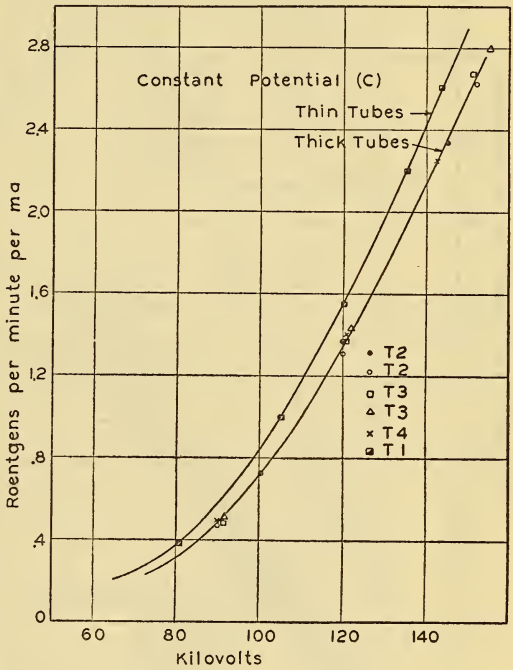

FIGURE 3.—*Output of X-ray tubes on constant potential.*

It should be emphasized that the basing of any general conclusions regarding the relative efficiency of tubes based on measurements of peak voltage and average tube current is unsafe. Depending upon the generator and tube current, such a wide range of outputs is obtainable under supposedly the same conditions as to render the results almost meaningless.

4. X-RAY OUTPUT PER EFFECTIVE MILLIAMPERE

Earlier investigations with thin-walled tubes operated on a group of representative generators, showed a much closer agreement in output at any given values of the effective tube current and effective voltage.

[13] See footnote no. 4, p. 341.

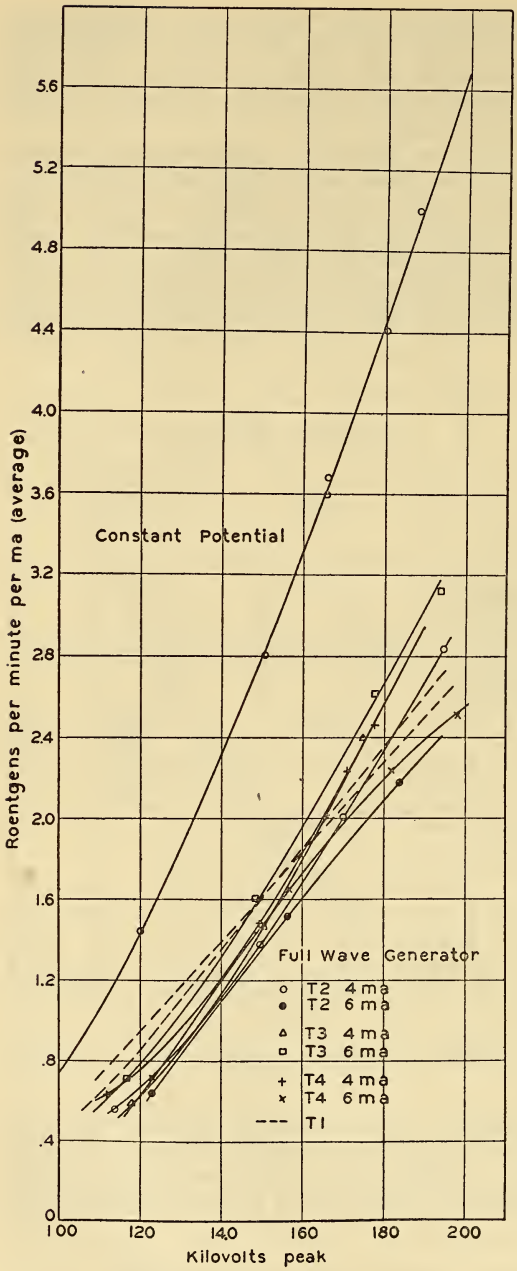

FIGURE 4.—*Output per average ma of X-ray tubes as a function of peak voltage on full-wave generator.*

The curves in figures 7, 8, and 9 likewise show a close relationship for the thick-walled tubes on full-wave (E), half-wave (D), and mechanical rectifier (B), respectively. Data plotted for the thin tube are taken as before from a recent paper and corrected as noted above to the larger field area used in this study. The lower broken-line curve in figures 7 to 9 is for constant potential on the thick tubes and is taken from figure 3.

In figure 7 for the full-wave generator (E) the points for the various tubes are scattered somewhat at random about the constant potential curve; in general the outputs per effective milliampere are approximately the same. The upper broken-line curve is for constant potential (from fig. 3) on the thin tube (*T1*) and the two adjacent curves are for the same tube on the full-wave generator. The separation between the two constant potential curves is to be ascribed to the difference in filtration of the thin and thick glass walls.

In figure 8, for the half-wave generator, it is again seen that the outputs per effective milliampere are grouped fairly closely and at random about the constant potential curve. To obtain these curves, the actual meter readings of the voltage and current were corrected, as in our earlier work, by the factors $\sqrt{2}$ and $\sqrt{1/2}$, respectively, in order to make proper allowance for the suppressed half wave.[14] The two full-line curves for the

[14] See footnote no. 4, p. 341.

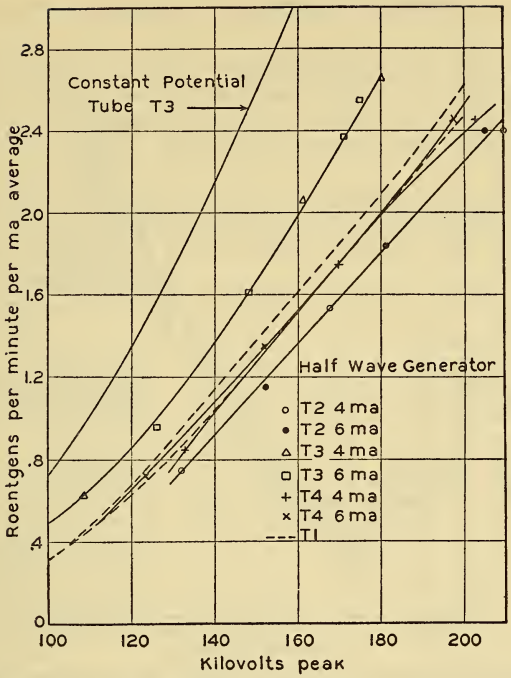

FIGURE 5.—*Output per average ma of X-ray tubes as a function of peak voltage on on half-wave generator.*

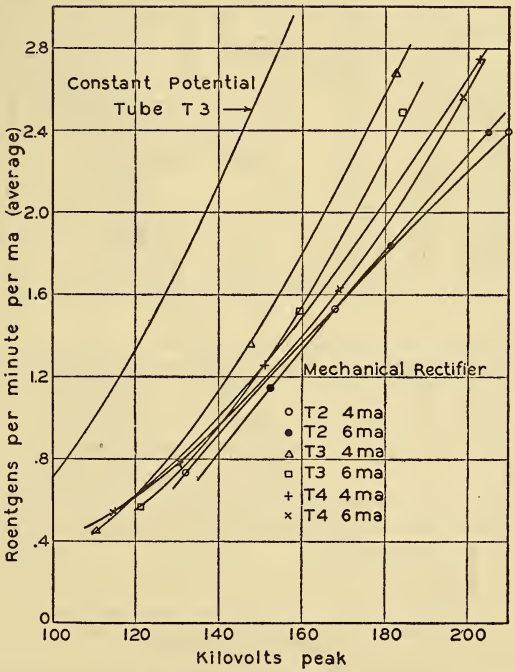

FIGURE 6.—*Output per average ma of X-ray tubes as a function of peak voltage on mechanical rectifier.*

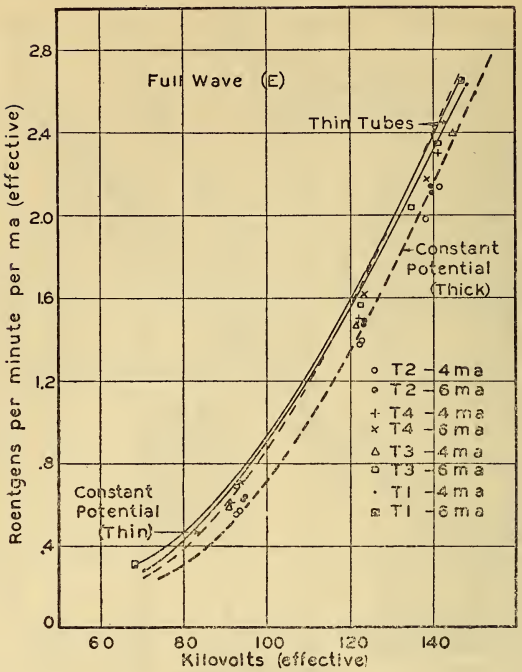

FIGURE 7.—*Output per effective ma of X-ray tubes as a function of effective voltage on full-wave rectifier.*

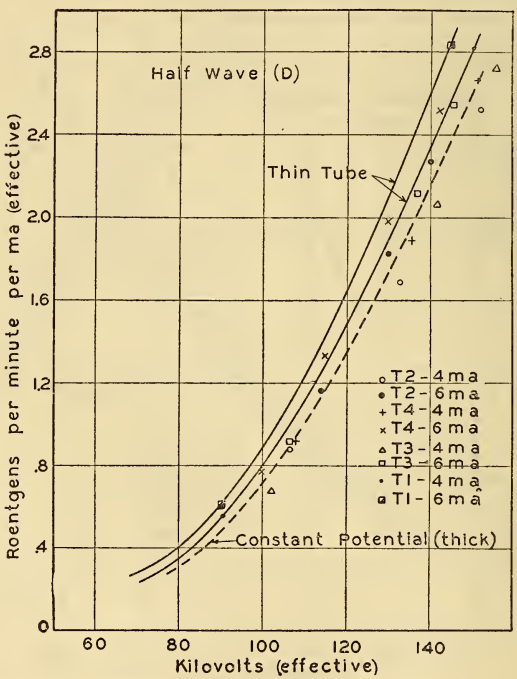

FIGURE 8.—*Output per effective ma of X-ray tubes as a function of effective voltage on half-wave rectifier.*

thin tube (*T1*) again show a consistently higher output at a given voltage.

Figure 9 for the mechanical rectifier (B) shows appreciably higher outputs than for constant potential of the same effective voltage. This, however, corresponds to earlier findings and in any case the agreement with constant potential is much closer than by any other method of measurement.

To summarize the results in the last three sets of curves, it may be said that the relationships between output per effective milliampere and effective voltage for thick-walled X-ray tubes follows closely the more detailed results previously presented for thin-walled tubes.

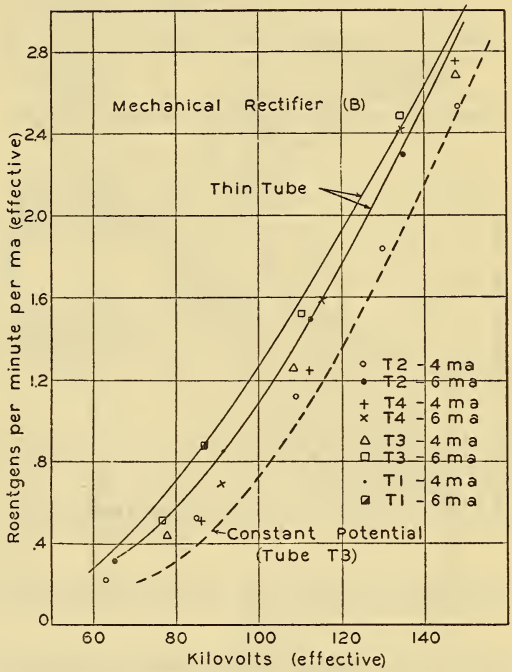

FIGURE 9.—*Output per effective ma of X-ray tubes as a function of effective voltage on mechanical rectifier.*

5. MEASUREMENTS ON METAL-CENTERED TUBE (T5)

Due to the fundamentally different construction of the metal-centered tube (*T5*) as compared with the glass-walled tubes, the output measurements thereon do not fall in with the other curves.

The curves in figure 10 show for this tube the output per milliampere as a function of the applied voltage. The curves are individually labeled as to whether the ordinates are for average or effective tube current, and the abscissae for peak or effective voltage. The tube was operated at the single current of 4 ma (average) which is its maximum rating.

It will be noted that on constant potential the output per milliampere of the metal-centered tube is about 35 percent less than for the thin-walled tube and about 16 percent less than for the thick-walled tube. As previously noted, this lowered output is probably due partly to the loss of stem radiation which is prevented, by the metal shield, from leaving the tube.

It is also seen that the output per average milliamper as a function of the peak voltage is less than the average value for all the other tubes on the full-wave generator. The shaded area indicates the region within which the output curves for the glass-walled tubes lie. For the half-wave generator, the output per average milliampere for the metal-centered tube is some 30 percent lower than on the full-wave generator at the same peak voltage, whereas we have shown before

that for glass-walled tubes the difference introduced by use of the two types of wave form has comparatively little effect on the output per milliampere. This great decrease in output on the half-wave generator is due to the wave distortion introduced by the current limiting characteristics of such tubes.

As contrasted to the behavior of this tube on half- and full-wave generators when controlled by average current and peak voltage, it is found that the output per effective milliampere, as a function of the effective voltage, follows closely the output for constant potential. On this basis of comparison then the X-ray output for this tube (*T5*) is the same for all generators and thus conforms to the results found with glass tubes.

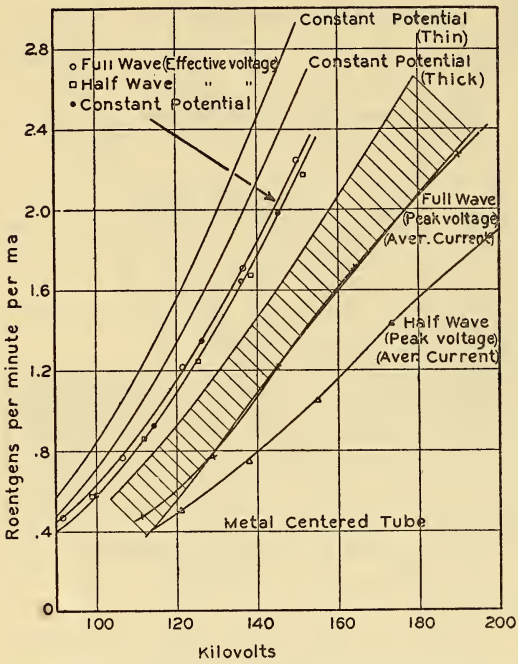

FIGURE 10.—*Output per ma of metal-centered tube on different generator.*

6. THE RELATIONSHIP OF X-RAY QUALITY TO VOLTAGE MEASUREMENTS

It has been shown by Silberstein [15] that radiations having the same complete absorption curves in copper (or aluminum) have likewise the same effective spectral distribution. Also, we have shown in recent studies, using thin-walled tubes, that radiations produced by the same effective voltage (by whatever voltage wave form, including constant potential) yield very closely the same full copper-absorption curve, regardless of the peak voltage.

This is corroborated by the semilogarithmic copper-absorption curves in figure 11. Curves A are for the tubes *T1* to *T5* operated on a constant potential of 141.4 kv. It is seen that at least after an initial filtration of 0.28 mm of copper, the absorption curves, and hence the quality, are all alike within reasonable limits. Tubes *T1* and *T4* do, however, appear to give a very slightly softer radiation than *T2* and *T3* which is to be expected since the latter tubes have the heaviest walls of the group.

Curves B show similar results for tubes *T3* on all generators, and tube *T5* on constant potential and full-wave rectifiers, all at 141.4 kv (effective) but at very different peak voltages. The two curves are identical with those in A and show that again the qualities are essentially the same on all generators at a given effective voltage. (The

[15] L. Silberstein, Phil. Mag., ser. 7, vol. 15, p. 375, 1933.

measured value of the effective voltage for the half-wave generator of 100 kv for the full cycle, was corrected by the factor $\sqrt{2}$ to give the true value during the useful half cycle.) Tube *T5* appears to yield a slightly harder radiation than the glass tubes, on both constant potential and full-wave rectification. This is probably due to the loss of the softer stem radiation which cannot contribute to the final result as in the case of the other tubes.

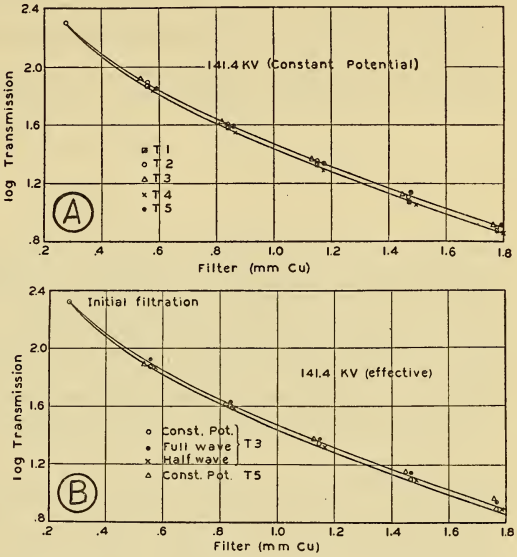

FIGURE 11.—(*A*) *Copper-absorption curves obtained with various glass X-ray tubes on constant potential.* (*B*) *Copper-absorption curves obtained with thick glass X-ray tube and metal centered tube on various generators.*

Our earlier conclusion is thus corroborated that (1) the quality of any X-ray beam may be adequately specified in terms of the constant voltage necessary to produce the same absorption curve, and (2) the qualities of the X-ray beams produced by any tube, in conjunction with different generators, are the same for a given effective (rms) voltage applied to the tube; (3) while there are necessarily small differences in output, due to such factors as wall thickness or elimination of stem radiation, these sources are readily recognized and allowances made therefor; and (4) with the conventional methods of measuring tube voltage and current, a wide range of outputs and qualities are obtainable.

This work has been made possible through the cordial cooperation of the American manufacturers of X-ray tubes and equipment, to whom we express our appreciation.

WASHINGTON, May 10, 1933.