THE ENERGY OF X-RAYS

By H. M. Terrill

Abstract

An apparatus is described to determine the total energy of x-rays from a tube by the conversion of this energy into heat. The x-rays are absorbed in a lead coil connected with a resistance thermometer bridge, and the amount of heat developed is determined from the current that must be passed through the coil to give the same temperature rise. The energy thus found is compared with the power input to determine the efficiency of the production of x-rays.

A tungsten target tube is excited by constant potential direct current at from 30 to 100 KV and the energy per unit solid angle is found to be 39 to 305×10^{-6} times the power supplied. This corresponds to an approximate total output of the tube of .00025 to .00192 times the input for the same range of voltages. Plotted against the square of the voltage these values give a straight line to 69.3 KV where a change of slope occurs, probably due to the selective absorption of the target itself.

Purpose of the Investigation

The purpose of the present investigation is to measure the total x-ray energy output of an x-ray tube by the conversion of this energy into heat. The energy thus found is compared with the power input to determine the efficiency. This problem is comparatively old, and a valuable summary of the early results is given by Weeks.[1]

In view of the importance of the problem, it is desirable to repeat and extend the measurements, using a tube excited with constant potential direct current. The voltage may be then measured directly by means of a high resistance multiplier. The power supplied the tube is subject to precise control and measurement, and furthermore the quality of the x-rays obtained is independent of any wave form.

Water-cooled Coolidge tubes are used, not only minimizing the possibility of heat leakages into the measuring apparatus, but also permitting higher current to be used with consequent increase in sensitivity.

Method

A bolometer, or resistance thermometer method is employed, the x-rays being converted into heat by absorption in lead. One of a pair of lead wire coils is exposed to x-rays, and the temperature rise determined by its change in resistance, the other coil occupying the opposite arm of the thermometer bridge for compensation. The amount of heat received from the x-rays is then determined by measuring the current that must be passed through the coil to give the same temperature rise.

[1] Weeks, Phys. Rev. **10**, 564 (1917).

The coils must be constructed so as to have as high a resistance as possible to insure sensitivity, and yet contain just sufficient lead to absorb all the x-rays that fall on them. This condition is secured by using a rather fine wire, No. 26 single silk-covered being about as fine as is convenient to wind.

The general shape and arrangement is shown in Fig. 1. The coils are of the pancake type, about 5 cm in diameter, and .28 cm thick and have a 1 cm hole in the center. They are wound to a resistance of 36 ohms per coil. The weight of one of the coils is 32 gm or 1.6 gm per cm^2 of area. That this is sufficient to absorb all radiation up to 100 KV is shown by the fact that no further increase is obtained by the use of a coil 30 percent thicker.

To shield the coils from outside radiation and to insure that temperature changes in the surroundings will affect them both equally, they are enclosed in a lead lined housing of heavy sheet brass with aluminum

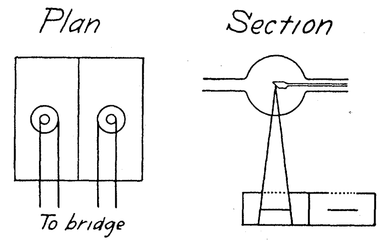

Fig. 1. Apparatus in position beneath x-ray tube.

windows. Save for the actual path of the beam of x-rays, the space within the housing is filled with wool batting, upon which the coils rest, separated by a lead partition. The windows are made of two sheets of .002 cm aluminum foil separated by a .5 cm air space, and there is also in the path of the rays another sheet of the same foil close to the tube, as well as a sheet of lens paper, both of which serve to cut down air currents. Thus, the total amount of material between the coil and the tube probably does not amount to more than 10 percent of the wall of the tube itself. The tube is contained in a lead covered box through which air is continuously circulated by a powerful blower. The efficiency of the shielding is high, blank runs being made to show that the bridge balance is not affected by temperature changes in the outside room, heat from the filament of the x-ray tube, nor from the body of the observer.

Extra precautions are taken to secure accuracy in measuring the distances of the coils and ionization chamber from the target of the tube. Pinhole photographs of the target are first made to locate the position of the focal spot, and the distance from the center of the focal spot to the measuring device is then determined with the aid of a cathetometer. A fluoroscope is used to center the measuring coil under the x-ray tube and to adjust diaphragms to limit the beam, so that, while the coil is completely radiated, very little radiation gets past its edges to cause error by scattering back upon it.

Some time before readings are made, the windows before the coils are closed by lead shutters, the x-ray tube switched on, and temperature conditions allowed to come to equilibrium. The bridge being balanced, if x-rays are allowed to fall upon one of the lead coils by opening the shutter, the galvanometer starts to move and, with an intense beam of x-rays, would in a minute or so be entirely off the scale unless resistance is continually cut in by means of the slide wire.

To determine the heat collected, the coil is radiated for a period of five minutes, readings being taken on the galvanometer or slide wire at half-minute intervals, after which the x-rays are shut off and the coil allowed to cool. It is then disconnected from the bridge by a mercury switch and current passed through it of such value, found by trial, as to give the same galvanometer deflections or slide wire readings within the same time intervals. The energy, computed by the I^2R relation, is assumed to be equal to the energy of the x-rays.

The total measuring current used is .012 amperes and is switched on for each reading only long enough to permit the galvanometer to come to rest, thus avoiding unnecessary heating of the coils.

Total Energy as a Fraction of the Input

A measurement of the energy of a definite quantity of x-rays implies that this definite quantity of x-rays is determined by some other method. There are two methods commonly used.

The heat energy may be determined as a fraction of the power supplied to the tube, thus leading to an idea of efficiency. This fraction is a function of the voltage and the measurements should be extended over a range of voltages. On the other hand, the heat energy may be measured of a beam of x-rays whose intensity has been determined by an ionization method. This leads to a determination of the ratio of ionizing effect to energy and the ratio being a function of the wave-length, the measurements should be made with monochromatic rays, and over a range of wave-lengths. Both methods are employed in the work with this apparatus and will be treated in separate articles.

For measurements of the total energy as a fraction of the input, which is the subject of the present investigation, a tungsten target tube is used.

The radiated coil is held at 27.3 cm from the target and subtends .027 units of solid angle, or 1/466 of the whole sphere.

The voltage is varied upward from 30 KV in steps of 10 KV. The current is adjusted so as to keep the output approximately constant. While preliminary runs show that the energy collected is proportional to the current through the tube, it is advisable to make all readings at approximately constant output. The lead coil then receives the same amount of heat each time, and errors due to heat losses, etc., affect only the absolute value of the results. In these measurements, this amount of heat is 39×10^5 ergs in a five minute period.

In Table I is listed for each voltage the fraction of the input radiated in unit solid angle. The third column gives the product of these values and 2π, being the energy that would be radiated were the intensity uniform over the lighted hemisphere. This is an approximation to the total amount of x-ray energy actually radiated from the tube. The next column gives the preceding multiplied by 2, giving approximately the total amount of x-rays produced at the target, including the energy in the dark hemisphere that is absorbed by the metal of the target.

TABLE I

Data on efficiency of x-ray tube

Voltage *KV*	Fraction of input in unit solid angle	Col 2 $\times 2\pi$	Col 2 $\times 4\pi$
30	39×10^{-6}	.00025	.00050
40	68 "	.00043	.00086
50	96 "	.00061	.00122
60	137 "	.00086	.00172
70	179 "	.00112	.00224
80	215 "	.00135	.00271
90	260 "	.00163	.00326
100	305 "	.00192	.00384

To investigate the general law followed by the values in column 2, they are plotted against the square of the voltage at *A* in Fig. 2. Up to 69 KV they lie quite closely on a straight line, there being but a slight deviation from this at the extreme low voltage end.

No corrections are made for the absorption in the walls of the tube. To throw further light on this point, the readings are repeated with interposed filters of one to three sheets of half millimeter aluminum, one of these sheets being roughly equivalent to the wall of the tube. The curves *B*, *C*, and *D* of Fig. 2 show the effect of these filters. It is seen that the filters have little effect on the general shape of the curve, all the points being lowered proportionately. Hence, by assuming that the wall of the tube has approximately the same effect as one of these filters, a visual estimate may be made as to what the curve would be, corrected for the absorption of the wall.

A downward change of slope occurs between 60 and 70 KV similar to an effect observed in the case of silver by Brainin.[2] A possible explanation for this may be found in the filtering action of the target itself. The face of the target stands at an angle of 70° to the direction of the cathode and 20° to that of the measuring apparatus. Hence, in all cases, the x-rays pass through more than twice as much tungsten as the cathode rays that produced them and this distance may be enormously increased by the presence of small pits and scratches in the face of the target. The sudden increase of the absorption above the K limit would thus affect the radiation produced at voltages over 69.3 KV, and so account for the change of slope at this point.

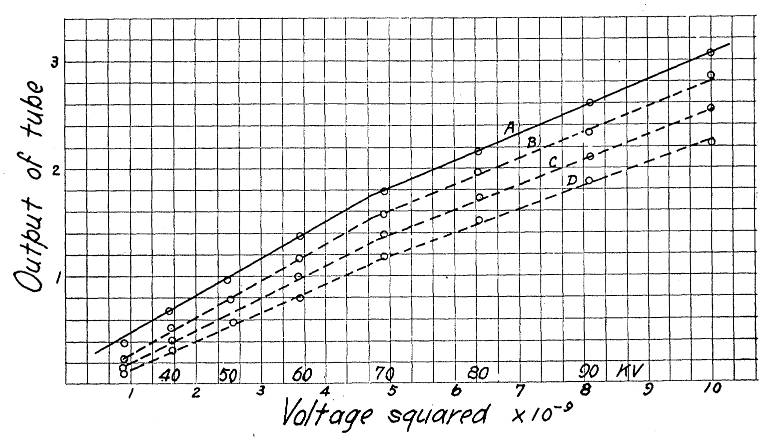

Fig. 2. Output as a function of the square of the voltage. The dotted lines represent effect of aluminum filters.

If this explanation be correct, the effect should decrease if the target stand at a sharper angle to the beam of cathode rays or the radiation be measured in a direction nearer the normal to the surface of the target. It is hoped to investigate this point in further experiments.

The present results are in agreement with the work of Ulrey[3] who found, by integrating curves obtained with a spectrometer, that the total emission of tungsten was proportional to the voltage squared, between the limits 20 and 50 KV.

[2] Brainin, Phys. Rev. **10,** 461 (1917).
[3] Ulrey, Phys. Rev. **11,** 401 (1918).

There is also very good agreement in absolute value with the results of Weeks,[4] who worked from 28 to 54 KV. It should be pointed out that x-ray tubes differ in output and too much importance should not be attached to exact agreement of the absolute value.

As shown by Coolidge,[5] a certain proportion of the radiation comes from the back and stem of the target, due presumably to electrons reflected or splashed out of the face, and this proportion may vary with the size and shape of the target, the cathode distance, the size of the focal spot, and the size and shape of the glass bulb, and even with the location of surrounding external objects such as shields and supports in so far as they affect the field within the tube.

The condition of the surface of the target as well as the angle at which it is inclined to the beam of cathode rays are also factors of the efficiency, a pitted or cracked surface increasing the filtering effect due to the target itself, and so decreasing the amount of energy radiated.

The absolute value of the efficiency is thus seen to be dependent to a certain extent upon the design and condition of the tube. To estimate how closely the present values approximate the ideal efficiency requires a rather elaborate discussion which will be made the subject of a future article in which it is hoped also to extend these results to higher voltages.

Besides comparing the total energy with the power input, it may be compared with the ionization in air. This work is at present partially completed and the results will be published shortly.

This series of investigations of the energy of x-rays were undertaken at the suggestion of Dr. Francis Carter Wood, and have been made possible by his development of a high voltage x-ray laboratory.

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June 15, 1926.

[4] Weeks, *loc. cit.*, p. 570.
[5] Coolidge, Am. Jour. Roent. **2,** 882 (1915).