A DETERMINATION OF THE EFFICIENCY OF PRODUCTION OF X-RAYS.

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THE purpose of this investigation was to measure the energy of the X-rays emitted by a Coolidge tube by means of their heating effect; to determine the efficiency of production of X-rays, *i. e.*, the ratio between the energy of the X-rays and the energy supplied to the X-ray tube; and to determine the variation of this efficiency with the potential across the tube.

A variety of methods have been used for the measurement of X-ray energy.

The first measurement was made by Dorn[1] in 1897 by means of a differential air thermometer. A bolometer method was used by Schöps[2] in 1899, by Rutherford and McClung[3] in 1900, by Wien[4] in 1905, by Angerer[5] and Carter[6] in 1906. Bumstead[7] in 1906 measured the energy by means of a radiometer and Adams[8] in 1907 used a radiomicrometer. A thermopile was employed by Wien[4] and by Hoepner[9] in 1915. In several cases the energy supplied to the tube was not determined so that no conclusions could be drawn as to the efficiency of production of the X-rays. Wien,[4] Angerer,[5] and Carter,[6] however, measured the energy carried by the cathode rays and determined the value of the efficiency. Carter also determined the variation of the efficiency over a considerable range of voltage.

The ionization produced by X-rays has also been used as a means of determining the efficiency of production of the X-rays. Rutherford and McClung[3] early found a value for the energy required to produce an ion in air by X-rays. In 1913 Beatty[10] determined the number of ions produced by the total absorption of X-rays. From the work of

[1] Wied. Ann., 63: 160.
[2] Dissertation, Halle.
[3] Proc. Roy. Soc., 67: 245.
[4] Ann. d. Phys., 18: 991.
[5] Ann. d. Phys., 21: 87.
[6] Ann. d. Phys., 21: 955.
[7] Phil. Mag., 11: 292.
[8] Proc. Am. Acad., 42: 671.
[9] Ann. d. Phys., 46: 577.
[10] Proc. Roy. Soc., 89: 314.

others he computed the total number of ions which would have been produced directly by the cathode rays which excited the X-rays. The ratio of these two quantities he took as the efficiency of transformation of energy from cathode rays to X-rays. He gives the following relation as the result of his work: $\frac{\text{X-ray energy}}{\text{cathode ray energy}} = 5.1 \times 10^{-5} A\beta^2$, where A is the atomic weight of the metal of the anode and β is the ratio of the velocity of the cathode rays to the velocity of light. In 1912 Eve and Day[1] determined the total number of ions produced in air by X-rays and found a value for the efficiency of production of X-rays from the energy supplied to the tube and the energy required to produce an ion, as determined from other experiments. Recently, 1915, Rutherford and Barnes[2] have made a determination of the energy output of a Coolidge tube from the total number of ions produced and the energy required to produce an ion by alpha rays. The energy supplied to the tube was measured and from this the efficiency computed.

Below is given a summary of the results of previous work. The values of the efficiency given are computed for the total energy which would appear on the outside of the tube on the supposition that the energy is emitted equally in all directions throughout a whole sphere.

Observer.	Method.	Potential.	Efficiency.
Wien	Bolometer	58.7 K.V.	.00143
Wien	Thermopile	58.7	.00183
Angerer	Bolometer	Low	.0004
Carter	Bolometer	59	.00062
Hoepner	Thermopile	65	.00029
Eve & Day	Ionization	(11 cm. gap)	.0001
Rutherford and Barnes	Ionization	48	.00059
Beatty	Ionization	48	.0019
(Abs. only by thin Al.)		59	.0023

In view of the differences in the values obtained by the various observers by means of the heating effect it seemed to be desirable to make a new determination under the more favorable conditions of better control of current and potential and larger power input made possible by the Coolidge tube.

Description of Apparatus.

A bolometer method was used, one of two similar resistances being exposed to the X-rays and the relative change in its resistance caused

[1] Phil. Mag., 23: 683.
[2] Phil. Mag., 30: 361.

by the heating effect detected by means of a Wheatstone's bridge and a galvanometer. The resistances were made of .056 mm. lead foil cut in grid form and folded back and forth on itself so as to form a continuous screen of about 1 mm. thickness which would absorb almost completely the incident radiation. Thin paper was used for the insulation between layers. The resistance of the grid which was exposed to the X-rays was 4.35 ohms and of the other 3.87 ohms. To protect the resistances from fluctuations in room temperature they were enclosed in a Dewar cylinder as shown in Fig. 1. The resistance to be exposed, called A, was placed in front of the comparison resistance, B. Between them was placed a 2 mm. lead screen and in front of A a similar screen with an opening 6.5 by 6.45 cm. This was 29.4 cm. from the target, so that it subtended /251.5 of the whole sphere. The end of the Dewar was closed with a cardboard .85 mm. thick. The Dewar was enclosed in a wood box and the end packed with wool to reduce the conduction of heat.

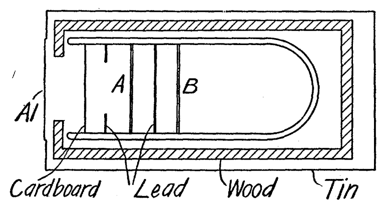

Fig. 1.

A D'Arsonval galvanometer was used, of the Leeds and Northrup high voltage sensitivity type. This was connected with a shunt so as to be very nearly critically damped. With a measuring current of .07 ampere a change of one thousandth part in the bridge ratio gave a deflection of 250 cm. at a scale distance of 4.8 meters. The entire bridge circuit was enclosed in a grounded metal cage to prevent inductive disturbances. The part of the cage in the path of the beam of X-rays was formed by a sheet of aluminum .09 mm. thick, which served also to cut off all direct heat radiation from the tube.

High potential uni-directional current was secured by means of a closed core transformer and mechanical rectifier. The tube current was measured by means of a D.-C. milliammeter. The filament of the X-ray tube was heated by means of a lead storage battery. For measuring the potential across the tube a sphere gap was first used. This was found to be unsatisfactory for measurements during the course of a run but served for calibrating. The sphere gap consisted of two brass spheres, each 6.5 cm. in diameter, placed horizontally. Each of these was connected to the line through a resistance of distilled water, the total resistance in series with the gap being of the order of 10 megohms. A tendency for the potential to rise to an abnormally high value before spark-over would occur was almost entirely eliminated by placing a tube containing some radium bromide close to the gap. For indicating the potential during the course of a run a balance form of electrostatic voltmeter was constructed. The movable part of this, a 4 cm. sphere, was suspended from a spiral spring and was immersed in oil above a flat metal plate. This voltmeter was easily read and was found to follow small changes in the potential with practically no lag.

Method of Observation.

Due to the inequality of the two resistances the measuring current produced a change in the resistance ratio. In addition there was unequal heating in the two from the stray heat conducted in from the outside. Consequently there was a continual drift of the spot of light. However this was not erratic and the rate was determined before each exposure by taking four or five readings at one-minute intervals. The rate of drift could be kept within the desired limits by varying the room temperature slightly. The time between exposures was ordinarily eight to ten minutes as it was necessary to wait for the target to cool as well as to determine the rate of drift.

Exposures were made for 30 seconds, the current and potential being held nearly constant during this time. In Fig. 2 is given a curve showing the galvanometer deflections during a typical exposure, the circles indicating the readings taken. Some corrections were necessary in determining from these readings the actual rate of heating due to the absorbed X-rays. By taking account of the rate of drift it was possible to determine the deflection due to the absorbed X-rays only. Then from the observed rate of cooling during the first 15 seconds after the exposure it was possible to correct for the cooling which took place during the exposure. Thus in the case shown in Fig. 2 the deflection due to the X-rays only was taken to be 6.90 cm. at the end of the exposure and 5.96 cm. 15 seconds later. These values give 15.95 cm. per minute for the rate of deflection due to the X-rays alone. From this rate of deflection and the heat sensibility of the bolometer, determined later, the amount of energy absorbed could be computed in joules per ampere-second of tube current. This multiplied by 251.5 gives the energy for the whole sphere.

A set of 5 to 10 exposures was made at one current and potential and then the tube adjustment changed or a different absorbing screen inserted in the path of the rays and a similar set obtained. For each potential several such sets were made on different days and with different values of tube current. Readings were taken at eleven different potentials and at four of these readings were taken with four different thicknesses of aluminum in the path of the rays for the purpose of determining the absorption curves. The results for each potential were derived from at least 20 and in some cases 40 separate exposures. For the absorption curves only from 10 to 20 exposures were made with each screen at each potential.

Calibration of the Bolometer.

The heat sensibility of the bolometer was determined by sending through the resistance *A* a known current for 30-second intervals and observing the resulting galvanometer deflections. While the heating current was flowing the measuring circuit was kept open. Readings were taken similar to those taken in the determination of the heating due to the X-rays and similar corrections were made. The heat produced in resistance *A* was computed from its resistance and the current flowing in it. Since *A* was in parallel with part of the bridge resistance the observed value of the current had to be corrected for the small current which flowed through the bridge. The mean sensibility obtained was 50 cm. per joule per .07 ampere measuring current.

Measurement of the Energy Supplied to the Tube.

If the tube had been operated by steady direct current it would have been sufficient to take the product of the tube current and the potential across the tube as the power supplied to the tube. However in the case of the rectified alternating current the current and voltage were both pulsating and the wave form of neither was known. Furthermore the voltmeter deflections were determined by the root mean square value of the potential and the milliammeter deflections by the mean value of the current. Therefore it was thought advisable to make a direct determination of the power by means of the heating effect.

The method employed was to immerse the tube in an oil bath and measure the energy supplied by means of the rise in temperature of the oil. The tank was made of tin and was enclosed in a wood box. It was just large enough to contain the tube and allow of sufficient insulation. Kerosene oil was used for the bath. The tube was covered over with a black insulating cloth which was also immersed in the oil. A small propeller driven by a motor served to keep the oil well stirred. The rise in temperature was indicated by means of two copper-advance thermocouples, two junctions being placed in different parts of the tank and two in a container of oil outside. The thermojunctions were connected in series with the galvanometer used in the previous measurements and with 950 ohms resistance and gave about 17 cm. deflection per 1° C.

Continuous runs were made, the potential and current being kept as nearly constant as possible and galvanometer deflections being noted every minute. The duration of each run was from 15 to 20 minutes and the rate of heating between 4 and 5 cm. per minute. The rate of cooling was found before and after each run and the mean added as a correction to the observed rate of heating. Several runs were made and gave concordant results. The tube potential was kept at 31.6 K.V. and the current at 4.80 m.-a. It was intended to make runs at other potentials, but at this point the tube developed a leak and could not be used further.

Observations were next made on the heating produced by sending current through a heating coil placed in the bottom of the tank. Conditions were kept as nearly as possible the same as before, the stirring device being kept in operation and the tube filament lighted. The current through the coil and the potential difference across its terminals were measured at intervals throughout the run. Runs were made with the power adjusted to give heating at rates somewhat above and somewhat below that produced by the operation of the tube. These gave 188 watts as the power corresponding to a tube potential of 31.6 K.V. and a tube current of 4.80 m.-a.

Calibration of the Voltmeter.

The voltmeter was calibrated by means of the spark gap and an electrostatic balance. This latter could be used only for the lower voltages on account of spark-over. It was found that a given voltmeter reading corresponded to a 20 per cent. higher R.M.S. potential, as determined by the balance, with rectified current than with alternating current. The difference was somewhat larger according to the spark gap readings but approached the same value at higher potentials. The oscillations introduced by the rectifier were probably responsible for the lower spark-over potentials with the rectified current. The differences in the voltmeter readings with alternating and rectified current were undoubtedly due to a leakage of charge over the surface of the glass jar containing the oil in which the attracted sphere was immersed. This would change the distribution of the field and so change the vertical force on the attracted sphere. A comparison of alternating potentials as determined by the electrostatic balance and by the spark gap indicated that the transformer used gave a wave form having a peak value 7 per cent. higher than a sine wave of the same R.M.S. value. The spark gap potentials used were those given by Peek[13] for 6.25 cm. spheres. The final calibration of the voltmeter was then determined from the

[13] "Dielectric Phenomena," by F. W. Peek; same in A. I. E. E. Standardization Rules, 1915.

alternating current spark-over voltages with the corrections indicated above.

Computation of Efficiencies.

In the experiment to determine the power supplied to the tube it was found that with a potential of 31.6 K.V. and 4.80 m.-a. current the power supplied was 188 watts. The product of kilovolts and milliamperes is 152. This gives a correction factor of 1.24. Inasmuch as the milliammeter read mean values of the current a rectified sine wave voltage and current would have given a factor larger than unity, but the large value found under the conditions of the experiment is surprising. It would have been desirable to determine this factor for other voltages. The efficiency of production of the X-rays was taken to be the ratio of the total number of joules of X-ray energy given out per ampere-second to the number of watts supplied per ampere. The values found for the efficiency are given in the fourth column of Table I.

Table I.

R. M. S. K. V.	Input $\frac{\text{Watts}}{\text{Amp.}}$.	Obs. X-Ray Energy $\frac{\text{Joules}}{\text{Amp.-sec.}}$.	Efficiency without Correction.	Absorption Factor.	Total Energy $\frac{\text{Joules}}{\text{Amp.-Sec.}}$.	Total Efficiency.
28.3	35.1×10^3	17.1	0.49×10^{-3}	1.20	20.5	0.58×10^{-3}
31.6	39.2	23.4	0.60	1.17	27.4	0.70
34.5	42.8	30.7	0.72	1.15	35.3	0.82
37.1	46.0	38.3	0.83	1.13	43.2	0.94
39.5	48.9	46.3	0.95	1.11	51.3	1.05
41.6	51.5	52.3	1.02	1.10	57.5	1.15
43.5	53.9	59.3	1.10	1.09	64.6	1.20
45.2	56.1	66.9	1.20	1.08	72.3	1.29
48.2	59.8	84.3	1.41	1.07	90.2	1.51
50.8	63.0	93.6	1.49	1.07	100.2	1.59
53.9	66.8	118.0	1.77	1.06	125.1	1.87

Correction for Absorption.

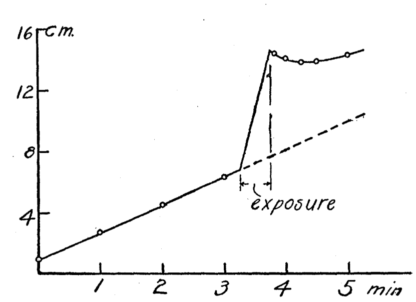

Fig. 2.

To determine the correction for the absorption in the screens which were in the path of the X-rays absorption curves were obtained for four different potentials. The results are shown in Fig. 3, Curves *A*, *B*, *C* and *D* corresponding to R.M.S. potentials of 50.8, 45.2, 39.5, and 31.6 K.V. respectively. These are plotted as percentage transmission against thickness of aluminum in millimeters. In the path of the rays was an aluminum screen .09 mm. thick and a cardboard screen .85 mm. thick. This latter was estimated to be equivalent to .08 mm. of aluminum. In Fig. 3 a line is drawn at the left of the axis at a distance corresponding

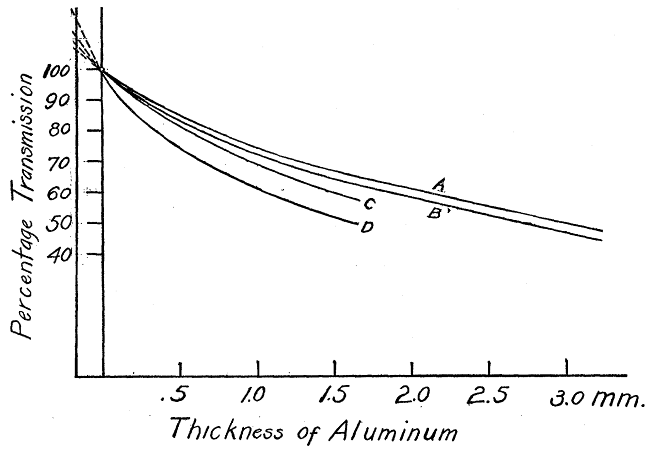

Fig. 3.

to .17 mm. and the absorption curves are continued to intersect this. The intercepts on this line give the correction factors for determining the total efficiency. The correction factors for intermediate potentials were found by interpolation. These values are given in the fifth column of Table I. In the seventh column are given the values of the total efficiency for the total energy outside of the tube. It is evident that no accurate estimate can be made of the energy absorbed in the walls of the tube.

Discussion of Results.

In Curve A of Fig. 4 is shown the variation of the efficiency, uncorrected for absorption, with the potential. In Curve B is shown the variation of the corrected efficiency with the potential. The shape of these curves is similar to that given by Carter.[6] It seems very possible that if correction for absorption in the tube could be made the efficiency might be found proportional to the potential as required by Beatty's formula (see p. 2). In Fig. 5 the efficiency is plotted against kilovolts squared, Curve A giving uncorrected values and Curve B the values corrected for absorption. From these it would seem that the X-ray energy emitted through the tube is nearly proportional to the cube of the potential. The fact that the photographic effect is proportional to the square of the potential, as found in practice, may be explained on the ground that the harder rays are absorbed to a less extent in the photographic emulsion and are also less effective because their wave-lengths are much less than those of the characteristic radiations of bromine and silver.

A comparison of the results given here with those obtained by other

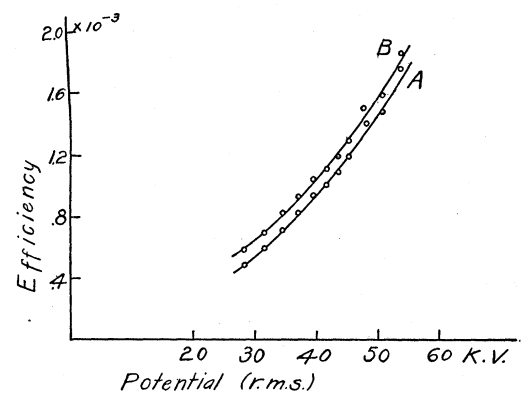

Fig. 4.

observers using the heating effect shows that the values of the efficiency are higher in general than those previously given. According to Rutherford and Barnes[12] Beatty's values should be divided by a factor of 2 or 3 for comparison with the other values given because in his experiment

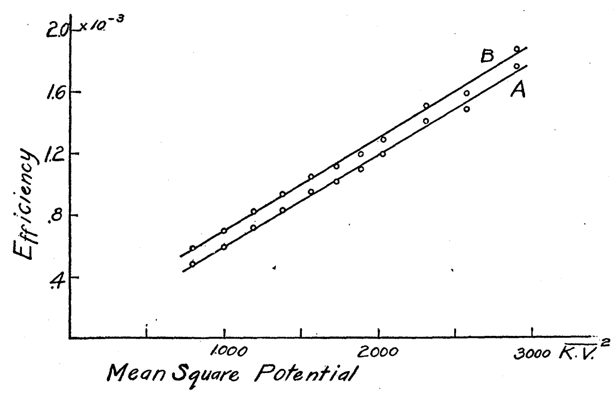

Fig. 5.

the X-rays did not pass through the glass wall of the tube but only through a thin aluminum window. Both Carter and Wien used an induction coil and measured the potential by means of a spark gap which would give very nearly peak values. It would seem that their values for

59 K.V. should be compared with a value given here for a potential between 40 and 50 K.V. On this assumption the results given here are somewhat below the corresponding results given by Wien and considerably above those given by Carter.

The values of the efficiency found are quite different from those found by ionization methods. The results given by Rutherford and Barnes are based on a value for the energy required to produce an ion which was determined from measurements with alpha rays. This was taken to be the same as the energy required to produce an ion by means of X-rays. A similar assumption is involved in Beatty's results, namely, that the same amount of energy is required to produce an ion by means of cathode rays as by X-rays. The work of Barkla and Philpot,[1] of Wilson[2] and of others[3] would indicate that ionization by X-rays takes place through the intermediate production of high-speed electrons. Hence the assumption made by Beatty seems justified if all the energy of the X-rays is given to these electrons. This has not been proven definitely. The work of Kleeman[4] indicates approximate proportionality between the ionization produced in different gases by alpha, beta and gamma rays. The work of Rutherford and Robinson[5] showed that in the case of alpha and gamma rays from radium C the heating and ionization were nearly proportional, although there were large errors involved. If this proportionality is accepted as established it would seem to justify the assumption made by Rutherford and Barnes in their determination of the efficiency of production of X-rays.

However if we compare the values for the energy required to produce an ion as found in this way and the values found by other means there are seen to be large discrepancies. A recent determination by Bishop[6] gives 1.67×10^{-10} ergs per ion, or one third of that given by Rutherford and Barnes, 5.1×10^{-11} ergs (33 volts). Using this value for the energy to produce an ion Rutherford's and Barnes's value for the efficiency of production of X-rays becomes $.2 \times 10^{-3}$ for 48 K.k. The value given by Eve and Day is based on an energy of 2×10^{-11} ergs per ion and is thus seen to be in fair accord with this as they used a somewhat lower potential. The value for ionizing energy obtained by Rutherford and McClung,[3] when corrected for the large value for "e" used by them, is 1.4×10^{-11} ergs per ion. The work of Rutherford and Barnes shows

[1] Phil. Mag., 25: 832.

[2] Proc. Roy. Soc., 87: 277.

[3] Bragg, "Studies in Radioactivity," Chapter 12. See also (14).

[4] Phil. Mag., 14: 618.

[5] Phil. Mag., 25: 312.

[6] Phys. Rev., 33: 325.

that at 48 K.V. there would be produced by a Coolidge tube 12×10^{13} ions per second per watt input. Using the value of efficiency found in the present investigation this would correspond to an X-ray energy of 1.5×10^4 ergs per second or 1.25×10^{-10} ergs per ion, a value nearly the same as that found by Rutherford and McClung by a similar method.

From these four investigations it would appear that the energy of the ions produced by X-rays is only a fraction of that emitted from the tube in the form of X-rays. To a less extent the same thing is true of alpha rays which appear to be more efficient than X-rays in producing ionization. These conclusions seem to contradict the evidence given by experiments with radioactive materials. To decide the point the heating effect and the total ionization should be determined simultaneously or under the same conditions.

SUMMARY.

The energy given out in the form of X-rays by a Coolidge tube has been determined by means of a bolometer. The values found lie between 20 and 125 joules per ampere-second for potentials between 28 and 54 K.V.

The energy supplied to the X-ray tube has been measured by its heating effect.

The ratio between the X-ray energy and the energy supplied to the tube, or the efficiency of production of the X-rays, has been found for these potentials. This ratio varies between 0.58 and 1.87×10^{-3}.

The X-ray energy is found to be nearly proportional to the cube of the potential across the tube.

A comparison of these results with those obtained by others on the total ionization produced by X-rays indicates that only a fraction of the energy of the X-rays is transformed into the energy of the ions produced on total absorption in air.

I wish to express my indebtedness to Professor J. S. Shearer and to other members of this department for suggestions and help given me and for the apparatus put at my disposal.

CORNELL UNIVERSITY,
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