COLD EMISSION FROM UNCONDITIONED SURFACES

By Willard H. Bennett*
Norman Bridge Laboratory of Physics, Pasadena, California

(Received January 26, 1931)

Abstract

The greatest difficulty in obtaining higher potentials in tubes is due to auto-electronic emission from the electrode surfaces. A study of emission from unconditioned metals is described leading to the result that either loose fine particles in a tube, or else the targets of emission will probably have more to do with the quantity of emission than will the kind and "conditioning" of the cathode itself.

NUMEROUS measurements have been made of the emission in high electric fields, from fine wires and fine points of metals, which have been heated nearly to melting, in vacuum, and thus thoroughly conditioned.[1] Since metal parts in high voltage tubes are so restricted in size and shape by the necessity of such heating, it has been considered of importance to investigate cold emission with a view to finding what else can be done to a metal surface to decrease the emission, besides heating to high temperatures. This problem is of particular interest in connection with the development of a design for a tube to give higher order potentials than those now obtainable with unconditioned or partially conditioned electrodes.[2]

1. Apparatus

The experimental apparatus was designed by Julius Pearson in accordance with plans outlined by R. A. Millikan, to measure the current passing between electrodes in high vacuum at known fields. Spherical electrodes were used at distances small compared with the radius of either electrode.

The cathode was mounted on a fixed steel post extending down into the evacuated bulb, as shown in Fig. 1. The anode was mounted on a steel post which could either be moved towards or away from the cathode by means of the micrometer screw, and also which could be rotated about the cathode by turning the movable part of the base, as shown in Fig. 2. When the latter rotation was made, the anode retained its orientation so that fresh surfaces both of the anode and of the cathode were brought together at each setting of the base. Several sets of readings were thus possible at each mounting of the electrodes.

* National Research Fellow.

[1] Rother, Ann. d. Physik **81,** 317 (1926) G. E. Co. of London, Phil. Mag. (7) **1,** 609 (1926); Eyring, MacKeown and Millikan, Phys. Rev. **31,** 900 (1928); Stern, Gossling and Fowler, Proc. Roy. Soc. **124,** 699 (1929).

[2] Lauritsen and Cassen, Phys. Rev. **36,** 988 (1930); Coolidge, J. Franklin Inst., **202,** 639 (1926); Tuve, Hafstad and Dahl, Phys. Rev. **35,** 1407 (1930); Brasche and Lange, Naturwiss. **18,** 765 (1930).

The anode post was sealed vacuum-tightly to the fixed part of the base by means of a copper syphon. Both the cathode post and the anode base were sealed to the glass bulb with red sealing wax. The bulb was connected to the pumps at all time. An ionization gauge was used for measuring pressures.

The source of potential was a Thordarson transformer and kenetron rectifier, the potential being smoothed out with a 0.25 microfarad condenser. This generator, which gave up to 20 kv steady potential, was connected through a 10,000,000 ohm xylene-alcohol resistance to the cathode post. The

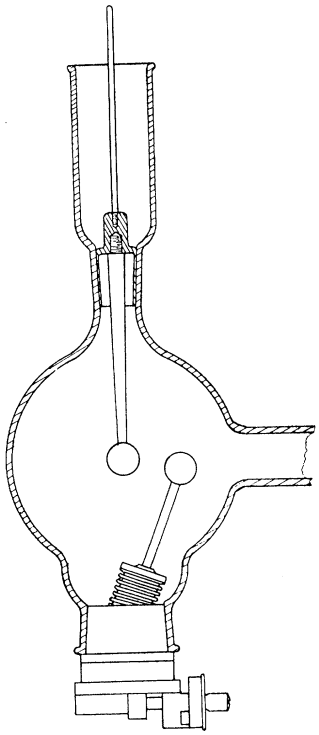

Fig. 1. Diagram of tube.

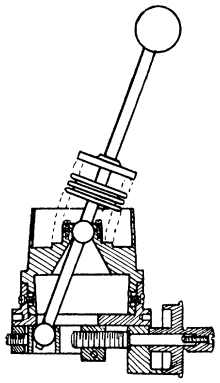

Fig. 2. Diagram of anode.

potential difference applied between the electrodes was measured by the electrostatic voltmeter which was calibrated with a sphere-gap. The anode base was connected to the current measuring circuit. The entire high-potential generator was enclosed in a grounded screen cage, since it was found that without it, leakage currents in the air would get to the galvanometer giving large deflections.

2. Method of Observation

Immediately before mounting, the electrodes were polished with 600 mesh carborundum powder held on the heel of the hand. They were washed in alcohol, dried without touching, and mounted.

The field between the electrodes could be varied by varying either the

distance between the electrodes or the applied potential. Numerous measurements showed that the two methods gave the same result.

After the first complete field-current curve had been measured, the potential was cut off and the electrodes touched to measure the setting of the micrometer for zero distance between electrodes. The e.m.f's in the rectifying tube (not more than 5 volts) were sufficient to give dependable deflections on the galvanometer upon contact. The largest emission previously drawn was again drawn at the corresponding field, and it was assumed that the intermediate determination of the zero had not effectively changed the surfaces for further study. When mixed electrodes were used (see section 6), zero distance was always measured after all measurements of emission were completed.

The data collected were plotted with the inverse field times 10^6 and the logarithm of the current, as coordinates. The points on the curves represent the lower limits of the current at each sitting. This was done because a study showed that in those comparatively few cases the current varied over a material range, the lowest value was quite near the final value if allowed to become steady. Most of the first emission curves are curled back at currents above 10^{-4} amperes because the drop in applied potential caused by the drop through the external resistance becomes appreciable at this value. No attempt has been made to draw straight lines to represent characteristics because it is believed to be more important to keep clearly in mind the probable uncertainty of the measurements. It is believed that reliable conclusions can be drawn only when the zone on a figure enclosing all of the emission from one kind of electrode surface is entirely separate from the zone enclosing all of the emission from another kind of an electrode surface.

3. General Observations

The behavior of surfaces which have not been "conditioned"is exceedingly erratic and unsystematic. In spite of this fact, a very considerable amount of data was taken in an attempt to determine statistically what relations (1) degree of polish, (2) purity, (3) electroplating, (4) hardness and (5) work function, have to emission. Measurements were made on cast iron, steel, armco iron, vacuum fused electrolytic iron, magnesium (two grades of purity), aluminum, copper, brass, zinc, gold-plated copper, nickel-plated brass, chromium-plated brass, and "Plymite" (an extremely hard compound of tungsten and carbon). This quite extensive study did not lead to any conclusive results.

It was established, however, that with fair polish and fair purity, or better, the first emission always began at a much higher field, and suffered a sudden spontaneous increase of a large order of magnitude at a still higher field, i.e., a "breakdown," than the fields at which emission was drawn from the same emitting surface subsequently.

4. Effect of Space Charge Due to Positives

The possibility suggested itself that positives liberated from the anode by the electron stream from the cathode, might follow the electron stream,

which is known to be well focussed, and set up a space charge which in turn increased the emission. This possibility was tested by measuring the emission in an apparatus as shown in Fig. 3. P is a needle-point of the metal to be studied. It was mounted on a screw-in-vacuum which could be moved by a magnet, in the direction of the point. A and B are polished copper bars, six inches long, 3/4 inch wide, and 1/8 inch thick, with edges rounded. There was a hole in A as shown, through which the point was extended toward B. A and P were at ground potential and B was at any desired potential up to 20,000 volts. Currents were measured from P. Any desired magnetic field up to 7,000 gauss could be applied perpendicularly to the figure by an electromagnet with pole-pieces as shown. The apparatus was always baked out before

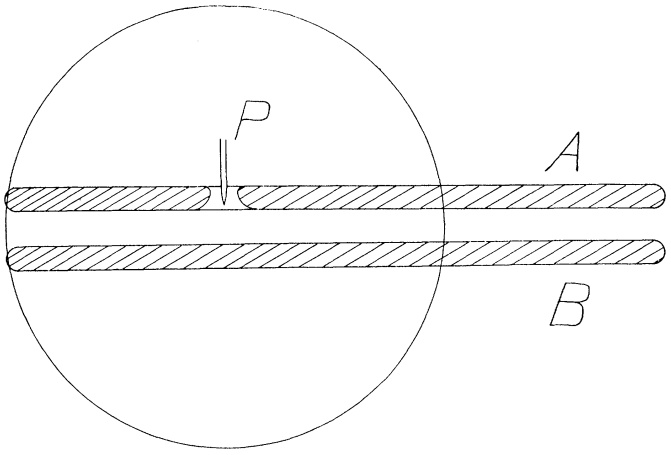

Fig. 3. Diagram of apparatus for measuring emission in magnetic field.

measurements were begun, and the pressure between the bars was, in all experiments, less than 1×10^{-5} mm, as shown by an ionization gauge at the opposite end of the tube from the pumping outlet.

Both a tungsten and a copper needle-point were tried. Emission began from the points at a comparatively low potential, and decreased (fatigued) even with increased potentials. There were times, however, during this fatigue, when the emission would remain steady within five percent for several minutes.

If the tip of the point, P is above the plane of the lower face of the upper plate, and a magnetic field of 7,000 guass is applied to apparatus of the dimensions used in this experiment, it can be shown that electrons emitted from P cannot arrive at the plate B directly below P, but will be displaced along B to some place beyond the region of this magnetic field.

The cycloidal path predicted by the theory was actually seen outlined on the glass walls opposite the space between the plates, and displaced down the tube to the edge of the region of high magnetic field.

Emission was drawn from P in the above position and the current measured while putting the magnetic field on and off. The magnetic field was

found to have no effect on the magnitude of the current, to within five percent, which was the degree of steadiness of the emission from the points.

The conclusion may be drawn that if the positives which are known to go from the anode to the cathode, produce a space charge near the emitting surface, the effect of this space charge on the field at the surface is *not* of importance in determining the magnitude of emission after breakdown.

5. Effect of Discharges through Hydrogen on Emitting Surfaces

Four filaments were mounted on the tube shown in Fig. 1 at the four quadrants about the center electrode. They were sealed in glass plugs which could be sealed with wax into the ground glass joints on the tube as shown in Fig. 4. At the side of one of these joints, the pumping tube V was attached.

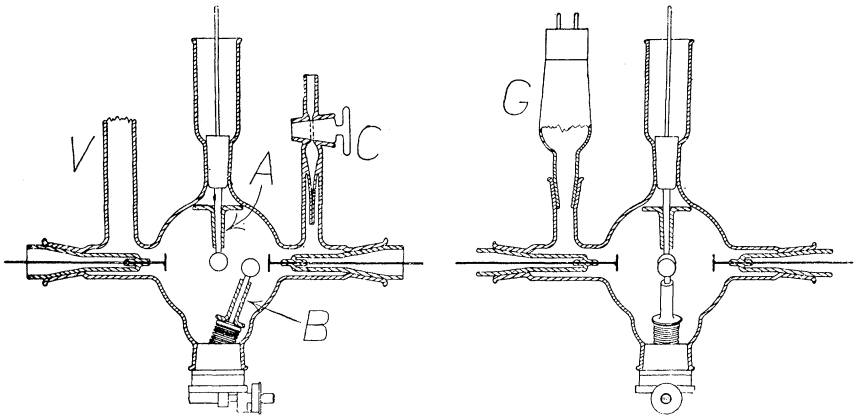

Fig. 4. Diagram of tube showing arrangement of four filaments.

At the side of another, the ionization gauge G was attached. At the side of a third, a slow gas inlet C consisting of a fine capillary and a stopcock was attached. Glass shields for both steel electrode posts, A and B, were mounted to eliminate emission from the posts and also to protect them from sputtering.

Copper electrodes were used throughout this work on the effect of discharge through hydrogen.

In order to differentiate sharply between the true effect of discharges upon the emitting surfaces and any auxiliary phenomena in the tube, tests were made of the effect of lighting the filaments introducing hydrogen to atmospheric pressure and pumping out, introducing air similarly, letting stand for up to sixteen hours, and bombarding with electrons (20 m.a., bringing the electrode to about 75°C temperature). The changes due to none of these treatments was materially greater than the changes observed between repeated measurements of the characteristic of a particular surface.

Fig. 5 is submitted as a basis of comparison for the following figures. Curves 1, 2, 3, and 4 are the first emission observed at each of four independent emitting areas. Curves 5, 6, 7 and 8 are the subsequent emissions for the same areas in order.

Each group of three curves in Fig. 6 represents the history of an independent emitting area. In each group, curve 1 represents the first emission, which emission followed bombardment with positives at the current and for

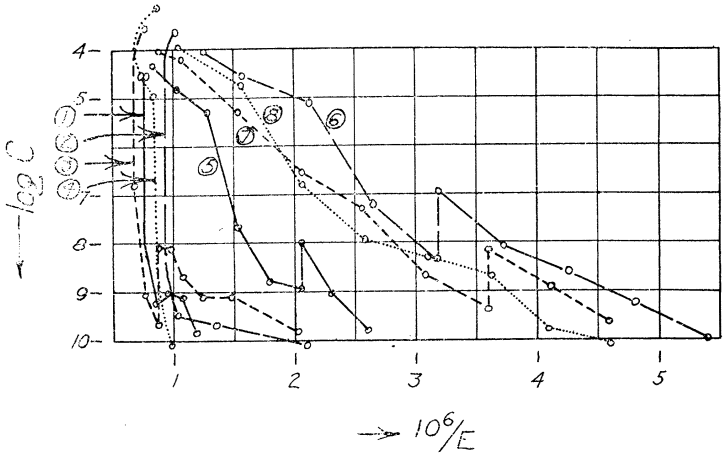

Fig. 5. Emission from untreated copper electrodes.

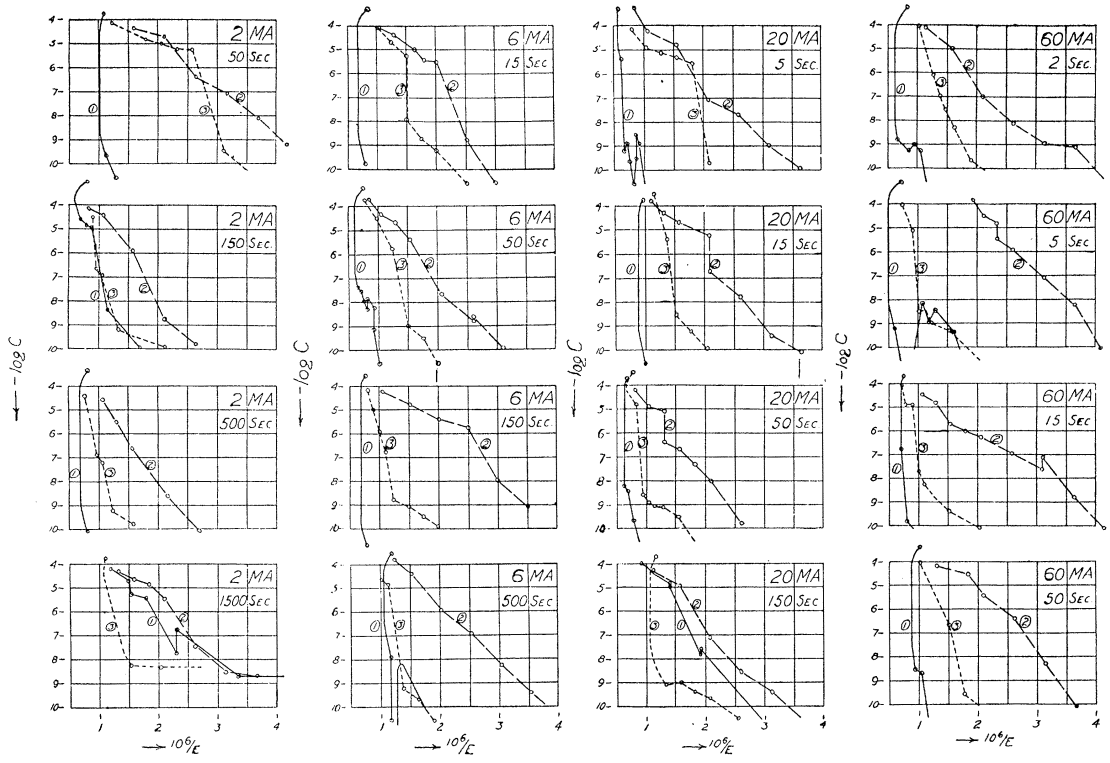

Fig. 6. Effect of discharge through hydrogen.

the time indicated. Curve 2 represents the subsequent emission, which was measured immediately following the first emission. Curve 3 represents the emission which followed another bombardment with positives at the same current and for the same time as before. These bombardments were made through hydrogen at the highest pressure (between 1 mm and 12 mm pressure) which would permit the negative glow completely to surround the bombarded electrode, which was the cathode in both the glow discharge and the measurement of the emission.

A study of the curves will show that up to a certain point, bombardment with positives does not seem to affect the field at which breakdown first occurs, but that there is a current and time for which a bombardment with positives restores the emitting surface after breakdown to the condition it had before breakdown occurred.

6. Effect of the Anode

Measurements were made of the emission from a copper cathode but with various anodes. Anodes used were of copper, iron, magnesium, zinc, plymite,

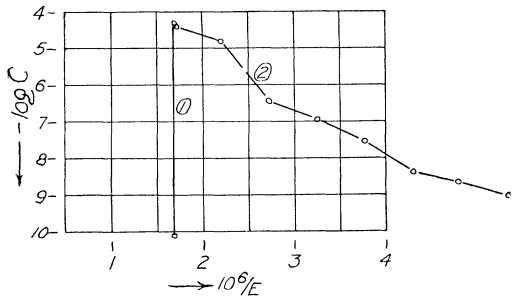

Fig. 7. Plymite anode.

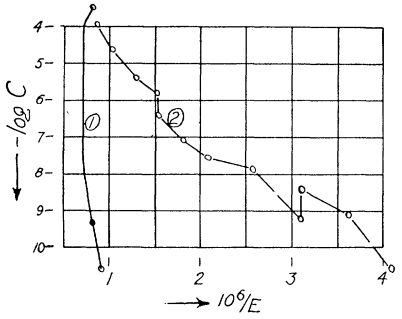

Fig. 8. Copper anode.

aluminum, chromium-plate, and molybdenum. Complete sets of measurements were made for at least four independent emitting areas for each combination of electrodes, and the set which appeared to be most typical for each kind of anode is shown with the corresponding label in Figs. 7 to 14. The curves are numbered in the order taken.

Repeated attempts to fatigue the emitting surfaces on copper cathodes, using copper, plymite, or iron anodes, giving emission like that shown in curve 2 of Figs. 7, 8 or 10, respectively, failed to give any significant change in slope. The change was uncertain with a zinc anode.

On the other hand, using either a molybdenum, aluminum, chromium, or magnesium anode, the emitting surface quickly fatigued to a new group of curves occupying a zone on the figure definitely removed from that occupied by subsequent emission curves for copper anodes, and corresponding to much lower currents from the same fields.

7. Temporary Breakdown

Frequently, with various electrodes, throughout the entire investigation, there have occurred very sudden large order increases in current (up to 10^6)

which behaved like premature breakdowns. These presently just as suddenly completely disappeared, accompanied by a distinct click of the glass, sounding as though a metal particle had hit the glass. On pushing the field up, the breakdown occurred at the usual field and all subsequent currents behaved the same as though the premature breakdown had not occurred.

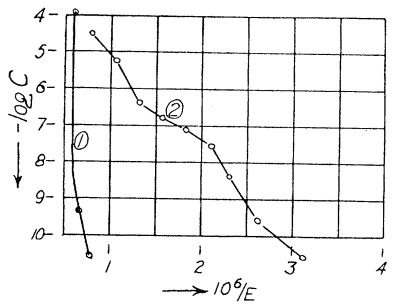

Fig. 9. Iron anode.

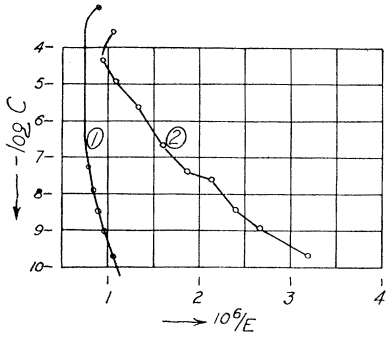

Fig. 10. Zinc anode.

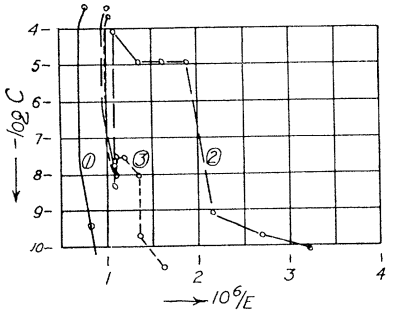

Fig. 11. Magnesium anode.

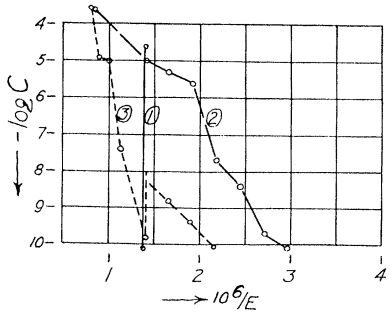

Fig. 12. Aluminum anode.

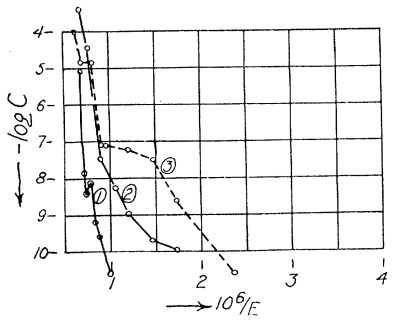

Fig. 13. Chromium plate anode.

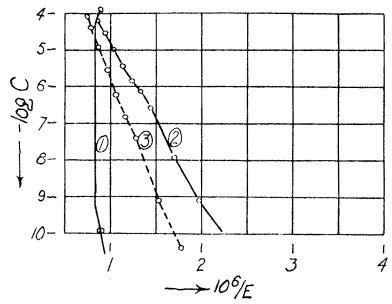

Fig. 14. Molybdenum anode.

8. Discussion

The idea that the first breakdown is simply due to a rupturing of the surface of the cathode and that the emission is determined by the composition and conditioning of the cathode, has appeared to be open to question from early in this investigation.

The phenomenon of premature breakdown seems to leave no doubt that foreign particles either from the anode or from parts of the tube other than the cathode, *can* fly through the tube to the cathode, adhere, give emission, and be torn from the cathode leaving no scar on the cathode of sufficient irregularity to give measurable emission.

Following excessive discharge through hydrogen (which was observed to give sputtering), the first emission was seen to behave either as though a complete breakdown has been produced during the discharge through hydrogen, or else as though no sensible effect had been produced on the cathode surface at all (see curves 1, each of the lower four groups in Fig. 6). It was never observed after sputtering had been produced in the tube either during these measurements or with any other electrodes under different conditions, that immediately subsequent field-current curves lay in the region between the two zones belonging to emission leading up to the usual breakdown, or the emission following the usual breakdown, respectively. This fact would seem to indicate that the adhesion of a loose particle to the cathode gives emission indistinguishable from that following the usual breakdown.

Following breakdown, when molybdenum, aluminum, chromium, or magnesium were used as anode, the lowest subsequent currents measurable occurred at fields much higher than those at which the lowest currents occurred when copper was used as the anode. The most plausible explanation of this seems to be that auto-electronic emission is from a particle torn from the anode and which is adhering to the cathode.

If, on the other hand, the breakdown is due to a rupturing of the copper cathode surface, it would be necessary to suppose that the steeper slopes, when one of the above four metals was used as anode, are due to beating down the ragged edges by positives coming from the anode at emission currents of less than 10^{-10} amperes, and that the emitting point is bombarded with positives of the same order of density as occur in a discharge through hydrogen of several milliamperes spread over the entire cathode surface. In view of the small size of the emitting points, this is a possible supposition. It is further supported by the fact that after prolonged auto-electronic discharge, the white color of the anode metal becomes distinguishable as a small spot at the emitting point on the copper cathode. This explanation, however, forces us to the conclusion that the emission measured is from a surface of metal originally composing the anode, and hence the emission is determined by the metal used as anode, anyhow.

In conclusion, the author wishes to thank Drs. Millikan, MacKeown, and Lauritsen for advice borne of their longer experience in this field, and also Dr. Millikan for making available the necessary facilities for this investigation.