FIELD EMISSION FROM A MULTIPLE EMITTER COMPOSITE CATHODE

by

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ABSTRACT

Field emission from very fine (1000 Å) multiple emitter cathodes was investigated. Experiments were performed using niobium-copper composites containing 9.8×10^6 parallel niobium field emitter elements. Steady currents of over 10 milliamperes were obtained at a voltage of 9 kilovolts. Results indicate that this approach may lead to practical field emission devices operating at comparatively low voltages.

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INTRODUCTION

Field emission is the emission of electrons from a metal by potential barrier penetration due to the presence of a high electric field at the surface. The field emission process has some unique characteristics: it requires no addition of energy to the emitter as in thermionic emission, the emitted electrons are essentially monoenergetic, the emission current density depends exponentially on the magnitude of the electric field, and large current densities may be obtained- in the range of 10^6 amperes per square centimeter. In practice, this means currents of several milliamperes from microscopic cathodes.

Field emitter cathodes are generally in the form of a sharp point with a radius of curvature in the neighborhood of 10^{-4} cm. or smaller so as to obtain a field concentration at the tip. The properties of the emitter and the emission process suggest several practical applications.[3]

The small size and high emission current densities available from the cathode result in an effective point source of monoenergetic electrons which is useful in electron optics (eg. a field emission microscope). These same properties also allow substantial miniaturization of field emitter devices.

The exponential current-field (voltage) relationship and the fact that the response time of the device is instantaneous, suggests uses in high voltage regulation, amplification and signal mixing, and emission

bunching of electrons in microwave components.

The nature of the device also leads to several disadvantages for practical use. The first is the necessity of generating and maintaining high electric fields (on the order of 10^7 volts/cm) at the cathode to achieve field emission. The exponential character of the voltage-current relationship means that even slight variations in voltage will yield large emission current changes; for some application this is undesirable. Further, large current densities lead to large power densities and heat dissipation. Damage to both cathode and anode may occur as a consequence.

PURPOSE OF THE EXPERIMENT

Field emission, at present, is the least practical electron source due to the difficulties arising from the necessity of generating very large electric fields. The purpose of this reasearch is to determine the characteristics of a microscopic multiple cathode field emitter. A single cathode field emitter requires rather large applied voltages to obtain a substantial emission current. A multiple emitter cathode, on the other hand, should yield large currents at considerablely lower applied voltages; thereby enhancing the feasibility of the device in practical applications by eliminating the need for large and bulky high voltage sources.

THEORY

The mechanism of field emission is explained by the "tunneling" of electrons through the potential barrier at a metal's surface which has been thinned and lowered by an applied electric field. Fowler and Nordheim[5], in 1928, were successful in applying the then-new quantum theory to the problem and the experimental verification of their theory was one of the first conf irmations of the validity of wave mechanics.

The equation developed by Fowler and Nordheim (with later numerical corrections) is:[1]

$$J = (1.54 \times 10^{-6} E^2 / \phi) \exp (-6.83 \times 10^9 \phi^{\frac{3}{2}} f(y) / E)$$

where:

J is the current density at the cathode surface in amp/m^2

E is the electric field strength normal to the cathode in volts/m

ϕ is the work function of the cathode in electron volts

f(y) is a dimensionaléss elliptic function of the variable

$$y = 3.79 \times 10^{-5} E^{\frac{1}{2}} / (\phi - \epsilon)$$

(introduced in accounting for the classical image force

ϵ is the electron kinetic energy in electron volts

The derivation makes the following assumptions:

1. Electrons in the metal are in a simple one-band distribution and obey Fermi-Dirac statistics

2. The metal-vacuum interface is a smooth, flat plane with irregularities of atomic dimensions neglected
3. An electron outside the metal is attracted to the metal surface by the classical image forge
4. The work function is uniform over the cathode surface

Inside the metal, a number of conduction electrons of energy impinge upon a unit area of surface in a unit time. This number is given by an electron supply function $N(\epsilon, T)$.

$$N(\epsilon, T) = (4\pi / h^3)\, mkT \ln (1 + e^{-\epsilon / kT})$$

The origin of the variable ϵ is the fermi level. (the upper limit of energy at $T = 0^\circ K$)

The potential energy of an electron in the metal due to the coulomb interaction between the electron and the ordered atoms in the crystal is as shown in figure 1 :

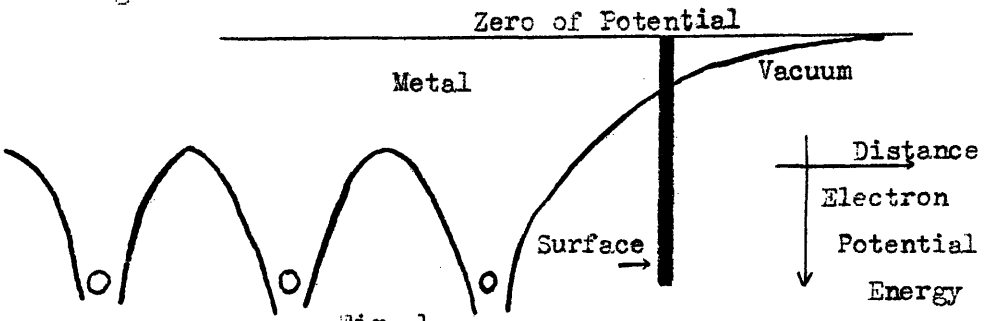


Fig. 1

At the boundary, V rises to its maximum because of the lack of compensating fields on the vacuum side. This creates an energy barrier of "infinite" thickness against electrons trying to leave the metal. For an electron to leave the metal, energy (thermal, photon excitation, etc)

must be supplied to surmount the barrier.

When an electric field is applied at the metal surface, the barrier no longer has "infinite" thickness. The higher the field, the lower and thinner the barrier becomes and the shape shown in figure 2 is attained.

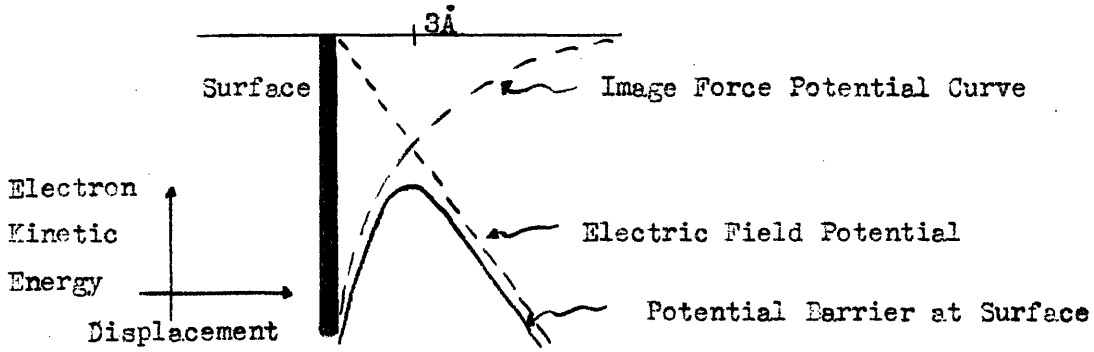


Fig. 2

Now, according to Quantum Theory, the position of the electron is indefinite; ie., there is a probability attached to its location. Therefore, electrons impinging on the now finite barrier have a certain probability of being found outside the metal. This probability may be expressed by a "transmission coefficient" $D (E, \phi, \epsilon)$ obtained from the time independent Schrodinger equation. The result is:

$$D (E, \phi, \epsilon) = \exp(-6.83 \times 10^{9} (\phi - \epsilon) f(y) / E)$$

The Fowler-Nordheim equation is just the integral of the supply function times the "transmission coefficient" over all energies.

The assumptions made deserve a little comment; assumption 1 states that we may expect the electrons to be emitted monoenergetically, assumption 2 asks that we neglect secondary sites of emission within a given emis-

-sion area, number three is important: a space charge effect is expected and emission may be partially masked as a consequence, assumption 4 literally asks for a single crystal but it is a good approximation over a region of a metal.

PRACTICAL FIELD EMISSION

It is difficult to measure J and E directly, and we will measure the terminal electric characteristics; I, the field emission current and V, the applied voltage. In principle, we could derive the current-voltage characteristics from the basic expression for J(E) in a straight forward manner. However, this is time consuming and we shall consider the following approximations for a field emission diode:

a. The emitter is assumed to have a simple shape for which an analytical expression for E may be calculated at the tip.(eg. a needle) The expression used is:

$$E = \beta V$$

V is the anode voltage

E is the field at the emitter tip

β is a parameter m^{-1}

b. The Fowler-Nordheim equation is used to calculate J at the emitter tip assuming constant ϕ over the surface.

c. The total emitted current I, is expressed as $I=J\bar{A}$ where $\bar{A}$ is the effective emitting area of the cathode.[6]

Therefore, the emitted current is: $I = \bar{A}\, J(\beta, V, \phi)$. The crucial parameter is β, the geometrical factor of the emitter tip. β is simply the ratio of the field at the cathode to the anode voltage and is determined solely by the tube geometry. It is assumed that the emitter radius is very much smaller than the anode-cathode spacing and is hence independent of anode shape.

There are several methods for computing the field multiplication

factor, β , from the cathode geometries by use of potential theory. All the methods consist of constructing from solutions of Laplace's equation, a family of equipotential surfaces which fit the experimental emitter tip. Once the proper surfaces are chosen, the value of β can be calculated at all points on the emitter surface. Several models have been proposed for calculating β ; the best being that due to Dyke.[6] This model replaces the emitter by one surface belonging to a family of equipotentials defined by a core consisting of a sphere-on-orthogonal cone (figure 3). The anode is replaced by another equipotential of the same family. The equation obtained for β is unwieldly and a "working" expression is used:[6]

$$\beta_{cm^{-1}} = \frac{1.7}{(R)^{.13}\, r^{.87}\, \alpha^{.33}}$$

where:

R is the cathode-anode spacing (cm)

r is the emitter radius (cm)

α is the half angle of the emitter shank

This empirical equation is a good approximation for most emitter geometries used in practice. It should be modified for very small emitter spacings.

Consider now a large number of identical emitters; that is, all with the same β . Ideally, each emitter should act independently of its neighbors and we should obtain a sizeable emission current from the array many times larger than that from a single emitter operated at the same voltage. In reality, this is difficult to achieve; the mechanics of forming a large

number of identical emitter tips is forbidding, and the interference of the field and charge cloud of neighboring emitters will limit emission. The problems to be solved for a multiple emitter cathode, then, are: formation of a large number of identical emitter tips and determining an optimum spacing consistent with the objective of miniaturization.

AN EXPERIMENTAL FIELD EMISSION DIODE

I. Elements

The field emitter cathode used in this experiment is a composite of 9.8×10^6 niobium (ϕ = 4.5 ev) filaments of diameter 1000 Å in a copper wire of diameter 0.13 centimeters.[2] (see fig. 4) The filaments are aligned axially, about one diameter apart, in the matrix. The cathode is formed by etching back the copper matrix a distance of about 10^{-3} cm. with nitric acid, thereby exposing the ends of the niobium filaments. The filament ends do not have to be further pointed as the diameters are already sufficiently small and of approximately constant β throughout. The cathode is then placed a distance of 5mm from the center of the anode.

The anode is a plane piece of 5 mil. niobium 1¼ inches square with corners rounded to prevent field concentrations at high voltages.

II. Experimental Arrangement.

The experimental apparatus is as sketched in figure 5. The experiments were conducted in a high vacuum ($1\text{-}10 \times 10^{-3}$ torr) to prevent sputtering of the emitter tips by heavy positive ions. High vacuum was achieved by roughing with a diffusion pump to 10^{-6} torr and baking at 200 °C for 48 hours. The system was then pinched off and pumping continued by an ion pump attached to the vacuum chamber.

The anode is connected to a high voltage feed-through by a ¼" diameter stainless steel rod. The cathode is mounted in a ¼" diameter OHFC copper rod and the rod connected to a high voltage feed-through. A copper

rod was used here to facilitate cooling the cathode during bake-out of the vacuum system. Cooling was achieved by circulating cold water around the feed-through flange and cooling the emitter by conduction along the rod. (It was necessary to cool the cathode to prevent annealing of the copper surrounding the emitters). Variation of the emitter to anode distance was allowed by the introduction of a bellows in the cathode arm of the vacuum system.

A 0 to 50 kilovolt, 60 milliampere, high voltage source was used in this experiment. The anode was placed at positive voltage relative to the cathode which was at ground. An electrometer was placed in the ground leg of the circuit to measure the field emission current. The circuitry of the experiment is shown in figure 5. A potential X-ray hazzard exists and lead shielding is necessary for voltages exceeding 20 kilovolts and a few milliamperes of current.

III. Results and Observations.

Field emission current verses applied voltage measurements were taken on two experimental cathodes in the 0-12 kilovolt range. The results are shown in figure 6. The high voltage was applied only for a short period of time to curtail damage to the emitters. For readings below 2kv, an auxilary lower-voltage source was necessary for accuracy.

At 12 kv, with cathode (1), the current was beyond the capabilites of the apparatus. (12 kv is also the upper limit of the high voltage

feed-throughs and breakdown here would invalidate any further readings).

When the voltage was raised above 9 kv, emission became somewhat unstable. At this voltage level, there is a large amount of power being dissipated- on the order of 200 watts- from a very small area and, as a consequence, the emitter tips are cleaning themselves; that is, adsorbed gases from the bake-out period are being boiled off. Also, a plasma is beginning to form between the cathode and anode and eventually an arc will travel through this medium.

Cathode number (2) was operated at a somewhat higher vacuum (2×10^{-7} torr) than cathode (1). All other conditions, however, were unchanged. As seen in figure 6, the data obtained closely matches that of cathode (1) up to 6 kv. The cathode was held at 6 kv for several minutes until the current stabilized at 14 milliamperes. Shortly thereafter, the current dropped rapidly and no further emission was achieved from the cathode. By holding the cathode at a high voltage as opposed to the previous style of measurement, the emitters were cleaned as mentioned before and subsequently destroyed by the heat or by heavy ion sputtering. (Ions are easily attracted to emitters this fine because of the very high field concentration at the tips).

DISCUSSION

We first examine the expected characteristics of a single field emitter of the size found in the multiple emitter cathode.

Consider a field emitter of radius 5×10^{-6} cm. (500 Å) at a distance 0.5 cm. from the anode, with cone half angle of 5° . Using the equation on page 12, β is found to be 4×10^{4} cm^{-1}. Assuming a threshold for field emission at an electric field of $\beta V = 10^{7}$ V/cm, the required applied voltage is 250 volts to initiate field emission. A measureable current will not be obtained, however, until around 1 kv. The resulting current for the single emitter at 5 and 10 kilovolts is expected to be 3 and 20 milliamperes respectively.

Field emission from multiple emitter cathodes at low voltages is greater than that from single emitters, but at higher voltages, the current from the multiple emitter cathode matches that from the single emitter. The current densities are, however, very different: A single emitter will yield $J = 2 \times 10^{8}$ amp/cm^{2} at 5 kv, while the multilpe cathode yields 12 amp/cm^{2} . The assumptions here are that the field at the emitters, in the multiple arrangement, is less than the field at a single emitter because of the neighboring fields; and also that all emitters are operating. (If only 1 emitter in 10 were operating, $J = 10^{2}$ amp/cm^{2}) The area used is the total area of the niobium filaments in the matrix.

The current from the multiple emitter cathode does not vary significantly from that expected from a single emitter except at very low voltages. This suggests that emission is severely space charge limited. The main factor seems to be the effect of emitter spacing. The close proximity of emitters leads to field overlap causing the gradient of the potential at each emitter to be reduced. This effect will cause substantial space charge inhibition of emission at fairly low voltages. (A single emitter will become space charge limited at a few thousand volts [6]). Future experiments will be conducted with emitter spacings of better than 100 diameters.

There is a definite possibility that part of the measured current is actually an ion current. One expects an ion current to give a linear relationship between current and voltage. In the data presented, this is not the case at voltages above 1 kv, but at lower voltages the plot is almost linear. However, no current is obtained below thw level of 300 volts and an ion current would be expected at voltages below this level. An ion current will vary with pressure, but good correlation with cathode (1) was obtained when operating cathode (2) at a substantially higher pressure. The evidence of the data leads to the conclusion that a sizeable ion current was not present.

CONCLUSIONS

Emitter proximity was found to be a hindrance to field emission and further experimentation is necessary to develop composites with optimum emitter spacing. One possibility is a tungsten-copper composite constructed in the same manner as the niobium-copper composite. Emitter tips may be formed by etching the tungsten with sodium hydroxide. The emitter separation should be on the order of several diameters.

The composites show very high current yields, especially the second cathode, but short operating liftimes before destruction. The liftime may be enhanced by placing a high voltage on the diode for only a very short period of time (not useful for practical applications) to prevent heating problems and substantial sputtering. A solution to the problem of continued operation may lie among the following:

1: To prevent sputtering, the vacuum must be improved; possibly into the 10^{-10} Torr range. The present equipment is designed to operate in this range and better bake-out procedures are necessary.

2: A cooling system for the cathode may be necessary to conduct heat away from the emitters while in operation.

3: By using finer emitters, we should achieve two results: lower voltages may be used and large field gradients will be confined to a very small region so that ions far away from the cathode will not be attracted to it. Experiments are planned using a 200 Å niobium-copper composite.

4: One possible modification of the experiment would be the insertion of a grid around the cathode placed at low positive voltage relative to ground. The grid would prevent an ion current and at the same time, cut down on sputtering effects.

Field emission was attained at very low voltages, demonstrating that the effect is enhanced by a multiple emitter cathode, but no improvement was achieved at higher voltages. The principle problem, as stated before, is the optimizing of the emitter separation. With the solving of this problem, the composite field emission cathode promises to be a very effective field emitter and a definite step towards the practical use of the field emission phenomena

TYPICAL EMITTER

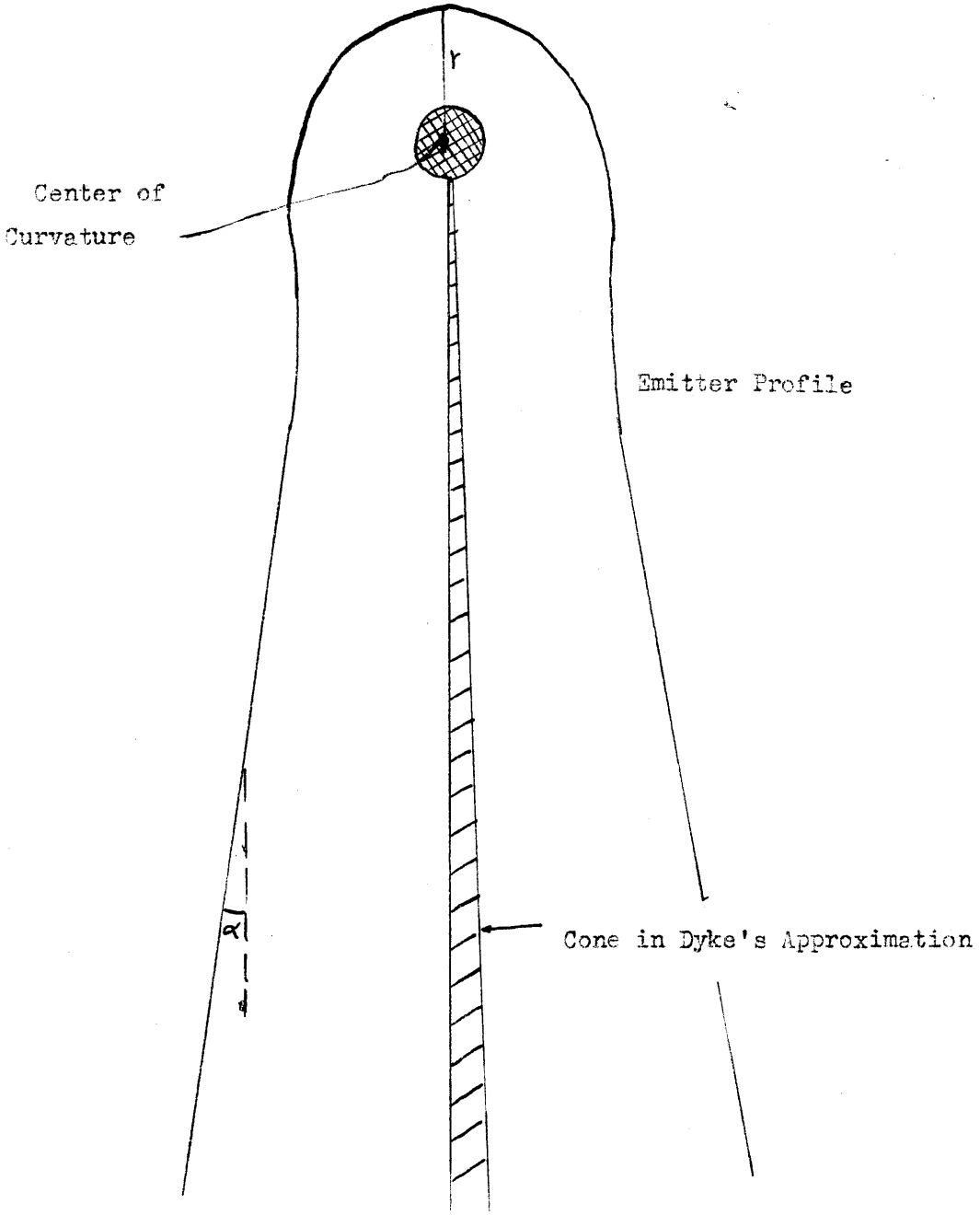
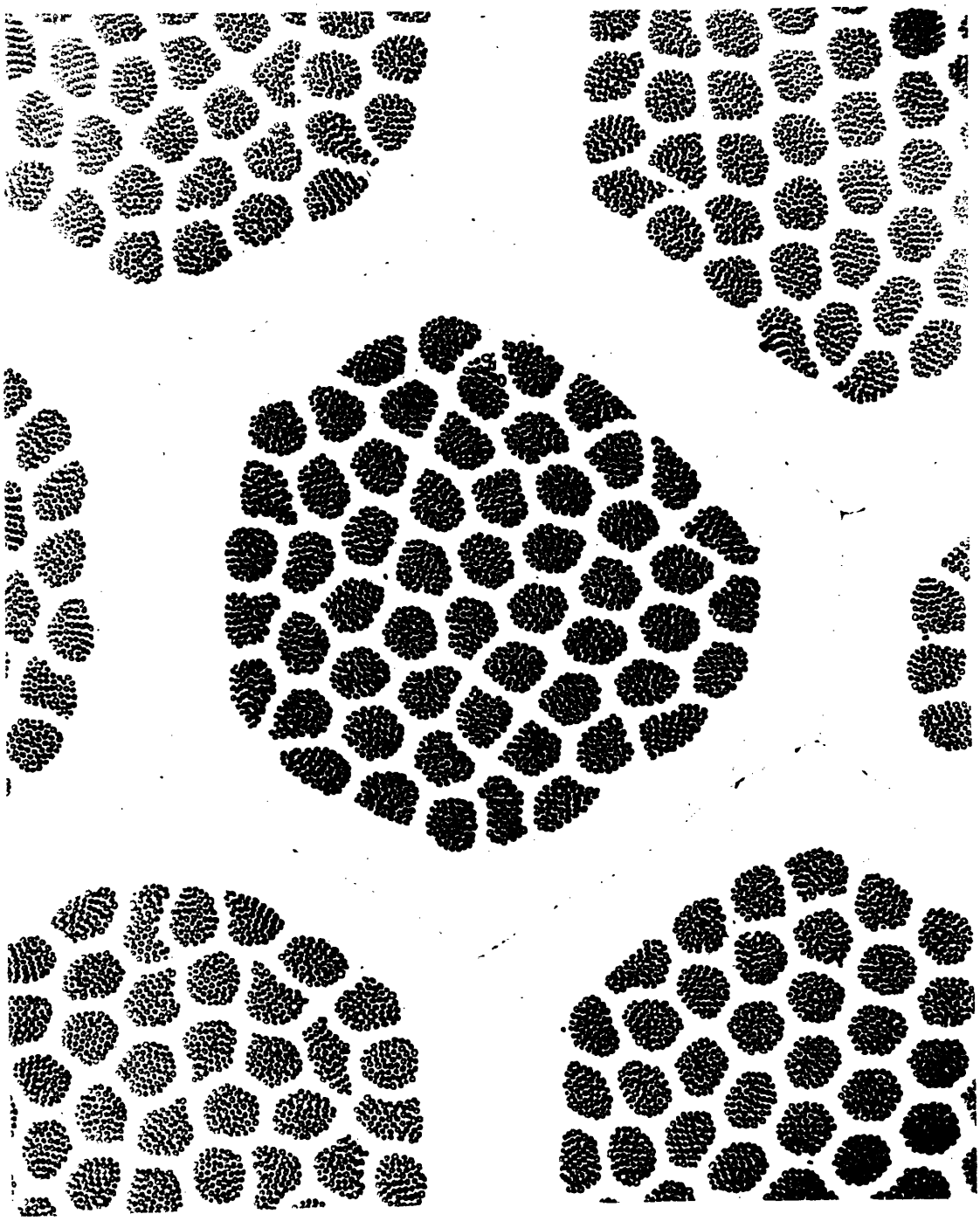


Fig. 3

Niobium - Copper Composite Cathode



Courtesy H.E. Cline

Fig 4

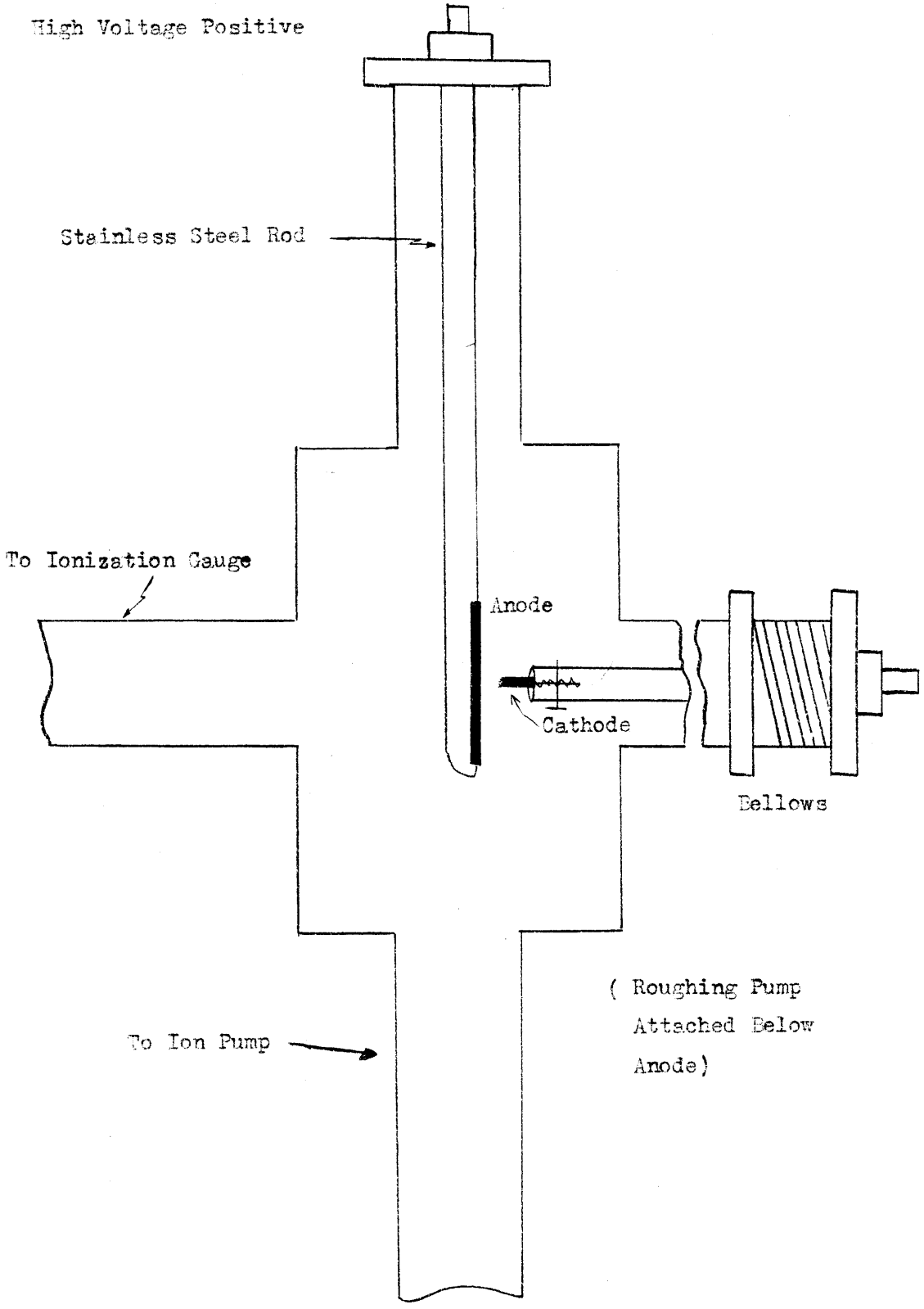
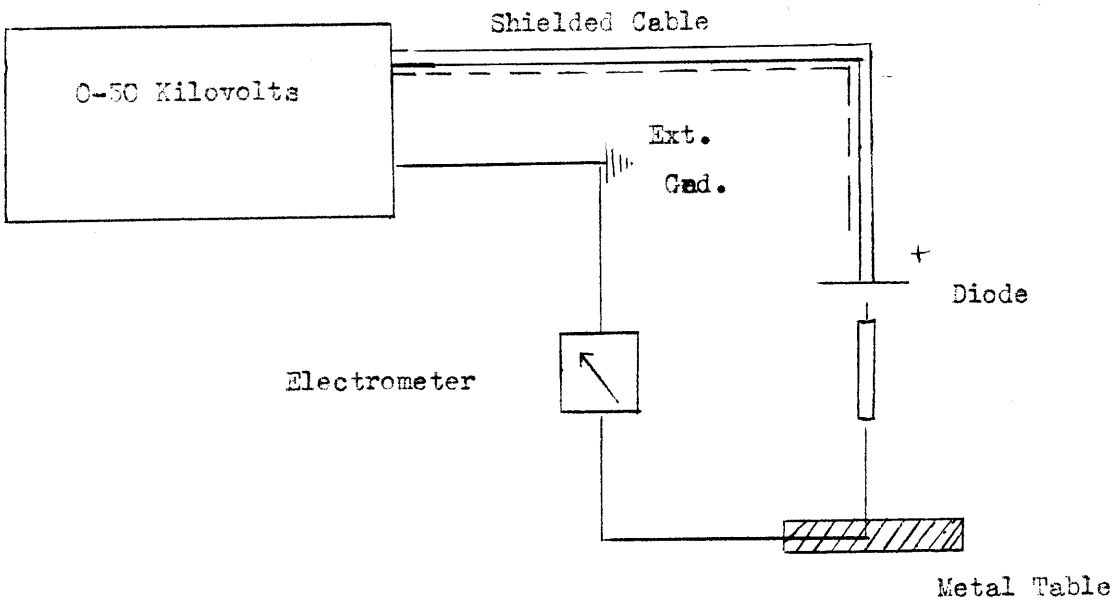

High Voltage Positive
Stainless Steel Rod
To Ionization Gauge
Anode
Cathode
Bellows
(Roughing Pump
Attached Below
Anode)
To Ion Pump

Fig 5a

CIRCUITRY



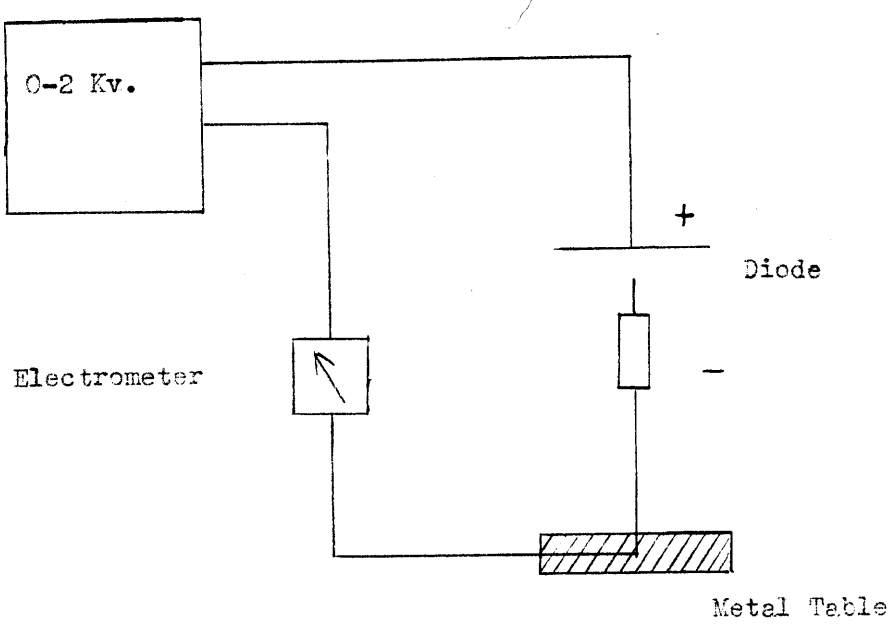


Fig 5b

Fig 6a.

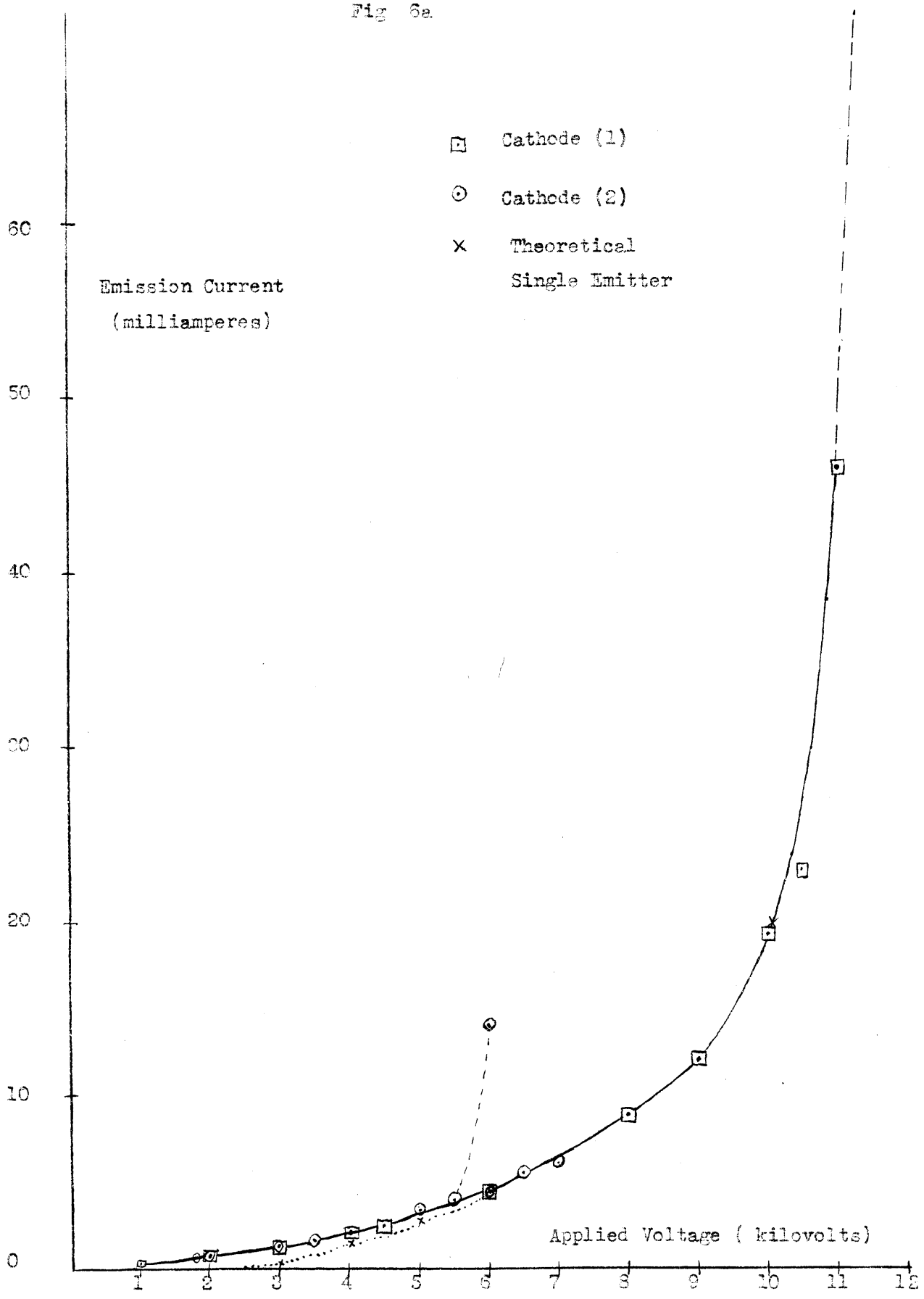
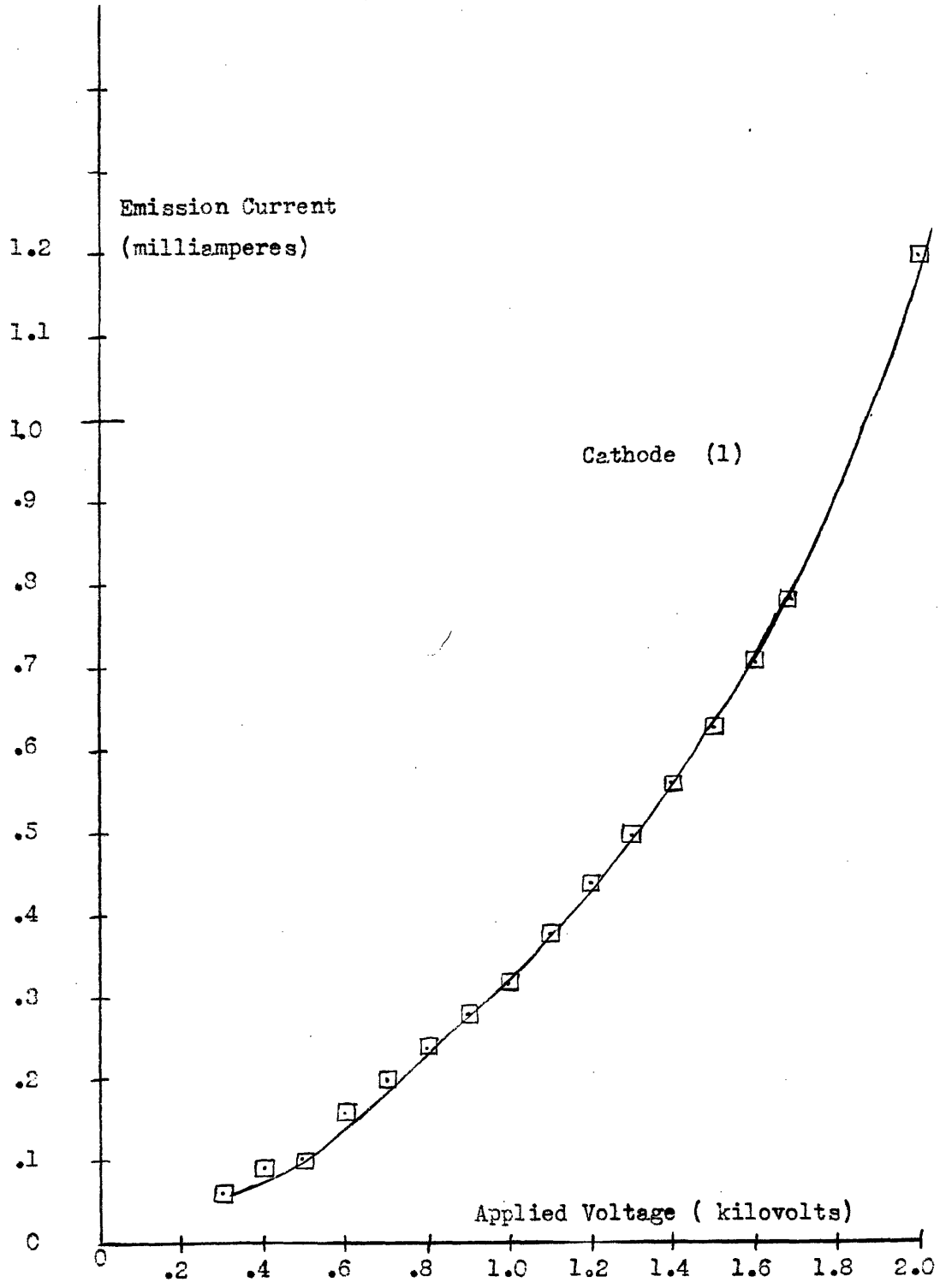

Cathode (1)
Cathode (2)
Theoretical
Single Emitter
Emission Current
(milliamperes)
60
50
40
30
20
10
0
Applied Voltage (kilovolts)
1
2
3
4
5
6
7
8
9
10
11
12

Fig 6b


Emission Current
(milliamperes)
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
0
Cathode (1)
Applied Voltage (kilovolts)
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0

DATA

VOLTAGE (KV)	CURRENT (MA)
Cathode (1)	
.2	0.00
.3	.06
.4	.09
.5	.10
.6	.16
.7	.20
.8	.24
.9	.28
1.0	.32
1.1	.38
1.2	.44
1.3	.50
1.4	.56
1.5	.63
1.6	.71
1.7	.78
1.8	.80
1.9	-
2.0	1.2
2.2	.8 +
3.0	1.1 , 1.6
3.5	1.4
4.0	1.75 , 1.9
4.5	2.7, 3.3
5.0	4.0
5.2	3.8
5.9	4.5
6.0	5.1 , 5.6
6.2	5.1
6.9	8.1
7.0	8.0

DATA

VOLTAGE (KV)	CURRENT (MA)
Cathode (1)	
8.0	10.6 , 9.5
9.0	9.5 unstable , 12.0
10.0	19.0+ , 28 (held for 5 sec at high voltage)
10.5	23.0+
11.0	46.0+
12.0	off scale

The data was taken over a period of one hour. Any changes in readings are noted by the second figure in the data table. Average pressure in the chamber was 6×10^{-8} Torr.

Cathode (2)	
1.8	.75
2.0	.75
3.0	1.30
3.5	1.80
3.8	2.00
5.0	3.30
5.5	4.00
6.0	4.40
6.5	5.40
7.0	6.00

The cathode was then held at 6 kv for a period of 5 minutes. The current attained was steady at 14.0 milliamperes. After this time the cathode was destroyed. Pressure was at 2×10^{-7} Torr .

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