Second Series *December, 1913* *Vol. II, No. 6*

THE

PHYSICAL REVIEW.

A POWERFUL RÖNTGEN RAY TUBE WITH A PURE ELECTRON DISCHARGE.

By W. D. Coolidge.

§ 1. Introduction.

In an earlier publication attention has been called[1] to the use of wrought tungsten for the anticathode, or target, of a Röntgen tube of the ordinary type. In the development of this target many different designs were made and mounted in tubes, and these tubes were operated on what was then the most powerful Röntgen apparatus on the market, a 10 K.W. transformer coupled to a mechanical rectifying device. The operation of tubes in this manner, to see how much energy it took to ruin the target, gave perhaps an unusual viewpoint. When, as a result of these experiments, a satisfactory form of target had been developed, the writer became interested in studying the remaining limitations in the tube. Some of these limitations are the following:

1. With low discharge currents the vacuum gradually improves, with a consequent increase in the penetrating power of the rays produced.
2. With high discharge currents there are very rapid vacuum changes, sometimes in one direction and sometimes in the other.
3. If a heavy discharge current is continued for more than a few seconds the target is heated to redness and then gives off so much gas that the tube may have to be reëxhausted.
4. If the temperature of the standard copper-backed target is allowed to get up to bright redness, a rapid deposition of metallic copper begins to take place on the bulb, continuing for some time after the cutting off of the current, owing to the very slow rate of cooling from such temperatures in the evacuated space.
5. Of the tubes tested, very many have failed from cracking of the

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[1] Coolidge, Trans. Am. Inst. E. E., June, 1912, pp. 870–872.

glass, and this, with one exception, always at the same point; that is, in the zone around the cathode. In many cases there has first been chipping-out of the glass from the inner surface of the tube at this point.

6. The focal spot on the target in many tubes wanders about very rapidly.[1] In many cases where it does not show a tendency to wander, it will be found after a heavy discharge to have permanently changed its location.

7. While it is relatively easy to lower the tube resistance by means of the various gas regulators, it is a relatively slow matter to raise it much.

8. With very heavy discharges, the central portion of the usual massive aluminum cathode melts, and the molten globules so formed are shot right across the tube, flattening themselves out on the glass and sticking to it. When the melted area is small, no harm is done except that the curvature of the cathode at this point may be changed, and the focal spot may, in consequence, be moved.

9. No two tubes are exactly alike in their electrical characteristics.

10. The characteristics are in general far from ideal, in that the penetrating power of the Röntgen rays produced, changes with the magnitude of the discharge current.

11. When operated on a periodically intermittent current, even though it be of constant potential, the tube, of necessity, gives a very heterogeneous bundle of primary Röntgen rays, for the reason that the break-down voltage of the tube is much higher than the running voltage.[2]

It was found that limitations 3 and 4 could be removed by the use of a massive all-tungsten (in place of the usual copper-backed) target. Such a target can be run continuously at intense white heat. Aside from eliminating the troubles incident to the use of copper, the all-tungsten target does not change the general characteristics of the tube.

An attempt was made to remove limitation 8, imposed by the low melting point of aluminum, by substituting for it a tungsten cathode of the same dimensions. Tubes made up in this way showed a behavior entirely different from that of the ordinary tube. They would have been absolutely hopeless from the standpoint of a practical radiographer. They were like the ordinary Röntgen tube which is in the condition which the radiographer describes as "cranky." Upon passing a discharge current of any magnitude through the tube, the resistance would quickly rise to a point where, even with an impressed potential difference of 100,000 volts, no further discharge would pass. The tube could be restored to its original condition by the liberation of gas from the vacuum

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[1] In radiographic work, movement of the focal spot during an exposure is of course detrimental to good definition.

[2] See F. Dessauer, Phys. Zeitschr., *14*, pp. 246–247 (1913).

regulator. The phenomena would repeat themselves as often as one cared to make the experiment. Continuous operation for even a few seconds seemed out of the question. It finally developed, however, that with the adoption of the following expedient, the situation changed. Gas was admitted from the regulator and a discharge passed through the tube. As soon as the resistance had risen, more gas was admitted and the tube was again excited. These operations were repeated as rapidly as possible. With each excitation of the tube, the cathode became hotter. There was evidently the same focusing of the positive ions bombarding the cathode as there was of the electrons at the anticathode, for there was a similar localization of heat at the two electrodes. A little conical depression which formed at the center of the cathode showed that, with the vacuum range employed, the positive ion bombardment was, at least mainly, confined to an area only about 2 mm. in diameter. As soon as the cathode had become heated to bright incandescence,[1] the behavior of the tube changed, and it could then be operated continuously for at least several minutes. Upon interrupting the discharge for a short time, and so allowing the cathode to cool, the "cranky" condition returned, and the tube could again be operated continuously only after repeating the procedure outlined above.

Tubes like the above with tungsten cathodes showed, upon operation, a rapid blackening of the bulb. The deposit proved to be metallic tungsten. The conical depression which invariably formed at the center of the cathode seemed to indicate that this was the source of the deposit, the disintegration of the metal at this point being doubtless due to the mechanical action of the positive ions which bombard it.

The extreme instability of vacuum attendant upon the use of a tungsten cathode in what was otherwise a standard Röntgen tube, called attention very forcibly to the part which is played by gases in the ordinary aluminum cathode. (The tungsten cathodes used must have been, from their method of manufacture, relatively very free from gas.)

A consideration of the above-mentioned limitations showed that they were for the most part incident to the use of gas and that they could therefore be made to disappear if a tube could be operated with a very

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[1] The magnitude of the heating effect at the cathode was much greater with tungsten than it is with aluminum cathodes. In one case the cathode and the anode, which functioned also as anticathode, were both made of tungsten, exactly alike in size and shape and symmetrically placed in the tube (concave faces towards each other). On continuous operation, both ran at white heat, and, as nearly as the eye could judge, at the same temperature. Where aluminum is used as the cathode material, much less heat is developed in the cathode than in the target. Willey (Vernon J. Willey, Archives of the Roentgen Ray, XII., p. 250, 1908) finds in tubes of the ordinary type that 75 to 85 per cent. of the total heat evolution in the tube, inclusive of the glass walls, takes place at the target.

much higher vacuum. In this case the electrons would have to be supplied in some other way than by bombardment of the cathode by positive ions.

Richardson[1] and others had shown that electrons might be produced by simply heating the cathode. But the values of the thermionic currents obtained by different observers had varied between wide limits, so much so as to suggest that a Röntgen tube based upon this principle might be as unstable in resistance as is the standard tube. Moreover, the fact that the substances usually worked with, platinum and carbon, are so difficult to completely free from gas, suggested strongly that with the cleaner conditions (greater freedom from gas) that could be realized by the use of tungsten, the thermionic currents might cease altogether.[2] Some experiments of Dr. Irving Langmuir,[3] however, on the thermionic currents between two tungsten filaments in a highly evacuated space, were very reassuring. According to his observations, after a certain high degree of exhaustion had been reached, the thermionic currents increased, up to a certain limiting value, as the tube became freer and freer from gas.

The idea of using a hot cathode in a Röntgen tube was not new, but, so far as the writer could learn, the principle had never been successfully applied in a vacuum good enough so that positive ions did not play an essential rôle.

Wehnelt and Trenkle[4] had used a hot lime cathode for the production of very soft Röntgen rays, working with voltages from 400 to 1,000. Wehnelt, in another article, describes the use of his lime cathode in a Braun tube, and here he says that it is not advisible to employ more than 1,000 volts, as otherwise cathode rays come off from that part of the platinum which is bare, giving bad disintegration.

The Röntgen rays produced by voltages as low as 1,000 are of course too "soft" for the ordinary applications.

Lilienfeld and Rosenthal[5] had described a Röntgen tube whose penetrating power is, they say, independent of vacuum. Their main alu-

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[1] Proc. Camb. Phil. Soc., XI., 286 (1902); Proc. Roy. Soc., LXXI, pp. 415–418 (1903).

[2] See Goldstein, Ann. der Physik, *24*, p. 91, 1885. He finds that platinum must be heated almost to its melting point to give an appreciable thermionic current. Also see H. A. Wilson, Proc. Roy. Soc., *72*, pp. 272–276 (1903). He concludes with the following statement: "It is probable that a pure platinum wire heated in a perfect vacuum would not discharge any electricity at all, either positive or negative, to an extent appreciable on a galvanometer."

[3] This work is just being published.

[4] A. Wehnelt and W. Trenkle, Sitzungsber. d. Phys.-Medic. Soc. in Erlangen, *37*, 312–315 (1905).

[5] J. E. Lilienfeld and W. J. Rosenthal, Fortschritte auf dem Gebiete der Röntgenstrahlen, *18*, 256–263 (1912).

minum cathode and their platinum anticathode are shaped and located like the electrodes in the ordinary Röntgen tube. Besides these they have an anode and an auxiliary hot cathode. Current from a low voltage source passes from the hot cathode to the anode and this current furnishes the positive ions which by their bombardment of the main cathode liberate electrons from it. Their tube is dependent for its operation on the presence of positive ions, for without these there is no means provided for getting electrons out from the main, aluminum, cathode. Lilienfeld concludes from his extended experiments in tube exhaustion that the complete removal of all gas from tube and electrodes would not do away with positive ions. There would according to this view be no such thing as a pure electron discharge. Lilienfeld's work in exhausting the gas from the tube itself and from the glass seems to have been excellent, but according to the experience of the writer, his electrodes were not sufficiently freed from gas to justify the conclusions drawn. Working even with tungsten electrodes in a tube so designed that the electrodes could be heated in place to very high temperatures, the writer has had the positive ion effects persist for hours, disappearing completely however as the electrodes become sufficiently freed from gas.

The work of Dr. Langmuir had shown that a hot tungsten cathode in a very high vacuum could be made to continuously yield a supply of electrons at a rate determined by the temperature.

Further work showed that very high voltages, up to at least 100,000, in no wise affect this rate of emission. For application to the fields of radiography and fluoroscopy, it was necessary to develop a satisfactory method of focusing. And, finally, the large amounts of energy transformed into heat in a Röntgen tube render imperative the use of a very heavy target, and this made it necessary to develop methods for sufficiently freeing from gas large masses of metal.

The result of efforts in this direction has been entirely successful, and tubes have been made, based upon this principle, which are free from all of the above-mentioned limitations. This is of particular physical interest because it brings all of the peculiarities of the Röntgen ray tube into accord with the modern conception of electronic conduction and gas molecule decomposition In the following, it will be sufficient to describe one type (a focusing tube) and its characteristics, leaving for later papers the description of other types.

§ 2. General Description of the New Type of Tube.

The structural features of the new tube which differ from those of the ordinary type are the following:

The pressure, instead of being, as in the ordinary tube, a few microns, is as low as it has been possible to make it, that is, not more than a few hundredths of a micron.

The cathode consists of a body which can be electrically heated (such as a tungsten or tantalum filament) and, suitably located with reference to this portion, an electrically conducting ring or cylinder, consisting preferably of molybdenum or tungsten or other refractory metal. The ring or cylinder is connected either to the heated portion of the cathode, or to an external source of current by means of which its potential may be brought to any desired value with respect to the heated portion. The heated portion of the cathode serves as the source of electrons, while the ring or cylinder assists in so shaping the electrical field in the neghborhood of the cathode that the desired degree of focusing of the cathode-ray stream upon the target shall result.

The anticathode, or target, functions at the same time as anode.

The operation is satisfactory only when the vacuum is exceedingly high, so high that the ordinary tube would carry no current even on 100,000 volts.

§ 3. THEORY OF OPERATION.

As will be seen from the characteristics of the tube, in § 5, it gives, in operation, no evidence of positive ions. This makes the theory of its operation exceedingly simple.

The discharge appears to be purely thermionic in character.

The rate of emission of electrons from the filament appears to be in accord with Richardson's Law, which says that the maximum thermionic current, which can be drawn from a hot filament is

$$i = a\sqrt{T}e^{-\frac{b}{T}},$$

where T is the absolute temperature, e is the base of the natural system of logarithms, and a and b are constants.

In the particular tube described in detail in this paper, over the range of temperatures and voltages included in the data of Table I., this simple law accounts perfectly for the conductivity of the tube. With still higher temperatures, however, the discharge currents would be found to increase at a much slower rate than that required by the above law. And the same applies, even in the temperature range of Table I., to a different tube design in which the distance between cathode and anode is greater. In these cases the failure to follow Richardson's Law at the higher temperatures has been accounted for by Dr. Langmuir[1] by the spacial density of negative electricity in the neighborhood of the cathode.

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[1] L. c.

§ 4. Detailed Description of Tube No. 147.

This description relates to tube No. 147, which was used in getting the data for the following tables. Fig. 1 shows a complete assembly, while Fig. 2 shows an enlarged detail of the cathode and of the front end of the target.

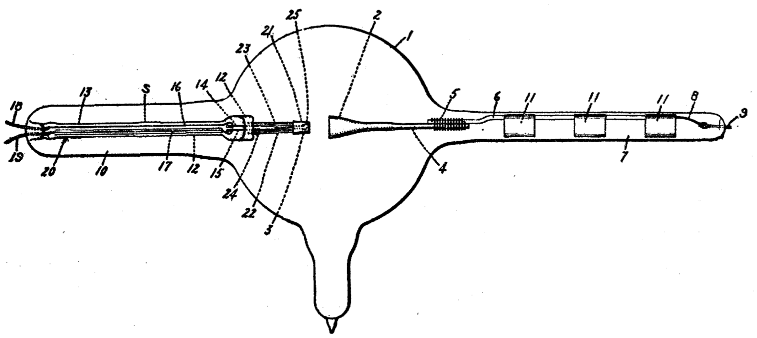

Fig. 1.

The Cathode.

In the diagrams, 25 is a tungsten filament in the shape of a flat, closely wound spiral. It consists of a wire 0.216 mm. in diameter and 33.4 mm. long with $5\frac{1}{2}$ convolutions, the outermost of which has a diameter of 3.5 mm. It is electrically welded to the ends of two heavy molybdenum wires 14 and 15, to the other extremities of which are welded the two copper wires 16 and 17. These in turn are welded to the platinum wires 18 and 19. The molybdenum wires are sealed directly into a piece of special glass, 12, which has essentially the same temperature coefficient of expansion as molybdenum. This first seal is simply to insure a rigid support for the hot filament, the outer seal being the one relied upon for vacuum tightness. The outer end, 13, of the support tube is of German glass like the bulb itself, and it is therefore necessary to interpose at S a series of intermediate glasses to take care of the difference in expansion coefficients between 12 and 13. The small glass tube, 20, prevents short-circuiting of the copper wires, 16 and 17.

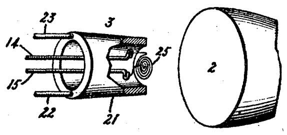

Fig. 2.

The filament is heated by current from a small storage battery which is, electrically, well insulated from the ground.

In the circuit are placed an ammeter and an adjustable rheostat and, by means of the latter, the filament current can be regulated, by very fine steps, from 3 to 5 amperes. Over this current range, the potential drop through the filament varies from 1.8 to 4.6 volts and the filament temperature from 1890 to 2540 degrees absolute.

The Focusing Device.

This consists of a cylindrical tube of molybdenum, 21. It is 6.3 mm. inside diameter and is mounted so as to be concentric with the tungsten filament, and so that its inner end projects 1.0 mm. beyond the plane of the latter. It is supported by the two stout molybdenum wires, 22 and 23, which are sealed into the end of the glass tube, 12. It is metallically connected to one of the filament leads, at 24.

Besides acting as a focusing device, it also prevents any discharge from the back of the heated portion of the cathode.

The Anticathode or Target.

The anticathode or target, 2, which also serves as anode, consists of a single piece of wrought tungsten, having at the end facing the cathode a diameter of 1.9 cm. (Its weight is about 100 gm.) By means of a molybdenum wire, 5, it is firmly bound to the molybdenum support, 6. This support is made up of a rectangular strip and, riveted to this, three split rings, 11, 11, 11, all of molybdenum. The split rings fit snugly in the glass anode arm, 7. They serve the double purpose of properly supporting the anode and of conducting heat away from the rectangular strip and so preventing too much heat flow to the seal of the lead-in-wire, 9.

The Bulb.

This is of German glass and about 18 cm. in diameter.

The Exhaust.

This is as thorough as possible.

For the earlier tubes, mercury pumps were used, with a liquid-air trap between tube and pump to eliminate mercury vapor. The whole tube, while connected to the pump, was in an oven and was heated at intervals to 470° C. Between heating operations the tube was operated with as heavy discharge currents as the condition of its vacuum would permit. For hours the tube would show the characteristics of an ordinary Röntgen tube, and in many cases a several days' application of the above treatment was required to entirely eliminate these characteristics and to realize an essentially pure electron discharge.

The exhaust time has been greatly reduced in two ways. The massive tungsten anode is given a preliminary firing to a very high temperature in a tungsten-tube vacuum furnace.[1] The molybdenum support is also fired, to a somewhat lower temperature, in the same manner. In the second place, a Gaede molecular pump has been substituted for the mercury pumps and, at the same time, a very large and short connection has been adopted between tube and pump.

In the later stages of the exhaust a very heavy discharge current is maintained continuously on the tube for perhaps an hour, the temperature of the bulb being kept from rising too high by the use of a fan.

The pressure in the finished tube is very low, certainly not more than a few hundredths of a micron and probably much less than this.

Connections and Method of Operating.

The tube was connected as shown in the diagram, Fig. 3, in which, *T* is the tube; *B* is a small storage battery; *A* is an ammeter; *R* is an adjustable rheostat which can be controlled from behind the lead screen which shields the operator from the Röntgen rays; *S* is an adjustable spark gap with pointed electrodes, which can also be operated from behind

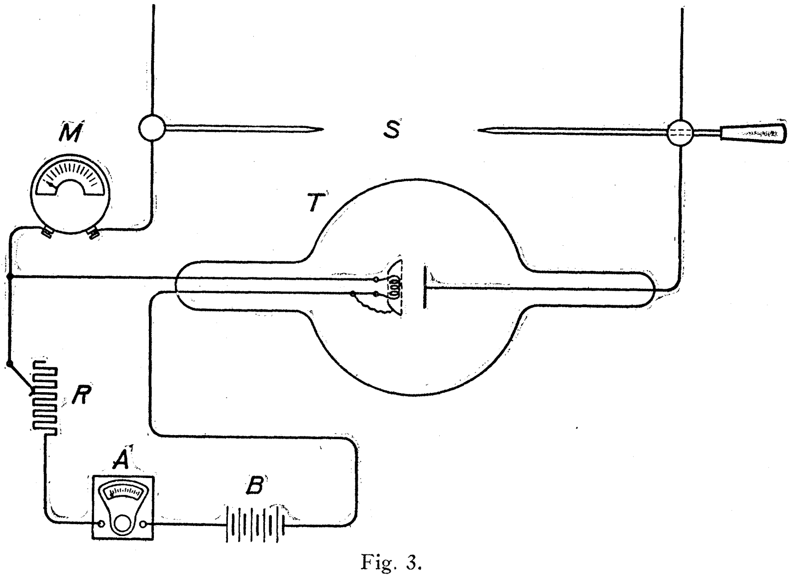

Fig. 3.

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[1] A description of this furnace will be published in the near future. The heating element consists of a tungsten tube 2.5 cm. inside diameter and 30 cm. long. This is fastened in an upright position and, by means of suitable terminals, is connected to a 100 K.W. transformer. The heating element is placed in a water-cooled metal cylinder and the space within connected to a pump which maintains, with the furnace at its highest temperature, a vacuum of a few microns.

the lead screen; and M is a milliampere-meter which can be read from behind the screen.

As the high potential is connected to the battery circuit it is necessary that the latter shall be thoroughly insulated from the ground.

As a high potential source, a 10 K.W. Snook machine, made by the Röntgen Apparatus Co., was used. This consists of a rotary converter driven from the direct current end and delivering alternating current at 150 volts and 60 cycles per second to a closed magnetic circuit step-up transformer with oil insulation. From the secondary of this transformer the high voltage current is passed through a mechanical rectifying switch (which is direct-connected to the shaft of the rotary) and the milliampere-meter, M, to the tube. The output of the transformer is controlled by a variable resistance in the primary.

Throughout these experiments a fan was kept blowing on the tube. Without this fan, the gas pressures in the tube would be slightly higher, and the discharge currents would be in consequence slightly lower.

§ 5. CHARACTERISTICS.

A. No Discharge Current unless Filament is Heated.

Unless the filament is heated, the tube shows no conductivity in either direction, even with voltages as high as 100,000.

B. Tube Allows Current to Pass in only One Direction.

The tube suppresses any current in the direction which does not make the hot filament cathode. It is therefore capable of rectifying its own current when supplied from an alternating source.

In the case of a focusing tube, however, the use of alternating current will very considerably lower the maximum allowable energy input. For as soon as the target becomes heated at the focal spot to a temperature approximating that of the filament, the tube will cease to completely rectify and, as the temperature of the focal spot rises, will allow more and more current to pass in the wrong direction. This, to be sure, will not cause either a harmful vacuum change or a metallic deposit on the bulb, as it would in the case of the ordinary tube, but it will give rise to needless heating of the bulb where it is bombarded by the cathode rays from the target, and to disturbing Röntgen rays emanating from the glass at this point. In the case of a tube which does not focus, but in which the cathode rays bombard the entire surface of the anode, the allowable energy input which the tube will completely rectify can be increased to any desired amount by simply increasing the surface of the anode.

C. *Discharge Current Determined Primarily by Filament Temperature.*

With a given design, the amount of discharge current which can be passed through the tube is determined primarily by the temperature of the filament, and responds instantly to changes in the same in either direction.

The effect of both temperature and voltage on the discharge current, in the case of tube No. 147, illustrated in Fig. 1, may be seen by referring to Table I., which gives the data on the finished tube after it had been sealed off from the pump. The focal spot was 3 mm. in diameter.

In the table, Column I. gives the length in centimeters of the equivalent spark gap.

Column II. gives the heating current (C) in the filament, expressed in amperes.

Column III. gives the filament temperature (T), expressed in degrees absolute, corresponding to the values of C in Column II. The temperature values were obtained by comparison with a previously calibrated tungsten lamp.

Column IV. gives the discharge current (i) through the tube, in milliamperes.

Column V. gives the calculated values of ($-\log i/\sqrt{T}$) to the base 10.

Column VI. gives calculated values of ($.434/T \times 10^6$).

To obtain the data in the table, the experimental procedure was as follows: The filament current was first set at a predetermined point. The spark gap was next set, also at a predetermined point. The tube was then excited and the voltage across the tube terminals adjusted (by varying the resistance in the primary circuit of the transformer) until sparks were occasionally jumping across the parallel spark gap. The discharge current value was then read off from the milliammeter.

The filament current was then raised to a second predetermined value. This increased the discharge current and lowered the potential across the tube terminals. The latter was then raised to its original value and and the new discharge current reading was obtained.

In this way the discharge current value, for a given voltage, was brought up by steps to the point where the tube finally began to show signs of instability. The temperature-current series was then repeated with a different voltage.

The values of discharge current and temperature, for each voltage, are plotted in Fig. 4. The different curves are seen to lie very close together, showing that over the range of voltages employed, the magnitude of the discharge current is practically independent of voltage.

This shows that the current in these experiments was always the saturation value.[1]

According to Richardson, the relation between the saturation current flowing from a hot filament and the absolute temperature of the filament, is expressed by the equation $i = a\sqrt{T}e^{-\frac{b}{T}}$, in which i is the current, T is the temperature, and a and b are constants of which the first has to do with the concentration of electrons within the hot body, and the second represents the amount of work required to get the electron through the surface of the metal. e is the base of the Naperian system of logarithms.

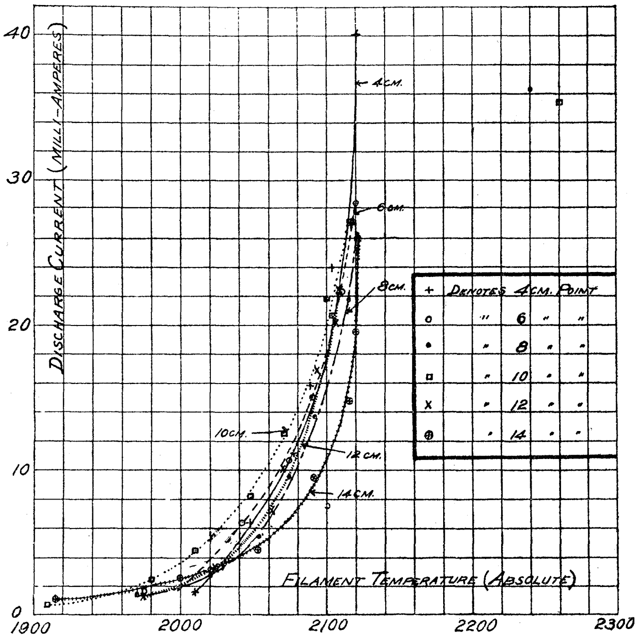

Fig. 4.

Richardson[2] applies this equation to his data by first taking the logarithm, to the base 10, of both sides of the equation, which gives

$$\log i = \log a + \tfrac{1}{2}\log T - \frac{b}{T}(.434)$$

or

$$-\log\frac{i}{\sqrt{T}} = b\,\frac{.434}{T} - \log a,$$

which is the equation of a straight line.

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[1] The two points to the extreme right of the curves correspond to an unstablec ondition of the tube. The instability disappears instantly upon lowering the filament temperature.

[2] O. W. Richardson, Proc. Camb. Phil. Soc., *11*, p. 293 (1901).

TABLE I.

I.	II.	III.	IV.	V.	VI.
Equivalent Spark Gap (Cm.).	Filament Current C (Amps.).	Filament Temp. T (Degs. Abs.).	Discharge Current i (Milliamps.).	$-\text{Log}\frac{i}{\sqrt{T}}$	$\frac{.434}{T} \times 10^6$
4	3.40	2010	1.7	1.4212	216.1
	3.45	2028	3.5	1.1094	214.1
	3.51	2049	6.4	.4985	212.0
	3.60	2077	11.3	.6056	209.1
	3.66	2088	15.8	.4611	208.0
	3.67	2104	24.0	.2813	206.4
	3.71	2116	27.0	.2313	205.3
	3.73	2121	40.0	.0611	204.8
6	3.29	1976	1.6	1.4438	219.8
	3.43	2020	3.3	1.1341	215.0
	3.52	2053	6.5	.8433	211.5
	3.59	2074	10.6	.6331	209.4
	3.64	2090	15.3	.4753	207.8
	3.70	2110	22.3	.3138	205.8
	3.72	2120	28.3	.2113	204.9
8	3.27	1970	1.6	1.4431	220.4
	3.43	2020	2.9	1.1902	215.0
	3.53	2055	5.7	.9005	211.3
	3.59	2074	9.7	.6716	209.4
	3.64	2090	13.8	.5201	207.8
	3.71	2116	21.8	.3242	205.3
	3.73	2121	26.2	.2449	204.8
	4.07	2240	36.2	.1164	193.9
10	3.09	1909	0.6	1.8411	227.5
	3.31	1980	2.5	1.2504	219.4
	3.40	2010	4.4	1.0081	216.1
	3.50	2046	8.2	.7416	212.3
	3.57	2070	12.6	.5576	209.8
	3.67	2104	20.7	.3455	206.4
	3.65	2096	21.8	.3222	207.2
	3.71	2116	27.0	.2313	205.2
	4.13	2259	35.4	.1279	192.3
12	3.28	1973	1.7	1.4171	220.2
	3.44	2023	3.4	1.1215	214.7
	3.55	2061	7.3	.7937	210.7
	3.57	2070	10.1	.6537	209.8
	3.65	2093	16.9	.4325	207.5
	3.68	2107	22.4	.3116	206.1
	3.68	2107	20.1	.3586	206.1
14	3.11	1917	1.0	1.6413	226.6
	3.36	1998	2.5	1.2624	217.4
	3.52	2053	4.5	1.0030	211.5
	3.64	2090	8.6	.7255	207.8
	3.71	2116	14.7	.4954	205.3
	3.72	2120	19.6	.3708	204.9
	3.73	2121	26.0	.2482	204.8

If then the values of Columns IV. and V. are plotted, they should lie along straight lines, provided conduction in the tube, between the voltage limits used, follows Richardson's Law.

Reference to the plots, Figs. 5 and 6, will show that the points are closely represented by straight lines. By reading off the tangents of the angles which the lines make with the horizontal axis we get the following values of the constant b:

Voltage Corresponding to Spark Gap of	Value of b.
4 cm.	115,000
6 cm.	93,000
8 cm.	94,000
10 cm.	71,000
12 cm.	76,000
14 cm.	60,000
Average	85,000

These values of b are interesting in that they all fall within the range of the values which are just being published by Dr. Langmuir. His values were obtained from an apparatus in which the electrodes were fine tungsten filaments having a total mass perhaps 1/100,000 of that of the target in the above tube. His results show the enormous effect of gas on the value of b, and the conclusion can, therefore, be drawn, that very large tungsten masses can be used in a tube without, to any appreciable extent, impairing the vacuum, even though these masses may be heated close to their melting point.

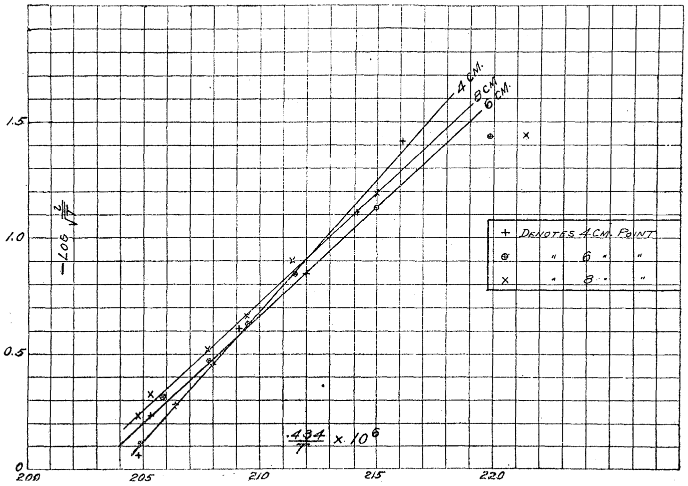

Fig. 5.

If the temperature of the filament is low, only a small number of electrons escape from it and, consequently, only a small discharge current (the saturation current) can be sent through the tube. Increasing the impressed voltage above that needed for this current value causes no further increase in current. It simply increases the velocity of the cathode rays and hence the penetrating power of the Röntgen rays.

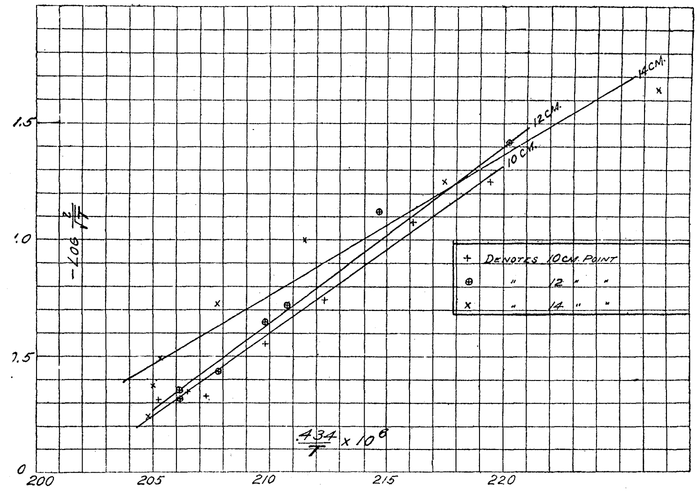

Fig. 6.

At higher filament temperatures there is a current-limiting factor, other than the number of electrons emitted by the hot filament, which plays a dominating part. This factor is the spacial density of negative electricity in front of the cathode, which amounts, in effect, to a back electromotive force. This factor would play a very important rôle at lower voltages; but in the case of the Röntgen ray tube the voltages involved are so high that, in case a suitable design is used, its influence can be entirely avoided, as is shown by the data of Table I.

D. Penetrating Power of Röntgen Rays Determined by Voltage across Tube Terminals.

The penetrating power of the Röntgen rays coming from the tube increases with the potential difference between tube terminals.

With the tube excited from a variable potential source, such as the transformer, it did not seem safe to predict that, with the same equivalent spark gap, the rays would show, photographically, the same penetrating power as those from a standard tube. But upon making the experiment, using a Benoist penetrometer,[1] it was found that they did.

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[1] M. L. Benoist, C. R., *134*, 225 (1902).

The experiment was interesting from another point of view in that it showed how readily the new tube could be adapted to a given set of conditions.

An exposure was made first with a standard tube of the ordinary type, and the discharge current and equivalent spark gap were noted. A tube of the new type was then set up in place of the standard. It was but the work of a moment to adjust the new tube to the point where it showed the same discharge current and equivalent spark gap as the standard tube. The radiographs of the penetrometer, made with the two tubes, showed the same penetration number.

E. Capable of Continuous Operation without Change of Characteristics.

That the tube may be operated continuously without showing an appreciable change in characteristics is shown by the following experiment on Tube No. 147, illustrated in Fig. 1.

The filament current was set at 4.1 amperes. This gave a discharge current of 25 milliamperes. The impressed voltage was then set at a point where the tube showed a 7 cm. equivalent spark gap.

The tube was then run continuously, with no adjustment of any kind, for 50 minutes. The readings of discharge current and equivalent spark gap, taken every two minutes, are given in Table II.

F. Sharpness of Focus.

Sharpness of focus is determined mainly by the design of the tube. If the filament temperature is such that, with the voltage employed, the discharge current does not represent the saturation value, the size of the focal spot will vary with the impressed voltage. But in the tube shown in Fig. 1, over the range of voltages corresponding to an equivalent spark gap ranging from 4 to 14 cm., the focal spot does not vary appreciably in size.

The tube may be made to focus more sharply by increasing the distance between the filament and the front (end facing the target) of the molybdenum tube. This change in design will also affect the temperature-current characteristics of the tube in the direction that a higher filament temperature will be needed for a given discharge current value.

Similarly it may be made to focus less sharply by decreasing the distance between the filament and the front of the focusing device.

All of the observations made are consistent with the idea that focusing is determined by the shape of the equipotential surfaces which may be drawn in the space between cathode and anode, and that the surfaces close to the cathode have the strongly preponderating influence.

TABLE II.

Time.	Discharge Current (Milliamps.).	Equivalent Spark Gap (Cm.).
11:48 A.M.	25	7.0
:50	25	7.0
:52	25	6.9
:54	25	6.5
:56	25	6.5
12:00 P.M.	25	6.7
:02	25	6.9
:04	25	6.5
:06	24	6.4
:08	24	6.5
:10	24	6.5
:12	23	6.6
:14	25	7.0
:16	25	6.8
:18	24	6.8
:20	25	6.9
:23½	23	6.7
:26	23	6.9
:28	25	6.9
:30	25	6.9
:32	25	7.0
:34	24	6.9
:36	25	7.0
:38	24	7.1

Near the cathode, the velocity of the electrons is relatively small, and the direction of their motion will therefore conform closely to the direction of the strong electric force. Near the anode, on the other hand, the velocity of the electrons is so high that the same force acting over the same length of path will produce but little deflection.

G. Fixity of Position of Focal Spot.

The focal spot on the anode does not wander, but remains perfectly fixed in position. This is in sharp contrast to the ordinary Röntgen tube in which the focal spot does move about, and often so rapidly as to be noticeable even during the shortest radiographic exposures.[1] The effect of movement of the focal spot is, of course, to cause in the radiograph or on the screen, a blurring of all lines except those parallel to the direction of motion. In the earlier stages of exhaustion, while the new tube is being operated with a relatively poor vacuum, the focal spot may dance about, but as the electrodes and the glass become freer from gas the

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[1] See Dr. Pfähler, Fortschritte auf dem Gebiete der Röntgenstrahlen, *18*, pp. 340–343 (1911–1912).

motility of the focal spot decreases and finally disappears completely. Its disappearance goes hand in hand with the disappearance of fluorescence of the glass, discussed in section *J*. Movement of the focal spot appears to be due to the action of positive ions in disturbing the distribution of static charge on the glass walls of the tube.

H. Tube not Sensitive to Considerable Changes in Gas Pressure.

The gas pressure within the tube is so low that it can increase severalfold, and apparently decrease without limit, without appreciably affecting the other characteristics.

The slight effect of pressure change may be seen from the following experiment:

While one of the tubes was being continuously operated on the pump, the pressure, as indicated by a McLeod gage, decreased from 0.113 to 0.035 micron.[1] The discharge current passing through the tube remained constant at 3.1 milliamperes, while the parallel spark gap backed up by the tube changed only from 7.9 to 8.6 cm. A corresponding pressure change in the case of an ordinary Röntgen tube would bring about an enormous change in current and voltage.

I. Capable of Continuous Operation with High Energy Input.

Owing to the fact that the tungsten target can run at such a high temperature, large amounts of energy can be continuously radiated.

J. No Fluorescence of Glass.

When operating properly the tube shows no fluorescence of the glass at any point. Corresponding to this, there is an absence of the usual strong local heating of the anterior hemisphere. The absence of fluorescence and of local heating seem to point to the fact that there is no bombardment of the glass by secondary cathode rays sent out from the target. This is in striking contradistinction to what takes place in an ordinary Röntgen tube, where, in the case of a platinum target, it has been found that there are about three-fourths as many electrons leaving the target, and going to the glass, as secondary cathode rays, as there are bombarding it, in the form of primary cathode rays. This elimination of secondary cathode ray bombardment prevents the production of a large part of the useless and disturbing Röntgen rays which emanate from the glass in the case of the ordinary tube.

The absence of bombardment of the glass is of interest both theoreti-

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[1] In the light of later experiments it seems doubtful whether a further pressure decrease, no matter how great, would have appreciably affected the tube characteristics.

cally and practically. Other explanations of the lack of fluorescence suggested themselves at first. A plausible hypothesis was that bombardment took place, but that the surface of the glass was much freer from gas than it is in the ordinary tube and that this accounted for the lack of fluorescence. But the fact that fluorescence appears so suddenly when a trace of gas is evolved, coupled with the fact that such fluorescence may appear in streaks and that these may rapidly change their location, seems to disprove the hypothesis. It also seemed possible at first that the fluorescence might be there, but that it could not be seen because of the strong light emission from both filament and target. But this hypothesis is disproved by the fact that with filament and target at their highest temperatures, fluorescence becomes suddenly strongly visible whenever gas is liberated.

The simple explanation appears to be based upon the fact that the large number of positive ions present in an ordinary Röntgen tube is here lacking. The inner surface of the glass becomes strongly negatively charged, when the tube is first operated, and, not being able to attract an appreciable number of positive ions, remains so. The presence of this negative charge upon the glass prevents further electrons, either in the shape of primary or secondary cathode rays, from going there.

K. Identity of Starting and Running Voltage.

The starting, or break-down, voltage of the tube is the same as the running voltage. This is very different from the state of affairs in the ordinary tube in which the break-down voltage is much higher than the running voltage.[1] The difference is to be explained as follows: In the ordinary tube the number of ions present when the circuit is closed is exceedingly small, being only that due to natural ionization causes, such as radioactive matter in the surroundings. After the discharge circuit is closed, the number of ions increases, by collision, very rapidly, and the voltage across the tube terminals falls in consequence. In the case of the new tube, on the other hand, the full supply of electrons is there the instant the discharge circuit is closed, and even before this, and the available number is not changed by the discharge current.

L. Permits of Realization of Homogeneous Bundle of Primary Röntgen Rays.

The tube must permit of the realization of a strong homogeneous bundle of primary Röntgen rays of any desired penetrating power. For this

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[1] See Dessauer, l. c.

purpose it should clearly be excited from a source of constant potential. The result should be attained even though the discharge is intermittent.[1]

M. No Heating of Cathode by Discharge Current and no Evidence of Cathodic Disintegration.

An earlier experiment showed that when a tube is made up with two similar concave tungsten electrodes, symmetrically located in the tube, and operated on direct current at an ordinary Röntgen tube vacuum, the heating effect at the cathode is as strong as that at the anode. Furthermore, the heat evolution at the cathode is as strongly localized as it is at the anode. In fact, it is impossible, when the tube is operating, to tell, by looking at it, which of the white hot electrodes is functioning as anode and which as cathode. There is a very rapid blackening of the bulb in such a tube, the material of the deposit coming evidently from the cathode, which shows a deep and sharply defined cavity at the point of local heating. The simple explanation seems to be that the cathode is bombarded by positive ions and that the emission of the electrons which constitute the cathode ray stream is due to this bombardment. So, also, the heating effect and the cathodic disintegration.

At the higher vacuum and with the relatively gas-free electrodes of the new tube there is no evidence of any bombardment of the cathode. In the earlier stages of gas removal, when a discharge can be made to pass through the tube without the heating current in the filament, the latter is seen to be strongly locally heated by the discharge current, as from bombardment by positive ions. But when the exhaustion has been completed and the tube is operated with the cathode hot, a voltmeter and ammeter in the filament circuit show no change even when a very heavy discharge is sent through the tube. Positive ion bombardment, if it existed to an appreciable extent, would raise the temperature and, hence, the resistance of the tungsten filament and would therefore be indicated by the instruments. If it were very local and considerable, it would be further indicated by a melting through of the filament at the point in question. The resistance change and local disintegration of the filament have been observed in only those cases where the vacuum, as shown by other effects, such as fluorescence of the glass, has been poor.

Disintegration of the cathode would also manifest itself in blackening of the bulb. Even after running for several hours, the deposit on the bulb is very slight, and what there is may well be entirely accounted for by vaporization of tungsten at the focal spot on the target.

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[1] For fluoroscopic work with the ordinary tube, it seems preferable to use an interrupted discharge so as to reduce heating of the tube and danger to patient and operator. The phosphorescence of the fluoroscopic screen makes possible frequent interruptions without appreciable loss of light.

N. The Target the Factor Limiting Allowable Energy Input.

There is one limitation with the new tube. With a sharp focusing tube and above a certain energy input the tube resistance is unstable, dropping suddenly to perhaps a small fraction of its original value, returning instantly to the old value however upon stopping the discharge or upon lowering it to the limiting value. The cause of this phenomenon appears to be as follows:

With a very high energy input and sharp focusing, the surface of the target melts at the focal spot and volatilizes. Owing to the fact that this tungsten vapor is produced at the focal spot, all of the primary cathode rays pass through it and, by collision, ionize it. This of course decreases the tube resistance. The larger the focal spot the greater is the limiting current. The design of the target also has a great deal to do with the limiting current value, as the face of a thin target is vaporized with a much lower energy input than a relatively thick one. For very short excitation of the tube, the limiting energy input is somewhat larger than for longer periods; but an input which can be carried for a few seconds can be carried indefinitely.

The effect of substituting any other single refractory metal for the tungsten of the target will be to lower the maximum allowable energy input. For the essential properties of a target material are: high density, high melting point, high heat conductivity, and low vapor pressure. Tungsten has a higher melting point and lower vapor pressure than any other metal. Its nearest competitor in point of refractoriness, tantalum, has only about one third of the heat conductivity. Molybdenum and iridium have vapor pressures altogether too high to entitle them to consideration, even if their melting points made them otherwise competitors. Osmium has only about one half of the heat conductivity of tungsten.

The ordinary copper-backed tungsten target would be very difficult to exhaust sufficiently. Otherwise its use might be desirable for certain classes of work, as it would raise the maximum allowable instantaneous energy input.

§ 6. DANGER CONNECTED WITH USE OF TUBE.

There has been in the old tube a certain element of safety in that it could not be run continuously with a very heavy energy input. The new tube, even when focusing sharply, can be operated, for example, on a 7 cm. parallel spark gap with currents as high as 25 milliamperes for hours at a time, and without the slightest attention.

For most purposes, other than diagnostic or radiographic work, there is no advantage in having the tube focus. In case it does not, the above-mentioned energy input limitation falls away and the tube can apparently be designed for any energy input whatsoever. This will permit, in this field, of the use of much greater Röntgen ray intensities than have heretofore been realized.

In the light of the above, it will be seen that the precautions which have been shown by years of experience to be sufficient for work with the old tube are not necessarily sufficient for the user of the new one.

§ 7. SUMMARY.

In the foregoing, a new and powerful Röntgen ray tube has been described. It differs in principle from the ordinary type in that the discharge current is purely thermionic in character. Both the tube and the electrodes are as thoroughly freed from gas as possible, and all of the characteristics seem to indicate that positive ions play no appreciable rôle.

The tube allows current to pass in only one direction and can therefore be operated from either direct or alternating current.

The intensity and the penetrating power of the Röntgen rays produced are both under the complete control of the operator, and each can be instantly increased or decreased independently of the other.

The tube can be operated continuously for hours, with either high or low discharge currents, without showing an appreciable change in either the intensity or the penetrating power of the resulting radiations.

The tube in operation shows no fluorescence of the glass and no local heating of the anterior hemisphere.

The starting and running voltage are the same.

The tube permits of the realization of intense homogeneous primary Röntgen rays of any desired penetrating power.

An article bearing especially upon the application of the new tube to radiographic and diagnostic and to therapeutic purposes will appear shortly in one of the Röntgen ray journals.

It is a pleasure to me, in closing, to express my appreciation of the services of Mr. Leonard Dempster, who has assisted me throughout this work.

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