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# THE HEAT ENERGY OF X-RAYS

BY ROY KEGERREIS

ABSTRACT

**Efficiency of a tungsten-target Coolidge x-ray tube operated at peak voltages from 100 to 200 kv.**—The efficiency of x-ray production was experimentally determined for voltages between one and two hundred kilovolts. The high voltage energy input into the x-ray tube was measured by means of an absorption calorimeter. The intensity of the x-rays was measured by means of the temperature rise of a lead absorption cup arranged so that the effects due to scattering and fluorescence of the x-rays as well as effects due to external temperature conditions were eliminated. Elaborate precautions were also taken to suppress electrostatic and electromagnetic induced effects from the high voltage circuits. The efficiency was found to be proportional to the peak voltage. The factor of proportionality was 0.0032 when the efficiency is expressed in percent and the peak voltage in kilovolts.

## I. INTRODUCTION

THE purpose of the present investigation is to extend our knowledge of the efficiency of x-ray production to the region of high voltage x-rays, 100–200 kv. The general problem of the efficiency of x-ray production has been examined by others, notably by Weeks[1] in 1917, in whose paper an excellent summary of the work prior to that date is given. Since then Ulrey[2] and Kuhlenkampff[3] have also examined the problem. However, the two latter writers used an ionization method to determine the energy of the x-rays. Boos[4] has shown that the ionization is not strictly proportional to the energy absorbed when different wave-lengths are compared. A more reliable method is to measure the heating effect as was done by Weeks. The most recent work on the heat energy of x-rays is by Terrill[5] who has extended the measurements to x-rays excited by a potential of 100 kv. Since much of present day therapeutic work is done with x-rays from a tube excited at 100 to 200 kv it is worth while to extend the measurements to x-rays of such penetrability.

## II. METHOD AND APPARATUS

In measuring the energy of x-rays care must be taken that none of the energy of the primary beam disappears in any form other than in heat energy absorbed in the calorimeter. This is done by causing the x-rays to pass into a deep cylindrical lead cup. Under these conditions the reflected, scattered and fluorescent x-rays as well as the beta-rays produced by the

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

[2] Clayton T. Ulrey, Phys. Rev. **11**, 408 (1918).

[3] Helmuth Kulenkampff, Ann. d. Physik, **69**, 548 (June 9, 1922).

[4] B. Boos, Zeits. f. Physik **10**, 1 (1922).

[5] H. M. Terrill, Phys. Rev. **28**, 431, (September, 1926).

primary x-rays are finally absorbed in the lead cup. A diagram of the calorimeter is presented in Fig. 1. The cup was made of lead 1.6 mm thick; such a thickness of lead will absorb at least 99 percent of the x-rays. The x-rays entered the cup through a circular aperture in a lead shield above the absorbing cup. The diameter of the aperture was 4.92 cm. The solid angle subtended by the aperture at the focal spot of the target of the x-ray tube was 0.000622. Four copper coaxial cups surrounded the lead absorbing cup in order to shield it from external temperature changes. Temperature measuring coils and rheostat heating coils are wound on these cups so that their temperatures might be determined and controlled. The resistance of each of the temperature measuring coils was about 107 ohms. The outermost cup *C* formed the inner wall of an oil bath which contained about six gallons of transil oil. It was necessary to have a window in the cover of each cup in order to allow the x-rays to enter without undue absorption. All windows were covered with a double thickness of aluminum foil (0.0025 cm thick) with one sheet of the thin paper (1.7 milligrams per sq. cm) between them. The pieces of aluminum foil were closely clamped to the covers of the cups so as to insure good thermal contact. One of the intermediate cups was made with the top and bottom three millimeters thick, the cylindrical walls were double and the intervening space was filled with water. The conductivity and heat capacity were accordingly rather large. The surfaces

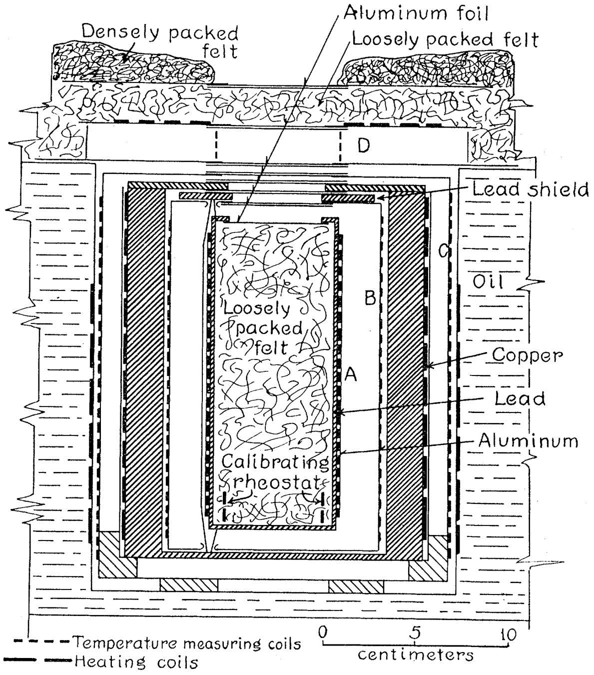

Fig. 1. Diagram of the calorimeter.

of all the cups were polished by buffing. The case which contained the system of cups was covered with two thicknesses of hair felt, one inch thick as shown in Fig. 1.

The entire success of the experiment depends on the maintenance of reproducible temperatures in and about the coaxial cups. The thermal conditions must be constant for all runs. It would be ideal to have exact temperature equilibrium throughout the system of coaxial cups but such a condition is exceedingly difficult to attain because of the very long time required for the heat transfers to take place. It was accordingly decided to set up exactly the same small temperature differences between the various parts at the start of each run. The temperatures of the inner parts were held slightly higher than that of their surroundings. All the parts of the apparatus were maintained at a constant temperature throughout a run except the three inner cups; the absorbing cup warmed up because of the absorption of the x-rays and the two cups immediately exterior to it were warmed by manually controlled heating currents through resistance coils. The conditions were thus nearly but not exactly those of thermal equilibrium.

A small coil (70.70 ohms resistance) which was wound with wire of negligible temperature coefficient of resistance was permanently placed in the bottom of the absorbing cup for calibrating purposes. Heating currents were sent through this coil for one minute out of each five while a calibration was being made.

A Snook Special x-ray machine was used as a source of high voltage. This machine gives a pulsating direct current of 120 pulses per second. As is well known this pulsating current causes static and leakage effects on any other electrical circuits which may be near. Much shielding and non-inductive winding of all coils was employed to minimize these effects but the total elimination of such influences from the results was accomplished only by operating the x-ray tube during an initial period of from one to four hours while equilibrium for constant temperature was being set up, with the residual of all the disturbing influences present. An actual measurement of the heat energy in x-rays was begun by removing a thick lead cover from the orifice in the bottom of the lead-lined box containing the x-ray tube, thus permitting the x-rays to enter the absorbing cup. No changes in the connections were made in the high voltage or Wheatstone bridge circuits when this piece of lead was removed. Constant electrical conditions during the initial period as well as during the run itself were thus unquestionably assured.

The target of the x-ray tube was of tungsten and during the part of the experiment in which the heating effect of the x-rays was being determined the tube was operated in an air space, in a box lined with lead one-fourth inch thick. Electric fans caused currents of air to circulate through the box and over the container of the absorbing cup and about the room generally. Three barriers of thin aluminum foil (0.0025 cm thick) were placed between the target and the box which contained the lead absorbing cup. During a particular run the peak voltage remained constant and was measured by means of a sphere gap in air. The current through the tube was maintained at 4 milliamperes during all runs.

The intensity of the beam of x-rays was corrected for the absorption which takes place in the glass of the x-ray tube. The absorption was determined from measurements taken with an ionization chamber and a gold leaf electroscope of rays which had passed through a second x-ray tube of the same type. The square root of the fraction of the x-rays transmitted through the two thicknesses of the glass gives the fraction transmitted through one thickness. No correction was made for the absorption by the various thicknesses of aluminum foil. It is a negligible factor in the work since the total thickness is less than 0.05 cm. The absorption by the 40 cm of air which was between the x-ray tube bulb and the absorbing cup was also neglected.

It has been pointed out by Weeks that the high voltage current in an x-ray tube does not follow a sine curve and that therefore the power input cannot be calculated directly from voltmeter and ammeter readings. Weeks determined the power input by measuring the heat produced in the x-ray tube by the bombardment of the target by electrons from the filament. This method was used in the present investigation. The power input was not measured at the same time as the heating effect of the x-rays. Instead a separate experiment was devised to measure the power input when the x-ray tube was operated at each one of a set of different peak voltages and a current of 4 milliamperes. This was accomplished by immersing the x-ray tube in a tank containing 45 gallons of oil The tank was made of wood lined with $\frac{1}{8}$ inch (3.2 mm) lead. The outside of the tank was covered with two layers of hair felt one inch thick. During a run the oil in the tank was kept stirred. The temperature rise per hour for a given voltage on the tube was determined by a mercury in glass thermometer. Correction was made for the heat produced by the filament current by running the filament with no production of x-rays. A curve was then plotted between the temperature rise per hour produced by the bombardment of the target with electrons and the peak voltage. Next a heating coil was placed in the oil and a curve plotted of the temperature rise per hour of the oil tank and the watts input. From these two curves it was possible to determine the relation between the power input into the tube and the peak voltage, the current always being kept at 4 milliamperes.

## III. Experimental Results

Typical curves for the heating effect of the x-rays are shown in Fig. 2a. The horizontal portions of the curves (Fig. 2a) represent readings before the x-rays were allowed to enter the absorbing cup, while the sloping portions represent readings when the x-rays were entering the cup. The slope of the rising part of each curve gives a measure of the power absorbed. The slope is expressed in increase in resistance in ohms per hour. The watts computed from the calibration curve of the lead absorbing cup (Fig. 2b) are a measure of the intensity of the x-rays which pass into the absorbing cup. The actual x-ray energy emitted by the focal spot into the absorbing cup is secured by correcting the value for the absorption in the glass of the x-ray tube and also for the shape of the curve for angular distribution of intensity. The total x-ray emission is then secured by multiplying this corrected value by the ratio between the total solid angle about the target and that subtended by the aperture above the absorbing cup. The final results are presented in Table I and in Fig. 3.

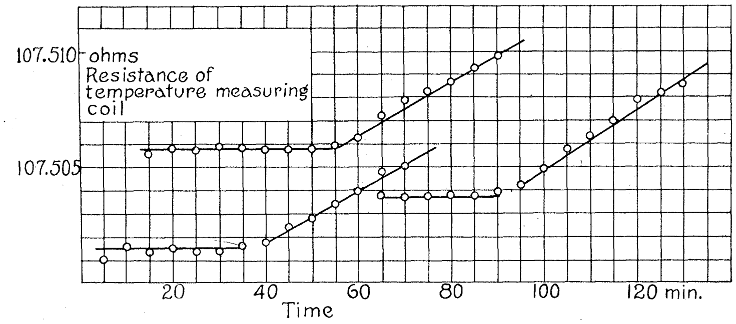

Fig. 2a. Showing the increase in temperature of the calorimeter after the x-rays are allowed to enter.

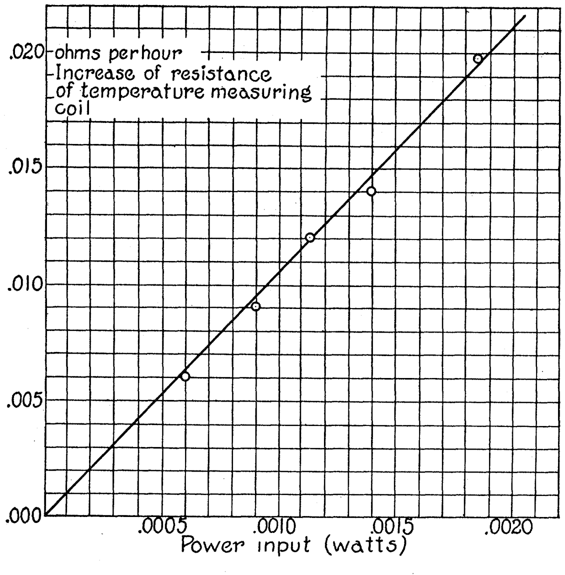

Fig. 2b. Calibration curve for the lead absorbing cup, showing the relation between the power input and the rate of increase in temperature.

In Fig. 3 a curve is plotted between the figures in the third column and the square of the peak voltage. It will be seen that the points fall approxi-

TABLE I

*Heat energy of x-rays.*

| Peak kv. | High voltage input (watts) | Power of x-rays in unit solid angle (watts) | $\frac{\text{Column 3}}{\text{Column 2}}$ | Efficiency<br>Column 4 ×2π | <br>Column 4 ×4π |
|---|---|---|---|---|---|
| 98.5 | 270 | 0.0796 | 0.000295 | 0.18% | 0.37% |
| 124.5 | 335 | .101 | 302 | .19 | .38 |
| 143.3 | 383 | .137 | 359 | .22 | .45 |
| 161.9 | 425 | .175 | 413 | .26 | .52 |
| 178.8 | 462 | .203 | 440 | .27 | .55 |
| 196.3 | 499 | .222 | 445 | .28 | .56 |

mately on a straight line, showing that the x-ray output varies nearly as the square of the applied voltage. Comparing the above figure for the efficiency at 98.5 kv with that obtained by Terrill at 100 kv it is seen that the two results are in fairly good agreement. The fifth column gives the ratio of output to input supposing the intensity to be uniform over the hemisphere exposed to radiation. This is an approximation to the energy actually radiated as x-rays from the tube. The next column gives the preceding multiplied by 2. These are the efficiencies when the x-ray energy absorbed by the target is included in the output. The figures in column 3 are for radiation in the direction of maximum intensity which was only one percent higher than the intensity in a direction perpendicular to the axis of the tube and at an angle of 45° to the target.

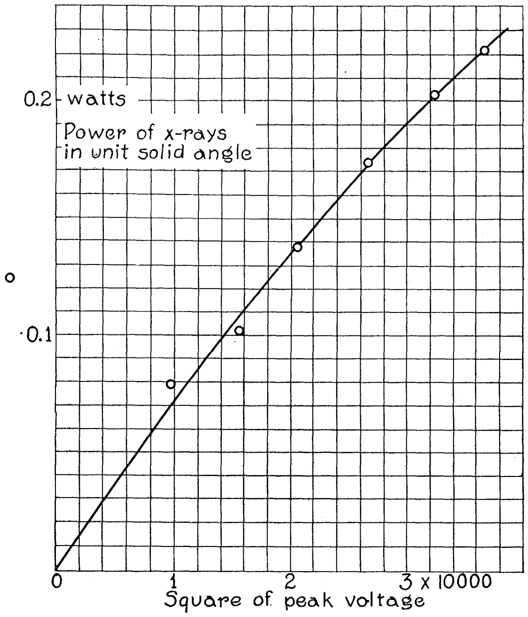

Fig. 3. Variation of the power of the x-rays with the square of the peak voltage.

It has been shown that the x-ray output varies nearly as the square of the applied voltage. Such a conclusion is also arrived at by Brainin,[6] Ulrey[2] and Kulenkampff[3] who used entirely different methods of measurement.

The values of the efficiency would be considerably increased if the very soft x-rays, which are completely absorbed by the glass of the x-ray tube and the air, were taken into account. (It is to be pointed out that the corrections which were made for the absorption in the walls of the tube apply only to those rays which are transmitted.) The efficiencies that have been found are based on a uniform intensity throughout the total solid angle which surrounds the target. Such an efficiency may be approached in apparatus as a limiting case.

The experiments upon which this report is based were performed in the Physics Laboratory of the University of Michigan.

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December 11, 1927

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[6] C. S. Brainin, Phys. Rev. **10**. 461 (June, 1917).