THE ENERGY OF HIGH VELOCITY ELECTRONS*

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ABSTRACT

Precision determination of the energy of high velocity electrons.—The *total heat generated in an x-ray tube* operated at potentials up to 25,000 volts was measured by immersing a Coolidge x-ray tube of the water-cooled type in an oil bath and noting the temperature rise of the oil for a precisely measured energy input. The current and voltage furnished to the tube by a high potential d.c. source were kept constant and were continuously measured by potentiometers. The heat energy given up to the oil by this "high potential" source was compared with that developed by the same quantity of "low potential" energy by taking alternate runs wherein the same potentiometers measured the current and voltage supplied from a storage battery to a heating coil immersed in the oil. The data proved with a probable error of about 0.2 percent, that, up to 25,000 volts, all of the energy input into a Coolidge tube is ultimately transformed into heat and that any sources or sinks of energy which may exist have a smaller effect than 0.2 percent. Ionization, photographic and pyrometric methods were used to test for the presence of radiations involving an *absorption of energy at the cathode.* No appreciable quantity of such energy could be detected. The results of these experiments indicate that all of the input energy must go into the energy of the moving electrons and their fields. It also follows that only a negligible portion of the current in a Coolidge tube is furnished by positive ions which actually reach the cathode, for otherwise the cathode would be heated.

INTRODUCTION

In much work[1] involving the motion of electrons under the influence of high voltages it has been tacitly assumed that all of the input energy goes into the energy of the moving electrons and their fields and that this energy reappears later, in exactly equal amount, whenever the electrons are stopped. This assumption has never been verified for electrons moving with speeds sufficiently high for the relativity variation in mass to be appreciable. It is quite conceivable that the heat energy output from an x-ray tube might be either more or less than the energy input. For example, any atomic or molecular change brought about by electronic bombardment might result in a release or absorption of energy.

In the present experiments a measure of the energy of a stream of electrons with velocities up to 25,000 equivalent volts was obtained by

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[1] Hupka, Ann. d. Physik **31**, 169 (1910); Jones and Pomeroy, Phil. Mag. **45**, 760 (1923), also Phys. Rev. **8**, 52 (1916); Guye and Ratnovsky, Comptes Rendus **150**, 326 (1910), also Arch. des Sciences **31**, 293 (1911), also Comptus Rendus **161**, 52 (1915); Guye and Lavanchy, Arch. des Sciences **42**, 286 (1916).

determining the heat developed by their impact upon the anti-cathode of an oil-immersed Coolidge x-ray tube of the water-cooled type. The heat thus generated by this "high potential" source was compared with that developed from the same amount of "low potential" energy, obtained by supplying current from a 25 volt storage battery to a resistance coil immersed in the oil bath. A second series of experiments was made to determine whether there was an appreciable absorption of the input energy at the cathode.

The design of the kenetron by Dushman[2] and its application to the generation of high tension continuous current (d.c.) by Hull[3] has made the technique of the production and precision measurement of powerful high voltage direct current comparatively simple. The accuracy of much of the older work involving high potential current has been limited by the well-known uncertainties of spark-gap measurements of voltage. In recent years this error has been greatly reduced by determining the voltage from direct measurements of the current through a known high resistance which is placed in parallel with the apparatus under investigation.

Description of Apparatus

The high potential continuous current was obtained by rectifying the current from a transformer, using a kenotron rectifier and condenser-inductance filter system. The arrangement of the apparatus is shown in Fig. 1. The transformer was supplied with power from a 500 cycle alternator, which was driven by a d.c. shunt motor. The latter was operated from a 120 volt storage battery, an arrangement which gave an exceedingly steady source of voltage. By properly varying the resistance in the alternator field circuit, any desired value of voltage could be obtained.

The condensers had a capacitance of about 0.1 mf each and the inductance was about 25 henries for the conditions under which it operated. From both calculation and experimental observation, the effect of the "ripples" on the d.c. voltage wave was found to be negligible, being less than 1 percent of the total voltage.

A resistance of approximately three megohms was placed in parallel with the x-ray tube. The resistance was especially designed for this purpose and was made of "advance" wire, whose temperature coefficient of resistance is very small. The value of the resistance was measured by a Wheatstone bridge, which had just been calibrated by the Bureau of

[2] Dushman, G. E. Rev. **18,** 156 (1915).

[3] Hull, G. E. Rev. **19,** 177 (1916); also Phys. Rev. **7,** 405 (1916).

Standards. Tests indicated that the special winding which was used made the resistance coil practically non-reactive. The voltage across the coil and tube was obtained by multiplying the resistance of the coil by the current through it. The latter was precisely measured and kept constant by a Leeds and Northrup type K potentiometer, which read the voltage drop over a standard 10 ohm resistance, placed in series with the 3 megohm coil. The current through the tube was measured by a second and similar potentiometer. (The milliammeters shown in the figure were introduced for securing preliminary adjustments.)

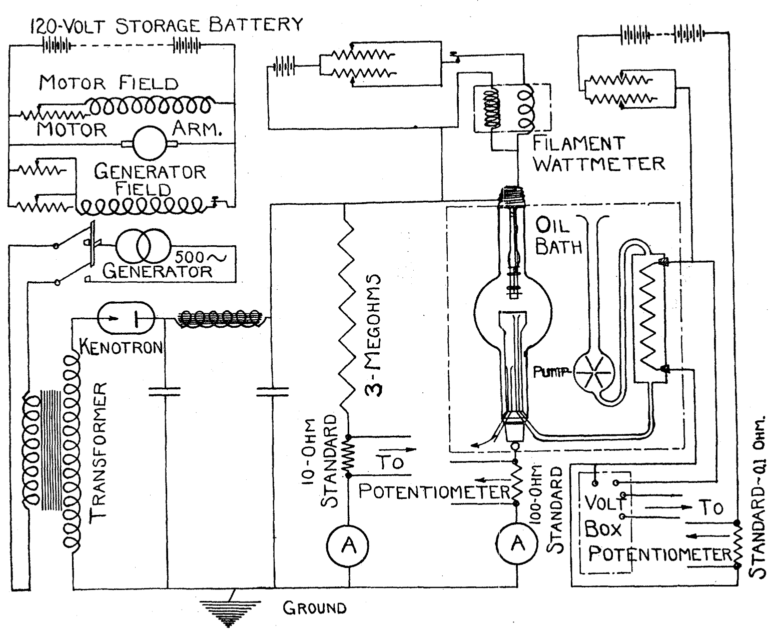

Fig. 1. Arrangement of apparatus.

The power supplied to the filament of the tube from a 12 volt storage battery was precisely measured by a specially designed Weston wattmeter, read by a telescope. A suitable arrangement of rheostats in parallel made it possible to adjust this power to the desired value and to keep it constant at that value with a precision of about 0.2 percent. The entire arrangement of filament battery, rheostats and wattmeter was enclosed in a metal case, in order to minimize corona and electrostatic effects in the wattmeter.

The x-ray tube was a standard, broad-focus, molybdenum-target, Coolidge tube of the water-cooled type. It was mounted vertically in a bath of transformer oil contained in a tin-plate lined box. The box was heat-insulated from its surroundings by layers of cork-board about 7.5 cm in thickness. The oil was forced through the anode by a pump which was driven by a motor whose speed, as shown by a tachometer, was held constant. The heat generated by the action of the pump was thus practically constant for all runs. This fact was repeatedly checked by observations. The oil intake to the pump was near the top of the bath and the exhaust of the heated oil from the target of the tube was near the bottom, so that the convection currents thereby set up in the oil, together with the stirring action of the pump shaft, kept all portions of the oil at nearly the same temperature. Measurements indicated that the maximum difference in temperature between any two points in the oil was only a few tenths of a degree.

A heating coil contained within a Pyrex tube was inserted in the pipe leading from the pump to the x-ray tube, the arrangement being such that the heat generated by this "low potential" coil was given up to the oil in much the same manner as during the "high potential" runs when the x-ray tube was operated. This was in order that the effects of thermal "radiation" would be approximately the same for the two types of runs. Current was supplied to the heating coil from a 25 volt storage battery, the value being accurately measured and kept constant by a potentiometer arrangement, using one of the potentiometers mentioned above. The voltage across the coil was measured with the second potentiometer, by the use of a "volt box."

Method of the Measurements

In order that the experimental conditions might be as nearly alike as possible on different days, no runs were made until the temperature of the room and calorimeter oil had reached approximately the same value, which was practically identical for the various observations. Before turning on the power, the pump was operated at constant speed for an hour or more, observations being taken of the temperature of the oil to determine the rate at which the pump itself was heating the oil. This "pump rate" remained practically constant for the various runs. Repeated observations indicated that comparatively large variations of room temperature had very little effect on the rate of heating of the oil during a run.

The oil temperatures were determined from the readings of two Centigrade thermometers, which were read through telescopes to 0.01 degree. The calibrations of the thermometers were only roughly checked, as we were interested only in the comparative temperature changes for different runs and not in the absolute value of the heat generated.

The experimental procedure consisted in applying the high potential to the x-ray tube for 60 minutes, keeping the voltage across the tube and the current through it constant. This was accomplished by balancing the potentiometers, and, with the galvanometer keys closed, keeping the spots of light from the galvanometer mirrors near the zeros of the scales by means of properly adjusting the resistances in the field of the alternator and in the tube filament circuit, respectively. By this method both the current and the voltage could be kept constantly at the desired value with considerable precision. The temperature of the oil was noted every 5 minutes. At the end of 60 min. the power was turned off and the temperature observations continued for 30 min. with the pump running at the same speed. This was in order to be sure that the contents of the box would reach an equilibrium temperature. Having added the power consumed by the filament to the "high potential" power, the temperature rise of the oil per watt of power was calculated for final temperatures taken 10, 15, 20 and 30 min., respectively, after the power had been shut off. Similar observations were then taken on alternate days with a

TABLE I

Temperature rise per unit power, using final temperatures taken 10, 15, 20 and 30 min. respectively after power was turned off. Each value (multiplied by 10^4) is expressed in degrees Centigrade per watt.

Voltage	10 min.	15 min.	20 min.	30 min.
10 kv.	1242	1216	1199	1168
	1242	1217	1200	1167
	1247	1224	1204	1170
	1242	1221	1199	1169
	1259	1238	1218	1183
	1247	1223	1204	1172
	1261	1236	1217	1183
Means	1249	1227	1206	1173
15 kv.	1249	1224	1210	1179
	1247	1226	1206	1174
	1266	1242	1223	1193
	1251	1227	1210	1178
	1253	1229	1207	1176
	1255	1233	1209	1176
Means	1253	1230	1211	1178
20 kv.	1256	1233	1215	1184
	1256	1227	1208	1174
	1246	1225	1205	1172
	1244	1220	1201	1166
	1254	1232	1213	1182
	1253	1229	1210	1175
	1256	1234	1215	1182
Means	1251	1229	1210	1177

Voltage	10 min.	15 min.	20 min.	30 min.
23 kv	1249	1228	1207	1177
	1253	1227	1210	1178
Means	1251	1228	1209	1177
25 kv	1256	1234	1213	1180
	1258	1237	1217	1185
	1258	1232	1213	1179
Means	1257	1234	1214	1181
Low potential	1252	1233	1214	1176
	1242	1219	1198	1163
	1246	1224	1203	1172
	1261	1234	1216	1183
	1263	1239	1221	1189
Means	1253	1230	1210	1177

different voltage (ranging from 10–25 kv) applied to the tube and the current through it proportionately changed, so as to keep the total power approximately constant. This was in order that the temperature rise of the oil would be practically the same for the different runs; thus the effects of heat "radiation" would be similar in each case. The filament power was about 25 watts and the "high potential" power about 150 watts.

The data obtained from the last 30 runs that were made are summarized in Table I and a résumé of the data in Table II. About 100 runs were taken previous to these here reported. While these former runs were not as precise as those reported, the results obtained do not differ materially from the ones herewith presented.

Alternating with the "high potential" observations were runs taken with the same quantity of "low potential" energy supplied from the resistance coil to the oil bath, as described above. During these observations the filament was operated at about the same power as in the high potential runs and other conditions were also kept the same, so that the results of the two types of runs are strictly comparable. The data thus obtained are included in Table I.

TABLE II

Résumé of data in Table I

Time	High Potential						Low Potential
	10 kv.	15 kv.	20 kv.	23 kv.	25 kv.	Average	
10 min.	1249	1253	1251	1251	1257	1252	1253
15	1227	1230	1229	1228	1234	1230	1230
20	1206	1211	1210	1209	1214	1210	1210
30	1173	1178	1177	1177	1181	1177	1177
Means	1217	1218	1217	1218	1221	1217	1217

DISCUSSION OF RESULTS

It will be observed from the data that the rate of heating per watt of power supplied is practically the same at the different voltages. This indicates that the energy of the electron stream is given by the usual energy relations, at least in the voltage range investigated, namely from 10 kv to 25 kv. The precision of the experiments was such that any systematic variation from the ordinary energy relations greater than 0.2 percent could have been observed. Such a variation would have manifested itself in a systematic increase or decrease in the temperature rise per watt as the voltage was changed. Inasmuch as there was not the slightest indication of any such variation, it was deemed inadvisable to continue the observations at higher potentials, on account of the difficulties which would have been encountered in making precision measurements of current and voltage, due to corona, insulation leakages, etc.

The fact that the rate of heating per watt from the "low potential" source was the same as that from the "high potential" source is equally conclusive proof that the energy equations are identical for high and low potentials. (The exact equivalence of the means for the high and low potentials was of course only accidental, though the experimental uncertainties were not large.)

It may be noted that the energy of the x-rays which were generated was also given up to the oil since these rays were totally absorbed by the oil and tinplate lining of the box containing the oil.

The immediate conclusions to be drawn from the data are that they not only constitute a proof of the principle of the conservation of energy, i.e., $Vit = JH$, for high velocity electrons, but also that no appreciable atomic or molecular changes involving an emission or absorption of heat are brought about in molybdenum, copper or glass when bombarded by electrons possessing an energy obtained from a potential difference of 25,000 volts. Furthermore, when taken in connection with the experiments described below, the data offer evidence that all of the input energy goes into the energy of the moving electrons and their fields.

We may classify as follows the forms into which the input energy might go: (1) Energy of the moving electrons and their fields, and subsequent development of heat and radiation at the anti-cathode and walls of the tube when the electrons are stopped; (2) Heat developed at the cathode due to positive ion bombardment; (3) Absorption of energy at the cathode, due to removal and acceleration of electrons; this would presumably show up either as rise in temperature of the cathode or radiation from the same or both; (4) Atomic or molecular changes at the cathode or anode or even slow transmutation of the atoms of the anode; this might cause either a source or sink of energy. A balanced source and sink would be difficult to account for, especially when cathode and anode are of different elements, as is the case in the experiments described.

Ionization and photographic methods were used in experiments[4] to study the possible radiations from the vicinity of the cathode of an x-ray tube. While certain feeble radiations were observed, their intensity and quality were such as to indicate that they were due to scattering of the primary beam. No appreciable portion of the total energy could be ascribed to such radiations.

An absorption of energy at the cathode due to positive ion bombardment would result in a rise in temperature of the same. To test this

[4] Performed by Mr. D. L. Harmon and others.

possibility, observations were made to determine whether there was an abnormally increased emission of heat at the cathode when the high potential was suddenly applied between the heated filament and the anode. A Féry radiation pyrometer was focused on the cathode filament and connected to a sensitive galvanometer. No change in the temperature of the filament could be observed when the high potential was repeatedly thrown on and off, although the sensitivity of the pyrometer and galvanometer was such a difference in the temperature of the filament could be observed caused by an adjustment of the filament current too small to be detected on the filament wattmeter. The entire absence of temperature change at the cathode when the high potential is thrown on and off is evidence that no appreciable part of the total energy input goes into a sink or source at the cathode.

Additional evidence that no energy is released at the cathode was obtained by closely watching the pointer of the filament wattmeter as the high potential was thrown on and off. The absence of any movement of the pointer proved the constancy of the filament temperature, for with constant voltage applied to the filament the power which it consumes is inversely proportional to its resistance and the latter is a function of its temperature. The sensitivity of the wattmeter was such that a movement of the pointer corresponding to a change of 0.02 watt (0.1 percent) would have been detected. We may therefore say with confidence that less than 0.1 percent, if any, of the heat generated in a Coolidge tube by the electron stream is released at the cathode. Hence the input energy must be carried by the electron stream itself.

Other experiments,[5] to be described more fully in a later paper, show that the energy of the cathode ray stream is not all given up at the target of the tube. Because of the "reflection" of electrons at the anode (which also includes secondary emission) the fraction of the energy of the cathode ray stream received at portions of the tube other than the target varies from 20 percent at 1.3 kv to a maximum of 22.5 percent at 4 kv and then falls off to 3 percent at 15 kv, where it remains approximately constant up to 30 kv.

CONCLUSIONS

These experiments indicate that all of the energy input into an x-ray tube goes into the moving electrons and their fields. Furthermore it is shown that, within 0.2 percent or less, this energy is as completely given up when the electrons are arrested, i.e., that $Vit=JH$ for electrons moving with velocities up to 25,000 equivalent volts. This shows, within

[5] Ham and White, Phys. Rev. **27**, 111 (1926); also Phys. Rev. **27**, 510 (1926).

the limits mentioned, that there are no atomic or molecular changes involving a source or sink of energy in a Coolidge tube at 25 kv. It also follows that only a negligible part of the current in a Coolidge tube is furnished by positive ions reaching the cathode, for otherwise the cathode would be heated a measurable amount. The heat received at the target of a water-cooled Coolidge tube may be only from 75 to 97 percent of the total energy input, the remainder of the energy being dissipated at the walls of the tube as a result of their bombardment by "reflected" electrons.

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