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APRIL 1963

Research Report

On the Characteristics of a Glow Discharge Between Coaxial Cylinders Immersed in a Magnetic Field

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Abstract

The effect of a strong magnetic field on the glow discharge between coaxial brass or aluminum cylinders is investigated. Pressures range from one to two hundred microns and the magnetic field varies from zero to five hundred gauss. Ignition and sustaining voltages are plotted against field strength and pressure. Tube current versus field strength is plotted with pressure and terminal voltage as parameters. Also, tube current versus terminal voltage is plotted with pressure and field strength as parameters. Comparison with the results of previous investigators and with available theory is made.

Contents

On the Characteristics of a Glow Discharge Between Coaxial Cylinders Immersed in a Magnetic Field

1. INTRODUCTION

Gas discharges in one form or another have been studied since about the beginning of the present century. Hundreds of investigators have been working in the field and have contributed to the store of theoretical and experimental knowledge. Generally, most of these studies were made using parallel plate electrode geometry, but other geometries have also been used. The more common of these are the sphere gap, point and plane, two points, and coaxial cylinders. Much of the work already done has neglected the effect of a magnetic field, but some investigators have used both longitudinal and transverse fields with the parallel plane geometry. A short summary of this work and the significant results follows.

Birkland found that when a discharge tube was placed in a longitudinal magnetic field, the potential required to produce a discharge was reduced.[1] Almy extended these measurements and observed the same results.[2] He also noted that when the magnetic field was applied, the discharge was confined to stream-like lines instead of filling the entire tube. Paalzow and Neeson found that at certain pressures a weak field facilitates a discharge while a stronger one decreases it. Phillips and Strut noticed that if two iron electrodes were placed in a vacuum, a discharge passed at a reduced potential if they were magnetized.[3,4]

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Willows investigated the effect of a transverse field applied to the electrodes separately.[5] He found that when the field was applied to the cathode only, there is a pressure below which the current is increased by the field and above which it is reduced. This "critical pressure" was found to depend on the value of the field and also on the initial current flowing in the tube. For the same initial current, an increase in the field increases the critical pressure. If, for the same field, the initial current is decreased, the critical pressure is rapidly lowered. When any other part of the tube was placed in the field, the current was reduced.

R. F. Earhart examined the discharge in a longitudinal field and found that upon application of the field, the soft glow changed to stream-like filaments.[6] The current for small fields was increased, while larger fields reduced it. If the field was strong enough, the current was reduced below the initial value observed when the field was absent. He also found that higher gas pressures required a higher magnetic field to obtain a reduction in current. His measurements were made with pressures in the range from 0.24 mm to 3.44 mm Hg.

Earhart and Green investigated the effect of a magnetic field upon the current between plane parallel electrodes.[7] They used both longitudinal and transverse fields and found that small transverse fields increased the current while stronger ones reduced it.

Takamine, Suga, and Yanagihara investigated the sparking potential between coaxial cylinders in air, without a magnetic field.[8] Several different sizes of cylinders were used in these experiments. Other experiments were performed in which they investigated the effects of a magnetic field on the light output of the tube. In these experiments, the parallel plate and the point-to-plane geometries were used with both transverse and longitudinal fields. Increased field strengths increased the light output and there appears to be a close resemblance between the effect of increased pressure and a magnetic field. This work was done for pressures ranging from 1 to 30 mm Hg and field strengths from 0 to 8000 gauss.

Several people have published articles in which they have attempted to derive equations to explain what occurs when a discharge tube is placed in a magnetic field. The articles by Hull and Somerville were outstanding in this regard.[9,10]

2. EXPERIMENTAL SETUP AND EQUIPMENT DESCRIPTION

The type of coaxial tube used in these experiments is shown in Figure 1. The inner and outer cylinders were constructed of either brass or aluminum.

Generally, both cylinders were made of the same material, but one tube was built with an aluminum inner cylinder and a brass outer one. The end pieces were made of one inch plexiglas, machined for a force fit and cemented into place with shellac. The pressure obtained with this type of construction was near one micron (10^{-3} mm Hg). During the machining operation, the end pieces for the aluminum tube became translucent, which prevented good visual observation of the discharge. However, those for the brass tube were transparent and visual observation was possible. Leads were attached to the inner cylinder with spring devices. Clamps were used for attaching leads to the outer cylinder.

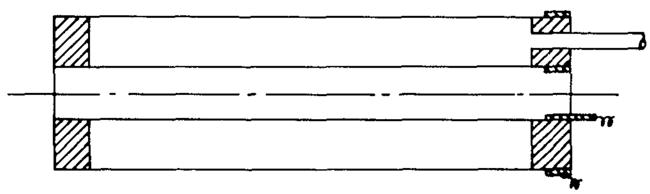


Figure 1.

Throughout the rest of this report, the tubes will be referred to by the names shown in the following table, which represent the material and dimensions. The greatest part of the experimental data was taken on the first three tubes. The hybrid tube has an aluminum inner cylinder and a brass outer cylinder. Numbers in parentheses are the centimeter equivalents of the measurement in inches.

The equipment used in the experiment is shown in Figure 2.

Table I.

Name	Length (Overall)	Length (Effective)	Diameter Inner		Diameter Outer		Spacing Between Cylinders
Brass No. 1	40.1" (101.6)	38.0" (96.52)	1.0" (2.54)	OD	3.0" (7.62)	ID	1.0" (2.54)
Aluminum No. 1	21.0" (53.34)	19.0" (48.26)	.625" (1.5875)	OD	2.117" (5.3772)	ID	.746" (1.895)
Hybrid	10.0" (25.4)	8.0" (20.32)	1.0" (2.54)	OD	3.0" (7.62)	ID	1.0" (2.54)

Table I (Cont)

Name	Length (Overall)	Length (Effective)	Diameter Inner		Diameter Outer		Spacing Between Cylinders
Brass No. 2	14.0" (35.56)	12.0" (30.48)	1.0" (2.54)	OD	2.404" (6.106)	ID	.702" (1.783)
Brass No. 3	10.0" (25.4)	8.0" (20.32)	1.0" (2.54)	OD	3.0" (7.62)	ID	1.0" (2.54)
Aluminum No. 2	21.0" (53.34)	19.0" (48.26)	.625" (1.5875)	OD	1.892" (4.806)	ID	.6335" (1.609)

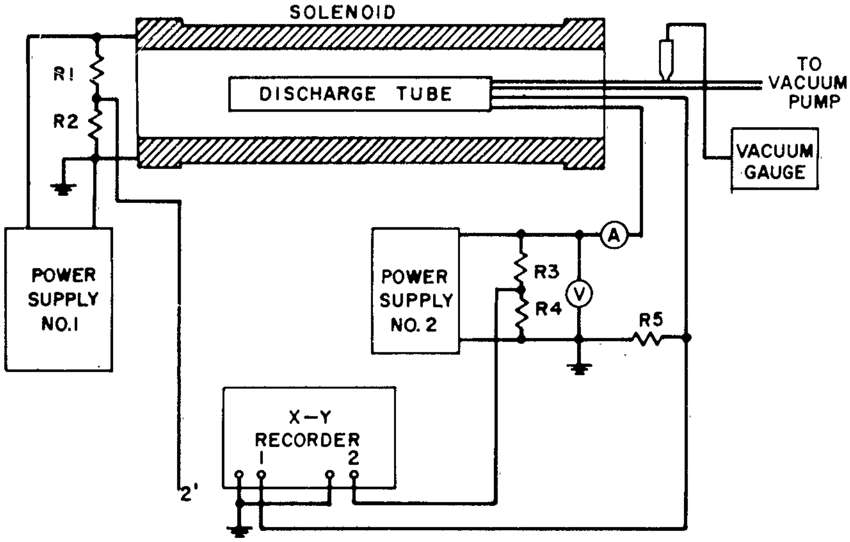


Figure 2.

The solenoid used to produce the magnetic field consists of a main coil and two compensating coils, one on either end. The overall length of the solenoid is 61 inches; the overall diameter is 12 inches. The usable inner diameter, with allowance for the coil frame, is about 8 inches. A flux density of about 500 gauss is measured on the axis with a current of 5 amperes flowing in the coils. The coils overheat if operated at this current for more than a few minutes, which limits the test time. At lower currents, below about 2.5 amperes, overheating is not so much of a problem and longer test periods were used. The field has been mapped and found to be uniform to within 3% over the central 50 inches, and to within 1% over the central 30 inches. It is uniform radially over the region occupied by the tube.

Power supply No. 1 is used to supply current to the solenoid. Since the resistance of the solenoid is quite high, it takes about 1500 volts to produce a current of 5 amperes. The resistive divider, consisting of R_1 and R_2, produces an output signal proportional to the flux. This is used for plotting purposes with the X - Y recorder.

Power supply No. 2 is variable and supplies the electrode voltage and current to the discharge tube. The power supply used in this experiment is a Model 500R regulated supply, built by Kepco Laboratories, Inc., of Flushing, N.Y., capable of supplying from 0 - 600 volts at from 0 - 300 ma. The resistive divider, R_3 and R_4, produces a signal proportional to tube voltage and R_5 produces one proportional to tube current.

The X - Y recorder is a Model HR-931, built by Houston Instrument Corporation, of Houston, Texas. It has a critically damped response, a pen speed of 7-1/2 in/sec, 10 mv/in sensitivity, and a specified accuracy of 1/2%. The resistive dividers were chosen so that their output signals would allow full scale excursion of the recorder. The recorder has built-in attenuators for final calibration. Calibration for voltage and current measurements was accomplished by placing a load on the power supply in place of the tube. Voltage was applied and the current noted. The recorder attenuators were adjusted to give proper excursion at the maximum signals to be applied, and the linearity was also checked. The same sort of procedure was used to calibrate the recorder when flux was plotted on one axis. A gaussmeter, Model 1890, manufactured by Radio Frequency Laboratories, Inc., of Boonton, N.J., was used to measure the flux at specified currents and the attenuator was adjusted for proper excursion. The data presented in this report for I_b vs E_b , and I_b vs B, are tracings of the X - Y plots.

A Cenco Hyvac 2 vacuum pump, manufactured by Central Scientific Company of Chicago, Ill., was used. The pressure was measured with a thermocouple vacuum gauge, Model 501, manufactured by NRC Equipment Corporation, of Newton, Mass.

3. EXPERIMENTAL DATA AND PROCEDURE

Previous to assembly, the cylinders were cleaned and polished to remove any foreign material and rough spots. Care was taken during assembly to insure that fingerprints were not left on the parts and that no dirt entered the tubes. They were then sealed, connected to the pump, and pumped down as far as possible. Since the ends were made of plexiglas, it was not possible to bake out the tubes at high temperatures. Additional outgassing was accomplished by initiating a glow discharge and establishing the maximum possible current. The initial glow discharges were slightly unstable in the brass tubes and quite unstable in the aluminum ones. The pressure rose during these initial discharges due to evolution of gas from the metal and this contributed to the instability. After being "seasoned" for a few hours, the ultimate pressure was much lower and stability had improved considerably.

An exception to the improved stability after the electrodes had been seasoned occurred in the case where the outer cylinder was being used as the cathode for the aluminum tubes. When the inner cylinder was the cathode, operation was quite stable, but when the polarity was reversed no combination of applied voltages and fields resulted in stable operation. A glow discharge was present, but it was interspersed with intermittent arcing, which became almost continuous at times. This prevented obtaining data both on the relationship between tube current and field strength, and on tube current versus terminal voltage in the case where the outer cylinder is used as the cathode.

The brass tubes were operated for several hours before any data was taken. Initial measurements of ignition voltage as a function of field strength were quite scattered, but after the electrodes had been "seasoned" for a few more hours, the data became reproducible. Data was obtained by setting the field at a selected value and increasing the voltage until breakdown occurred. It was then reduced below the breakdown or ignition voltage to allow the gas to deionize and for equilibrium conditions to become re-established. Then, several more readings were made at the same point. Repeatability of the readings was quite good for the brass tubes but was not quite as good for the aluminum ones. Sufficient data was taken at selected pressures and flux densities to plot the curves.

Initially, all six tubes were operated with flux densities ranging from 0 to 120 gauss. Upon completion of the new power supply for the solenoid, it was possible to obtain a flux density of about 500 gauss, so additional measurements were made for Brass Tube No. 1, Aluminum Tube No. 1 and the Hybrid Tube. Some interesting effects were noticed at flux densities in excess of 200 gauss, and these will be commented on in more detail later in this report.

Figures 3a through 10 pertain to Brass Tube No. 1. Figures 3a and 3b plot the ignition voltage as a function of magnetic flux density with pressure as a parameter, in the case where the outer cylinder is the anode. Figure 3b shows the left-hand portion of the curves with an expanded scale and some additional data. For pressure of about 40 microns and below, it was not possible to obtain a glow discharge with the voltages available when no external field was present. As the pressure increases, it becomes possible to obtain a glow discharge without an external field. The required voltage falls as the pressure rises until a minimum point is reached, after which it rises again. For pressures below 100 microns, the magnetic field has a great effect on the ignition voltage but for higher pressures, changes in flux have a much smaller effect. The curves for 150 and 200 microns are nearly horizontal as a function of flux density from 0 - 120 gauss. The minimum ignition voltage is about 260 volts and it occurs for a flux of 100 gauss.

Figures 4a and 4b plot the same thing as Figures 3a and 3b except that, in this case, the outer cylinder is the cathode. The curves are similar but the minimum voltage is considerably greater, on the order of 292 volts as against 260 volts for the opposite polarity.

Figure 5 plots the ignition voltage as a function of pressure, with flux density as a parameter, in the case where the outer cylinder is the anode. The minimum ignition voltage occurs for a flux of about 100 gauss and a pressure of about 47 microns. As the magnetic field is increased from 0 - 500 gauss, the minimum points on the curves move from right to left and downward until a low point is reached, after which they begin to move upward and to the right again. For flux densities in excess of about 300 gauss, the change in the ignition voltage with pressure is quite small. Figure 6 shows the curves in the case where the outer cylinder is the cathode.

Figure 7, a through d, shows the effect of the magnetic field on the current conducted by the tube. The curves are tracings of those made by the X - Y recorder. The terminal voltage was initially set at 350 volts and the flux was increased to the maximum and then decreased to zero while the current was recorded. The pressure was changed and additional curves were obtained. At low pressures, it requires a magnetic field to initiate the discharge at this voltage, while at higher pressures, the tube conducts without the field. At very low pressures, the current rises rapidly to a maximum and then rapidly falls to zero again as the flux increases. This is a rather smooth transition with no sharp discontinuities except at ignition and extinction. For higher pressures, there is a "critical field" at which the tube ceases to conduct, while for still greater pressures, the tube cannot be extinguished with the available field. Figure 7b shows a discontinuity between the current maximum and the cutoff point. This occurred only with the brass tube, as neither the aluminum nor hybrid tube showed this characteristic. The current maximums occur for higher values of flux as the pressure is increased. Terminal voltage falls as the current increases, reaching a minimum of 310 volts for a pressure of 1 micron and 280 volts for a pressure of 100 microns. Maximum currents at these points are 260 and 265 ma, respectively.

Figure 8, a through d, shows the current as a function of flux density in the case where the outer cylinder is the cathode. These curves are of similar form to those of Figure 5, with several exceptions. The 5 micron curve has a definite cutoff flux where a smooth but rapid transition existed in the previous case. A curve for 9 microns also showed a rapid but smooth transition when the outer cylinder was the anode. In this case, currents rise to their maximums at a lower flux and the peak currents are about 10% greater. Except where the pressure is very low, the critical fields are less when the outer cylinder is the cathode. Quite pronounced differences are observed for the different polarities when the pressure is 140 microns.

When the flux is decreasing, the tube re-ignites when the flux is reduced below the critical value. This occurs for both polarities, and conduction continues as the flux is reduced below the ignition value.

Figure 9, a through c, shows the tube current as a function of terminal voltage. The X - Y recorder was also used to obtain this data. The field was set at a specific value and the voltage was slowly increased until ignition occurred. After ignition, the variac on the power supply was further increased and the current also increased. When the outer cylinder is the anode, and for flux densities below 120 gauss, the voltage change is very large for a current change of 300 ma. As the field is increased, this voltage change becomes smaller, and is very small for strong fields. For fields greater than about 200 gauss, the tube ignites and then immediately drops down to a lower sustaining voltage which shows little change as the current increases. The 45° negative slope is due to the response characteristic of the recorder. Immediately after ignition, the voltage drops and the current rises, but this takes place too rapidly for the recorder to follow. It goes from the initial to final condition as rapidly as possible, resulting in the 45° line.

Figure 10, a through c, shows the current as a function of terminal voltage when the outer cylinder is the cathode. For flux densities below 110 gauss, operation is similar to the previous case except that the voltage change for similar current change is much smaller. For flux densities of 360 and 490 gauss, the tube begins to exhibit a negative resistance characteristic. The terminal voltage falls, and the current rises, as the power supply variac is increased. It appears that two values of cathode fall are possible, and that they are functions of current and magnetic field.

Figure 11 through Figure 16 pertain to Aluminum Tube No. 1. Figure 11 shows the ignition voltage as a function of flux density when the anode is the outer cylinder. For pressures below 100 microns and with the available voltages, the tube will not ignite without an external magnetic field, but ignition is possible at 200 microns. The minimum ignition points decrease with an increase in pressure in the range from 1 to 100 microns. Above this range they begin increasing again. The minimum ignition voltage is about 220 volts; it occurs at 120 gauss and 100 microns.

Figure 12 plots the same functions as Figure 11, when the outer cylinder is the cathode. The curves are quite close together and, except for low flux densities, pressure doesn't seem to have a very large effect on the ignition potentials. The minimum points on the curves occur at higher flux levels than they did in the previous case. The minimum ignition voltage is approximately 277 volts. It occurs for a pressure of about 60 microns and a flux density of between 120 and 180 gauss.

Figure 13 shows the ignition voltage as a function of pressure, with flux as a parameter when the outer cylinder is the anode. Changes in ignition voltage as a function of pressure, for a constant field, are nowhere as pronounced as they are for the brass tube.

Figure 14 plots the same functions when the cathode is the outer cylinder. Except at small values of flux, the pressure has a rather small effect on the ignition voltage.

Figure 15, a though f, shows tube current as a function of magnetic field when the outer cylinder is the anode. Currents for Figure 15, a through c, were obtained for an initial voltage of 300 volts. In Figure 15, d through f, the initial voltage was 350 volts. The current reaches its maximum at a higher flux than it did for the brass tube, and the critical field is reached soon after the maximum. For an initial voltage of 350 volts, the magnetic field is not able to cut the tube off sharply and the curve has a long trailing edge.

Figure 16, a through d, shows the current as a function of terminal voltage with flux as a parameter. For low fields and pressures, the tube behaves in a manner similar to that of the brass tube, but higher fluxes are required for conduction. As the field increases, the curves begin to take on a negative resistance characteristic. For a pressure of 40 microns, this effect only appears for the maximum field. At 70 and 100 microns, it is entirely absent. For higher pressures and fluxes, the tube ignites and the terminal voltage immediately drops to a lower sustaining voltage, which changes little as the current increases. For this condition, the tube is a rather good voltage regulator, but the regulating characteristics are extremely poor for low pressures and/or fluxes.

No data was taken with the X - Y recorder to obtain curves for the case where the outer cylinder is the cathode, due to instability of the discharge. Rapid intermittent arcing occurred with this polarity, which created extreme excursions in voltage and current. Any data obtained with the recorder would be meaningless.

Figure 17 through Figure 24 pertain to the Hybrid Tube. Its operating characteristics will be compared with those of the brass tube, since the respective diameters are equal.

Figure 17 and Figure 18 plot the ignition voltage as a function of flux density, with pressure as a parameter. The result obtained when the outer cylinder is the anode is shown in Figure 17; Figure 18 is for the opposite polarity. For the first case and similar pressures, the minimum ignition voltage is about 80% of the brass tube's value. When the outer cylinder is the cathode for the hybrid tube, the minimum ignition voltage is about 70% of the brass tube's value.

Figure 19 and Figure 20 are plots of ignition voltage as a function of pressure, with flux density as a parameter. For the values of flux plotted in Figure 19, pressure does not appear to have a great effect on the ignition voltage. This is consistent with the values obtained for the brass tube at similar pressures, but the values are considerably lower. Figure 20 is plotted for the case where the outer cylinder is the cathode. Changes in ignition voltage with pressure are somewhat greater in this case than in the previous one, at similar values of flux.

Figure 21, a through c, shows the current as a function of flux density when the outer cylinder is the anode. At 3 microns, a definite critical field exists. The current for the brass tube shows no sharp transition in this pressure range. At 40 microns, the critical field is considerably lower than it is for the brass tube at a similar pressure. At flux densities in excess of 250 gauss, the tube is very unstable at 100 microns. When the flux is decreasing, re-ignition occurs at a relatively higher value than it does for either the brass or aluminum tubes.

Figure 22 shows the current as a function of flux density when the outer cylinder is the cathode. The current is greater in this case, by 7 to 15%; the higher figure being applicable at lower pressures. When the flux is decreasing, the point at which the tube re-ignites is considerably lower than it is when the polarity is reversed.

Figure 23 shows the tube current as a function of terminal voltage, with flux density as the parameter, when the outer cylinder is the anode. For pressures of 40 microns or less, and flux densities of less than 60 gauss, the tube exhibits a negative resistance characteristic. Initially, current rises with increases in terminal voltage, but a point is reached at which saturation occurs. The current levels off and then begins to fall as the terminal voltage is increased further. It drops while the voltage changes by 50 to 80 volts, after which it levels off and starts to rise again. This effect was not observed at higher pressures or flux densities. Between 60 and 490 gauss, tube behavior was similar to the brass one.

As the flux was increased, the change in terminal voltage necessary to cause a specified change in current became smaller. This voltage change became constant at a value slightly larger than that obtained for the brass tube when the flux was in excess of 230 gauss.

Figure 24 shows the same functions as Figure 23 except now the outer cylinder is the cathode. No great differences in the characteristics are noted when the pressure is 6 microns, except that the voltages are not quite the same as they were for the opposite polarity. At 40 and 100 microns, two operating regions appear for flux densities in excess of 360 gauss. The shift between these two operating regions occurs for lower currents as the pressure is increased. Thus, the two values of cathode fall appear to be functions of pressure, flux density, and current.

In Figures 25, 26, and 27, the ignition and sustaining voltages are plotted against flux density for Brass Tube No. 1, Aluminum Tube No. 1, and the Hybrid Tube, respectively. At higher flux densities, when the outer cylinder is the anode, the tube ignites at one voltage and then immediately falls to another, or sustaining, voltage. As the flux is reduced, the ignition voltage becomes smaller while the sustaining voltage remains nearly constant. The two curves intersect, and there is no noticeable difference in the two voltages as the field is further reduced. An exception to this is found with the aluminum tube at a pressure of 20 microns and 490 gauss. Here, the sustaining and ignition voltages are very close together. For this field and pressure, Figure 16b shows two operating regions; the tube operates first in the upper one.

When the outer cylinder is the cathode, the sustaining voltage curves lie below those for the ignition voltage. There are no intersections of the two curves for the brass and aluminum tubes. The curves for the hybrid tube intersect between 70 and 80 gauss. The ignition and sustaining voltages for the hybrid tube are the same at 365 gauss and 100 microns. Two possible values of cathode fall occur in this case, as may be seen in Figure 24c.

Some information was obtained for Brass Tube No. 2 and Aluminum Tube No. 2. These were not operated as long as the other three tubes, and were therefore not as well "seasoned". This resulted in some scattering of the data. It was not possible to operate them with fields in excess of 124 gauss, due to the non-availability of a suitable power supply. This supply was completed only after all the initial data had been obtained and then additional data was taken for the other tubes. Therefore, none of these curves for ignition voltage as a function of flux density reach a well defined minimum point, as the minimum occurs at higher flux densities.

Aluminum Tubes No. 1 and No. 2 are the same length and have the same size inner cylinder, but tube No. 2 has a smaller outer cylinder. When the outer cylinder is the cathode, neither of them would operate stably under any combination of potentials and fields. Figure 28 and Figure 29 show the ignition voltage as a function of flux density, with pressure as the parameter. The ignition voltages are considerably greater for tube No. 2 at the same pressures and flux densities.

The X - Y recorder was used to obtain the data presented in Figures 30, 31, and 32. Figure 32 illustrates the relationship between tube current and terminal voltage when the flux is varied. For a selected pressure, the field was set close to the smallest one which would allow a discharge to start and still allow the current to reach nearly full scale as the field was increased. The glow discharge was initiated by increasing the voltage, and the resultant current and terminal voltage formed the first point on the curve. The field was increased to its maximum and then decreased to zero. Several points were marked on the resulting curve, indicating the value of the flux at that point. The terminal voltage falls and the current rises as the flux increases. Therefore, an increase in flux density reduces the tube's impedance.

Figure 33 through Figure 36 pertain to Brass Tube No. 2. The inner cylinder is the same diameter as that of tube No. 1; the outer cylinder is smaller.

No additional data will be presented for Brass Tube No. 3, since the cylinders are the same diameter as those in Brass Tube No. 1.

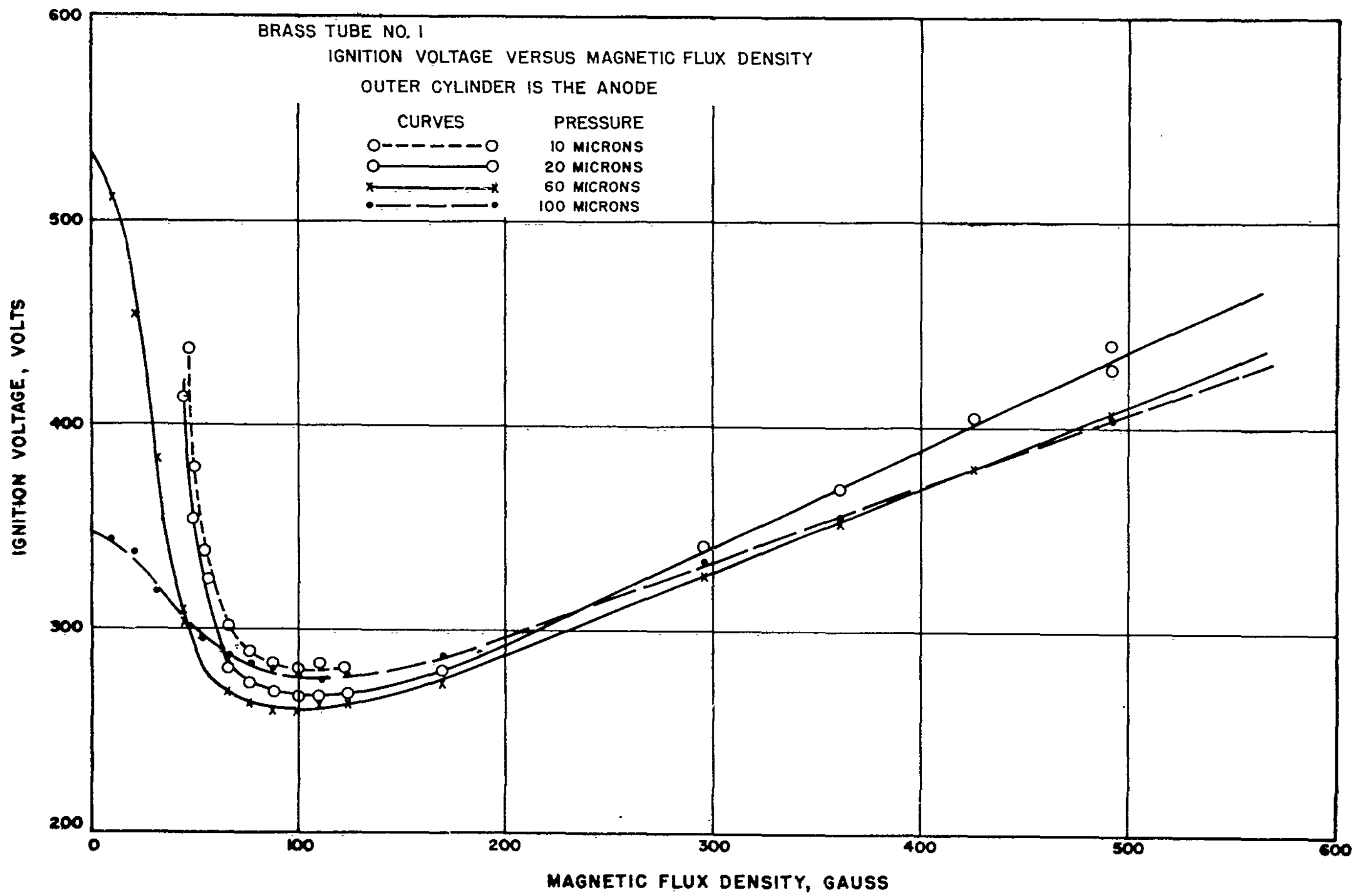

BRASS TUBE NO. 1
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVES
PRESSURE
10 MICRONS
20 MICRONS
60 MICRONS
100 MICRONS
600
500
400
300
200
IGNITION VOLTAGE, VOLTS
0
100
200
300
400
500
600
MAGNETIC FLUX DENSITY, GAUSS

Figure 3a

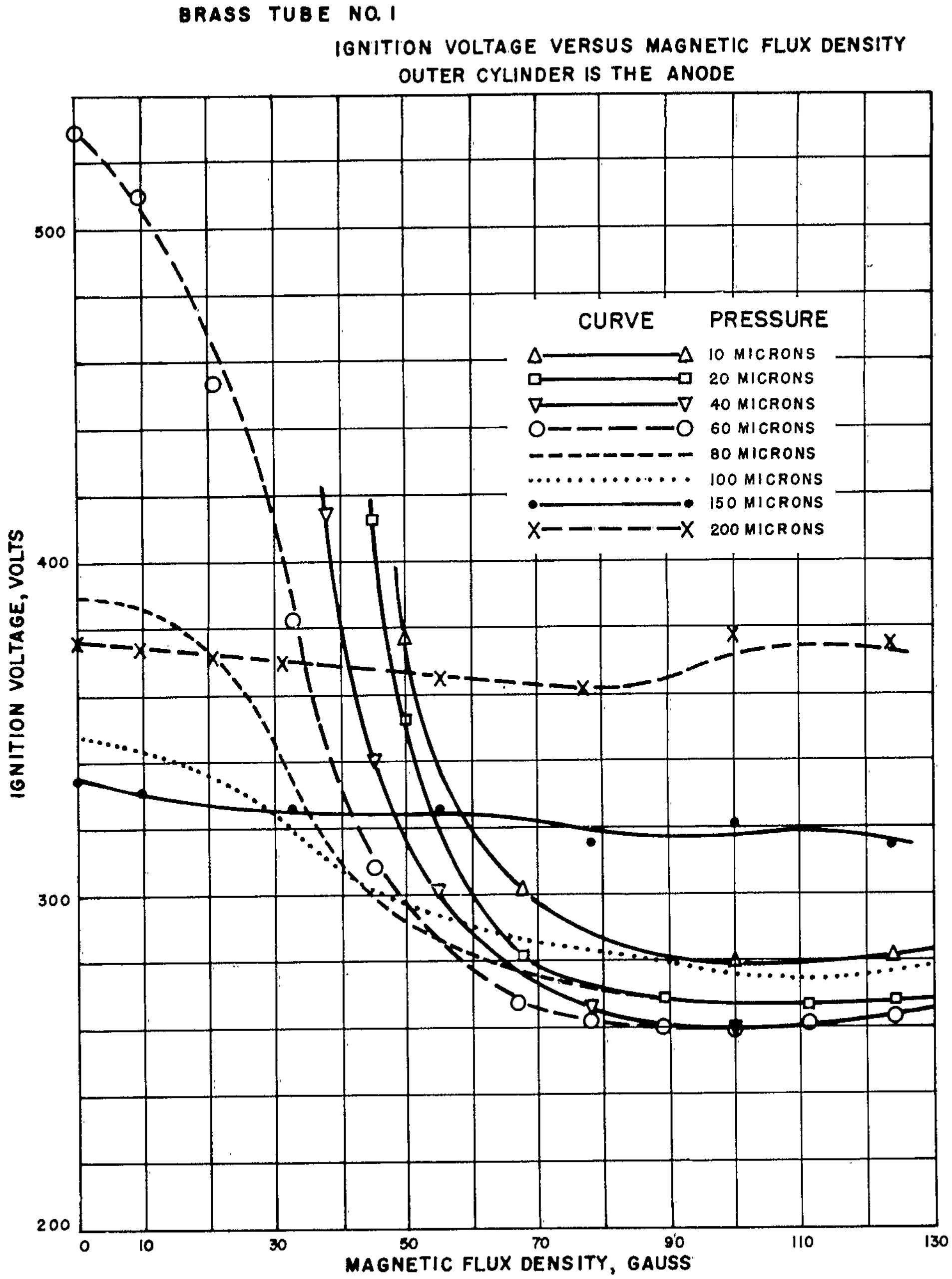
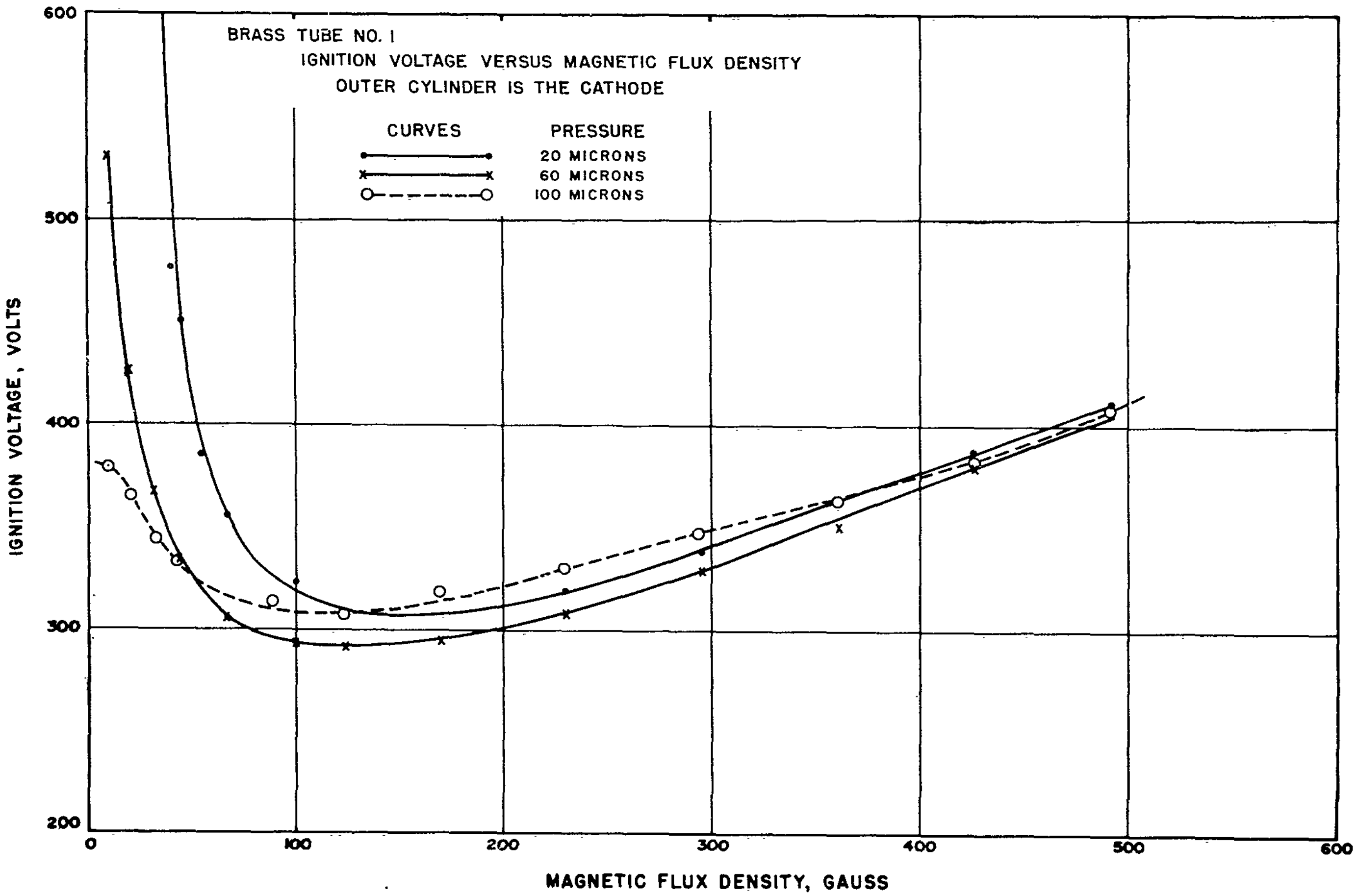

BRASS TUBE NO. I
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
10 MICRONS
20 MICRONS
40 MICRONS
60 MICRONS
80 MICRONS
100 MICRONS
150 MICRONS
200 MICRONS
IGNITION VOLTAGE, VOLTS
500
400
300
200
0
10
30
50
70
90
110
130
MAGNETIC FLUX DENSITY, GAUSS

Figure 3b



BRASS TUBE NO. 1
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVES
PRESSURE
20 MICRONS
60 MICRONS
100 MICRONS
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
100
200
300
400
500
600
MAGNETIC FLUX DENSITY, GAUSS

Figure 4a

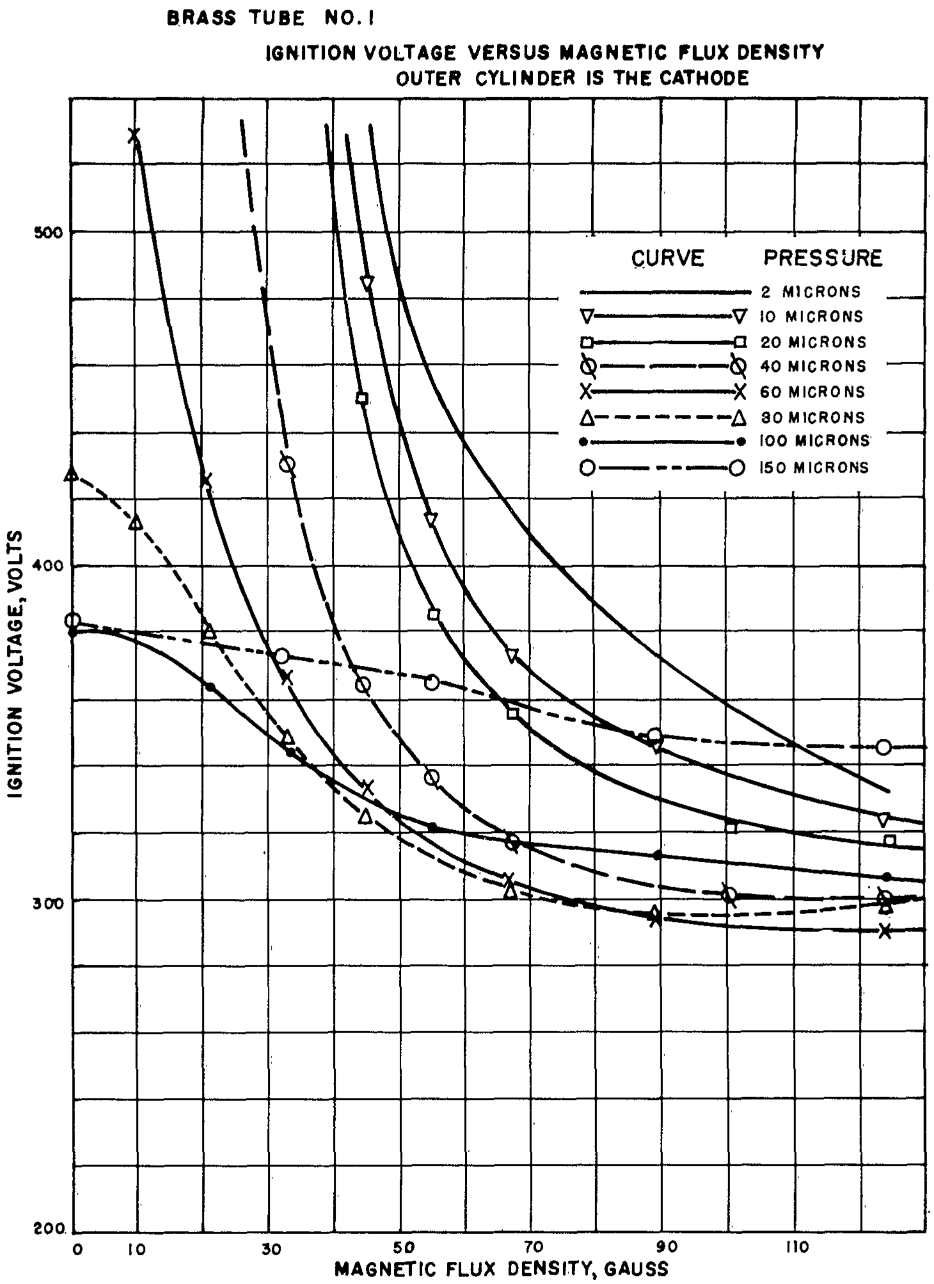

BRASS TUBE NO. I
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVE
PRESSURE
2 MICRONS
10 MICRONS
20 MICRONS
40 MICRONS
60 MICRONS
80 MICRONS
100 MICRONS
150 MICRONS
IGNITION VOLTAGE, VOLTS
500
400
300
200
0
10
30
50
70
90
110
MAGNETIC FLUX DENSITY, GAUSS

Figure 4b

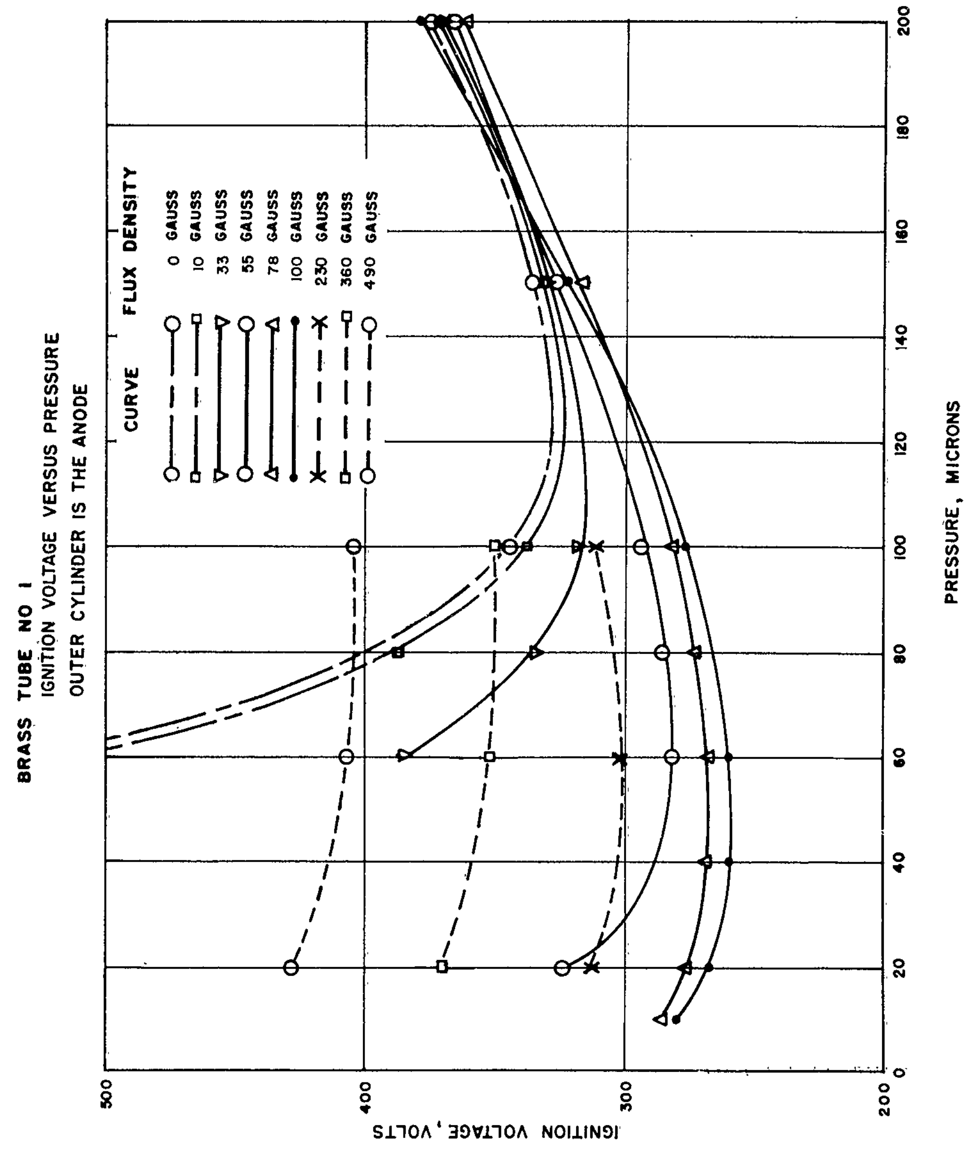

BRASS TUBE NO I
IGNITION VOLTAGE VERSUS PRESSURE
OUTER CYLINDER IS THE ANODE
CURVE
FLUX DENSITY
0 GAUSS
10 GAUSS
33 GAUSS
55 GAUSS
78 GAUSS
100 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
IGNITION VOLTAGE, VOLTS
500
400
300
200
0
20
40
60
80
100
120
140
160
180
200
PRESSURE, MICRONS

Figure 5

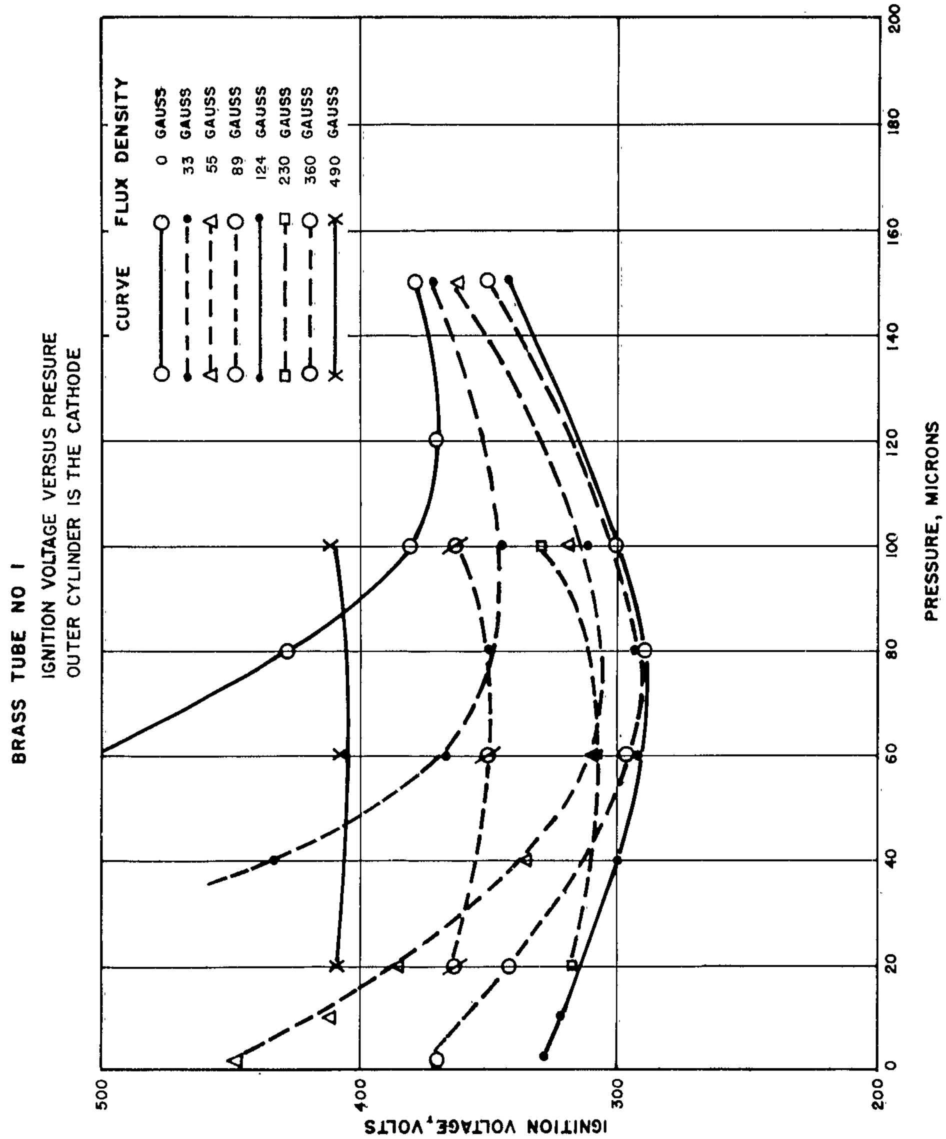

BRASS TUBE NO 1
IGNITION VOLTAGE VERSUS PRESURE
OUTER CYLINDER IS THE CATHODE
CURVE
FLUX DENSITY
0 GAUSS
33 GAUSS
55 GAUSS
89 GAUSS
124 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
IGNITION VOLTAGE, VOLTS
500
400
300
200
PRESSURE, MICRONS
0
20
40
60
80
100
120
140
160
180
200

Figure 6

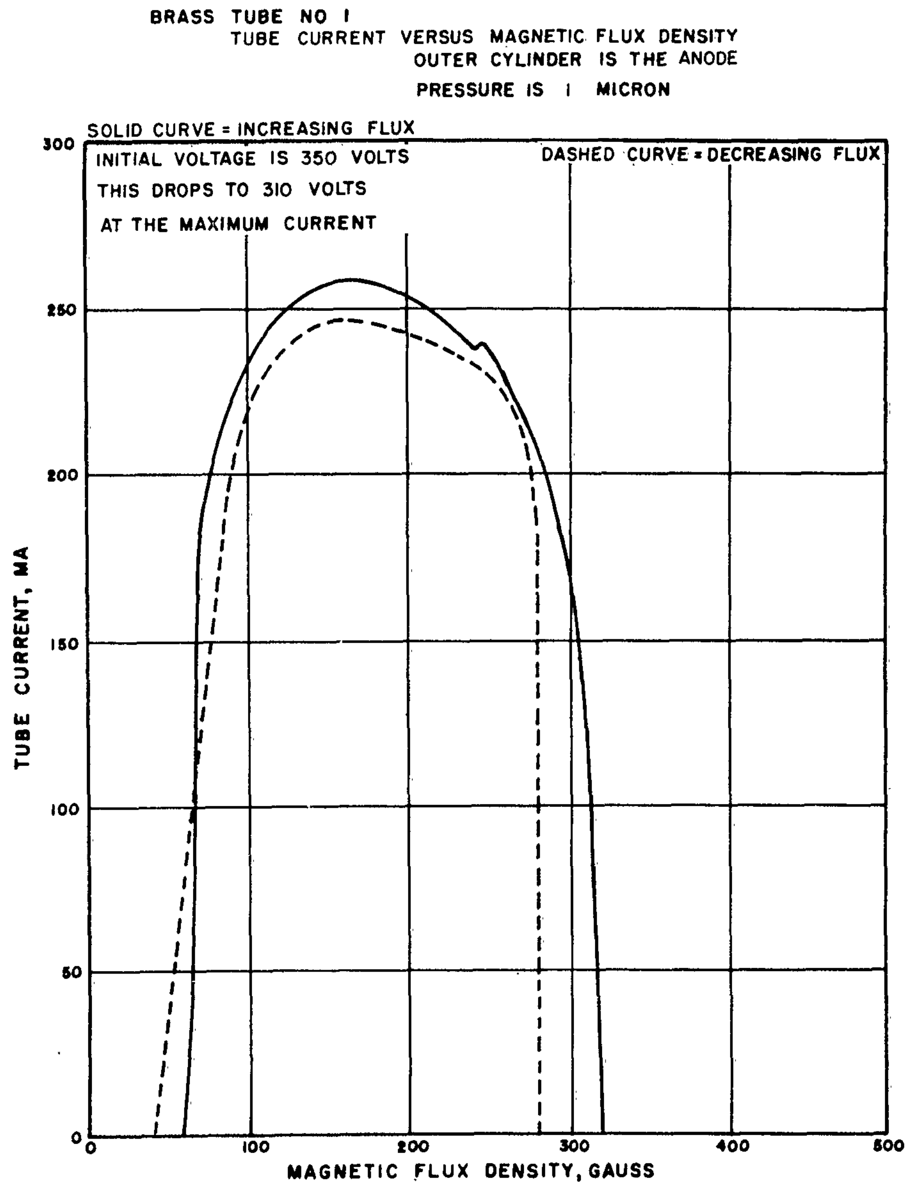
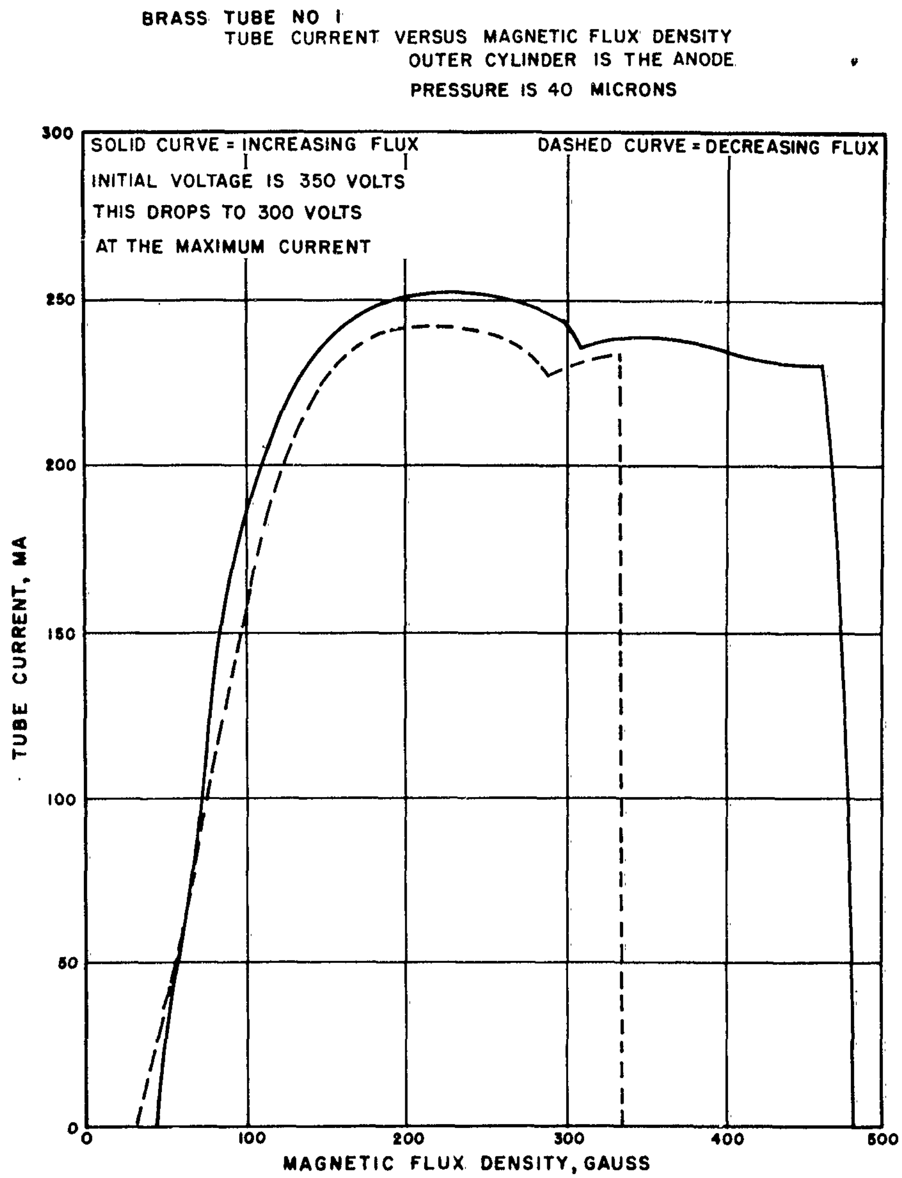

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS I MICRON
SOLID CURVE = INCREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 310 VOLTS
AT THE MAXIMUM CURRENT
DASHED CURVE = DECREASING FLUX
TUBE CURRENT, MA
0
50
100
150
200
250
300
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 7a



BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 40 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 300 VOLTS
AT THE MAXIMUM CURRENT
300
250
200
150
100
50
0
TUBE CURRENT, MA
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 7b

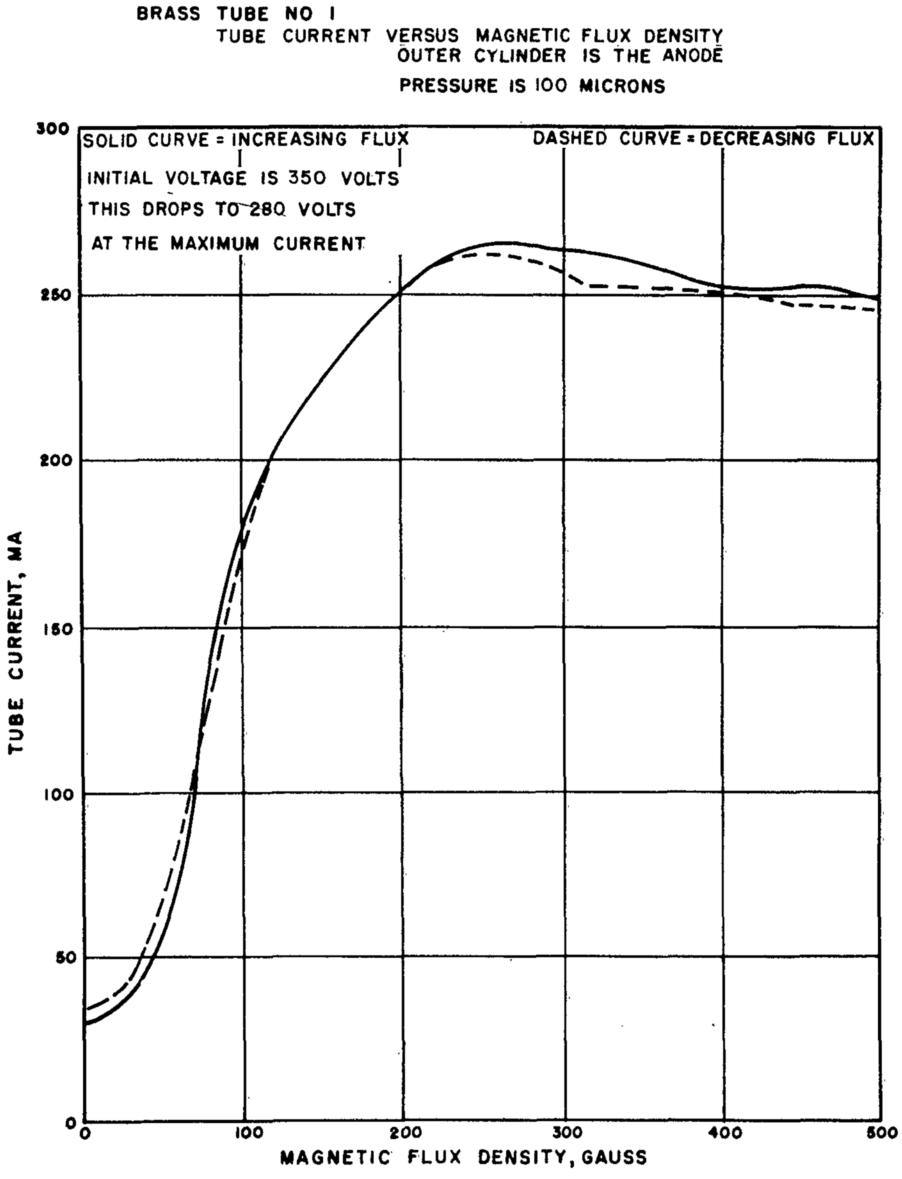

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 280 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
300
250
200
150
100
50
0
0
100
200
300
400
500

Figure 7c

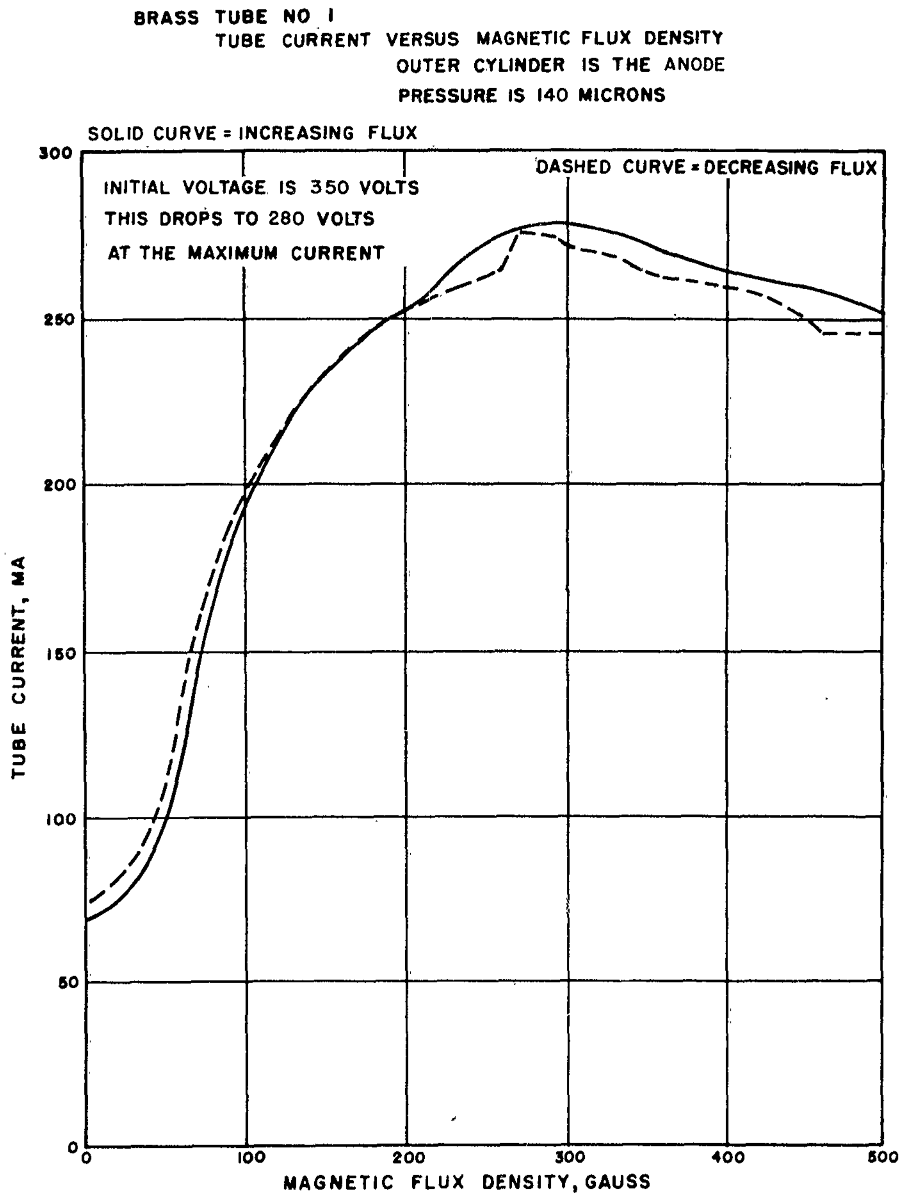

BRASS TUBE NO 1
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 140 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 280 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 7d

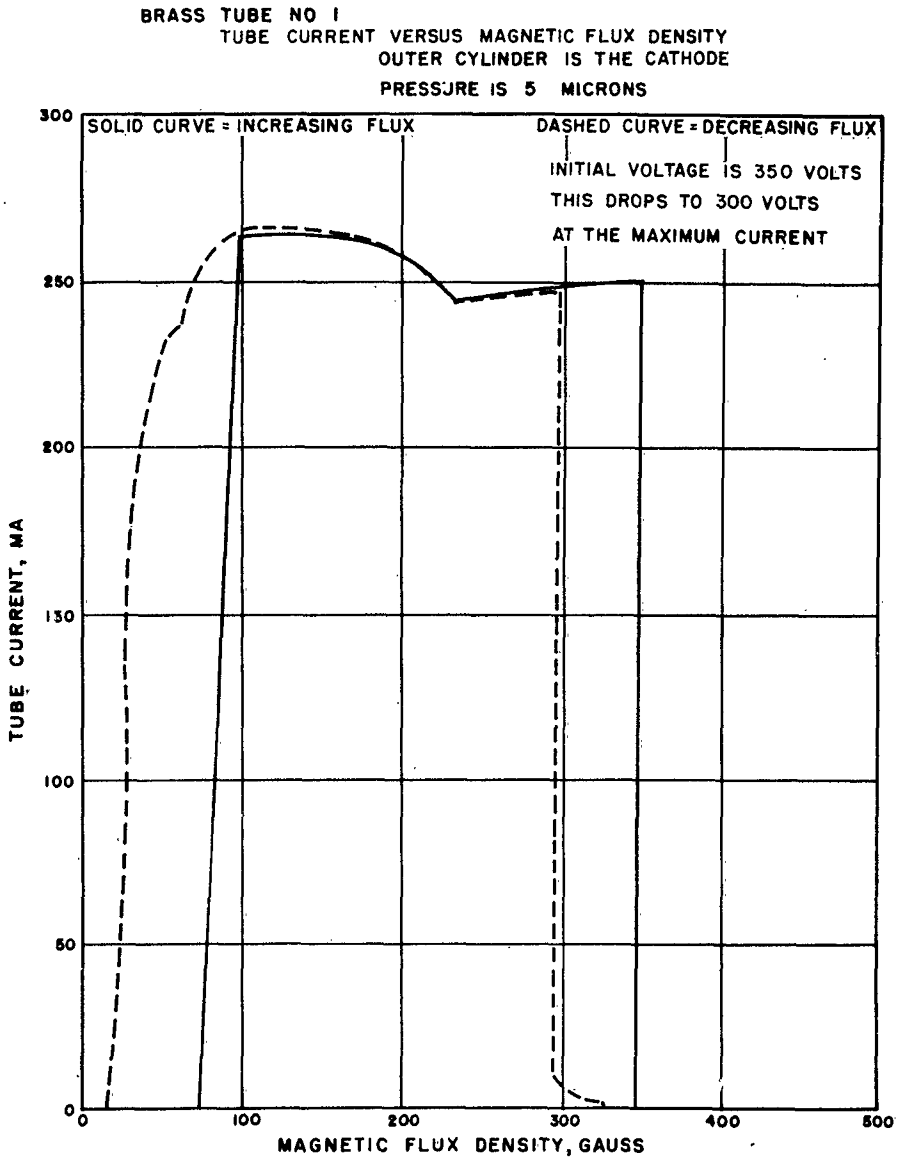

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 5 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 300 VOLTS
AT THE MAXIMUM CURRENT
300
250
200
130
100
50
0
0
100
200
300
400
500
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS

Figure 8a

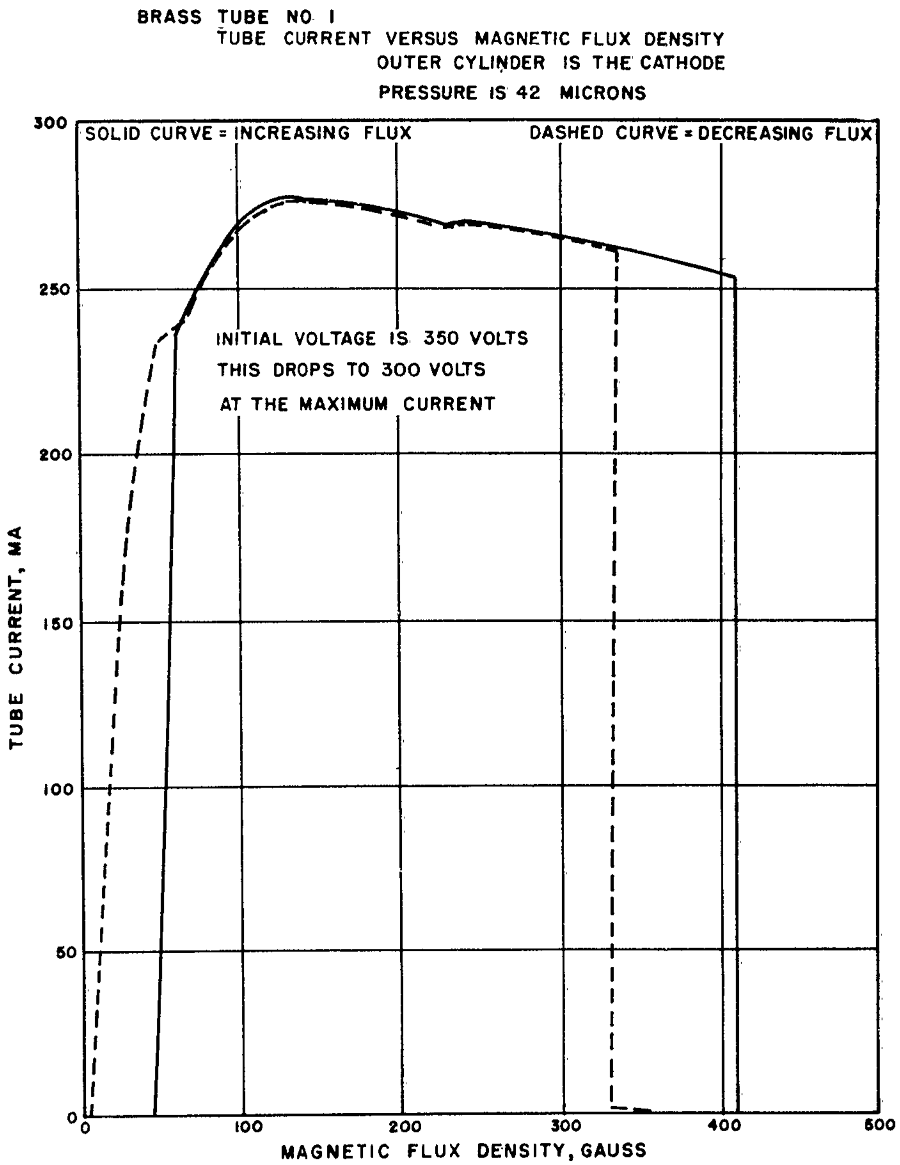

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 42 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 300 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 8b

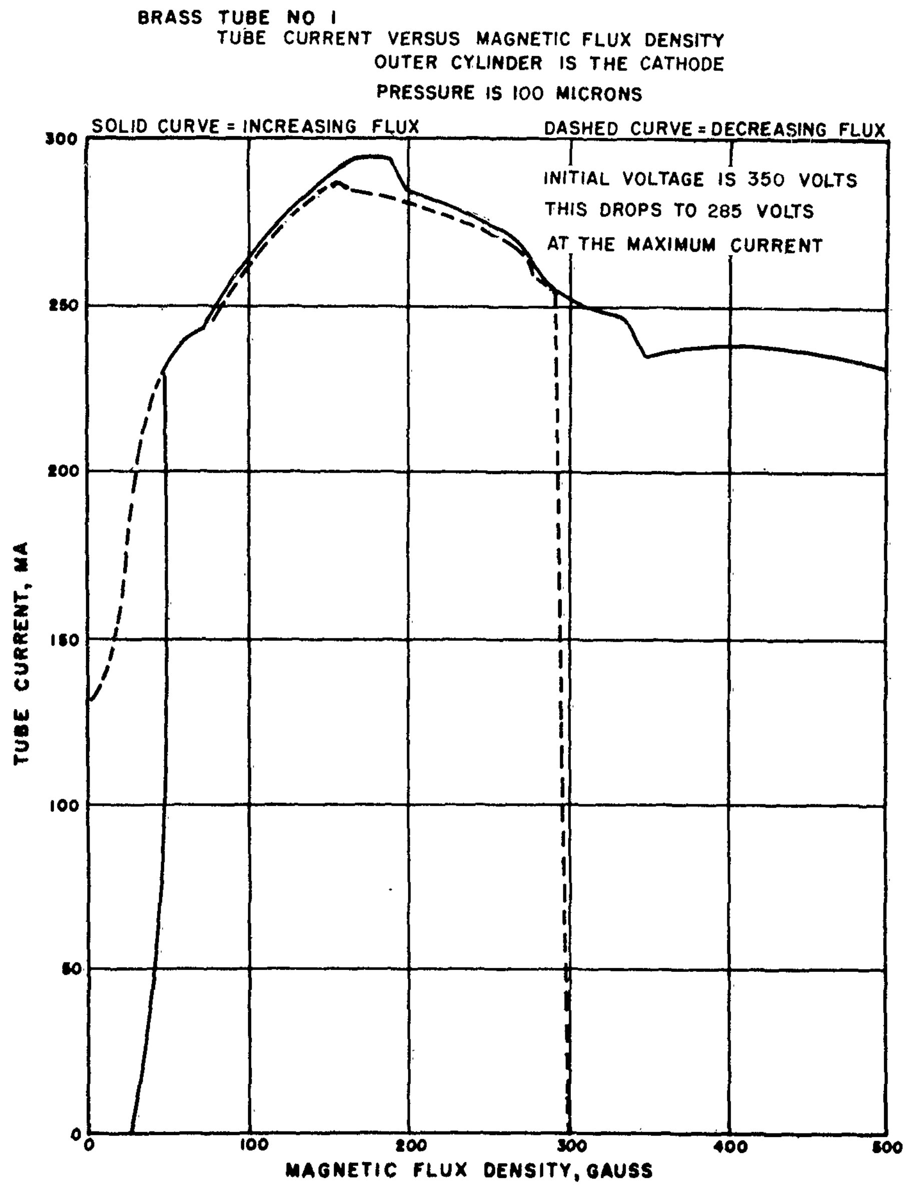

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 100 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 285 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
0
50
100
150
200
250
300
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 8c

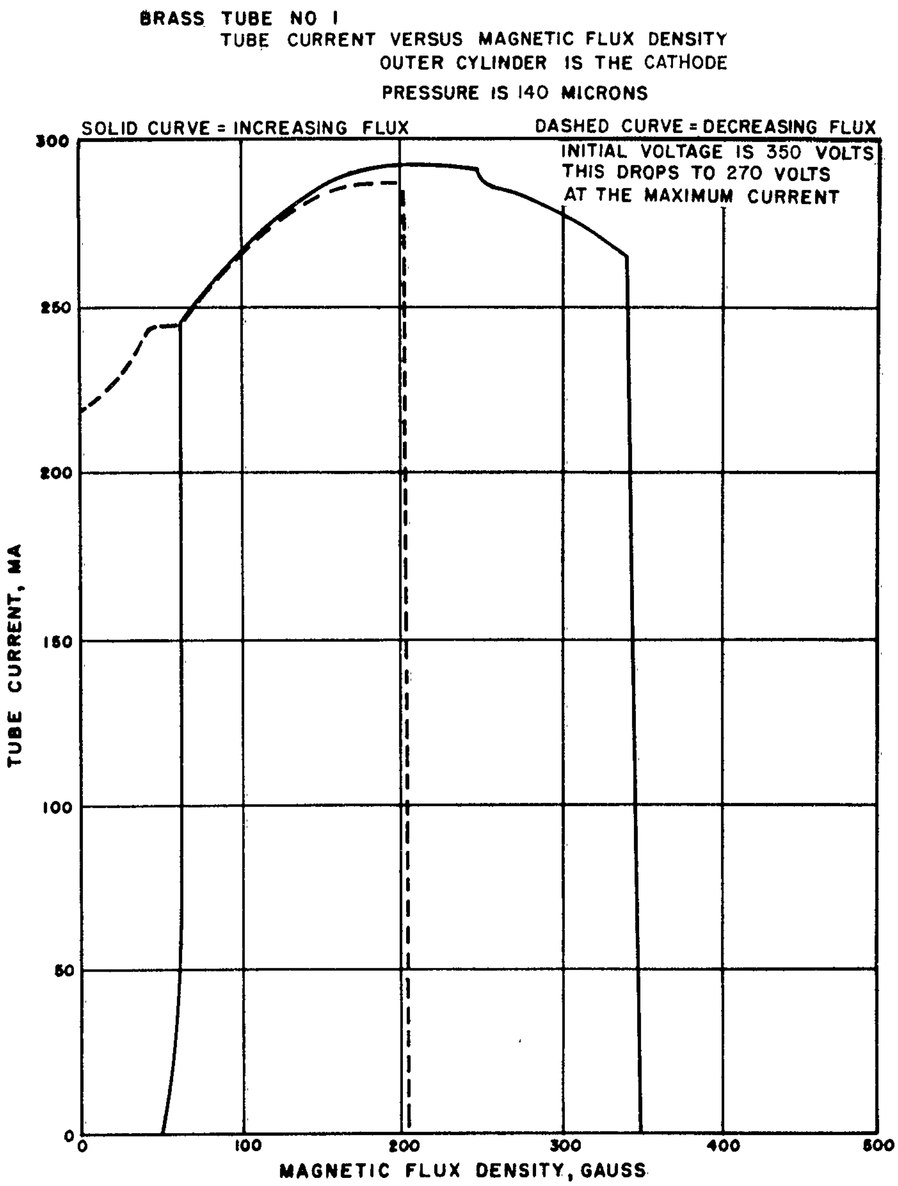

BRASS TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 140 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 270 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
100
200
300
400
500

Figure 8d

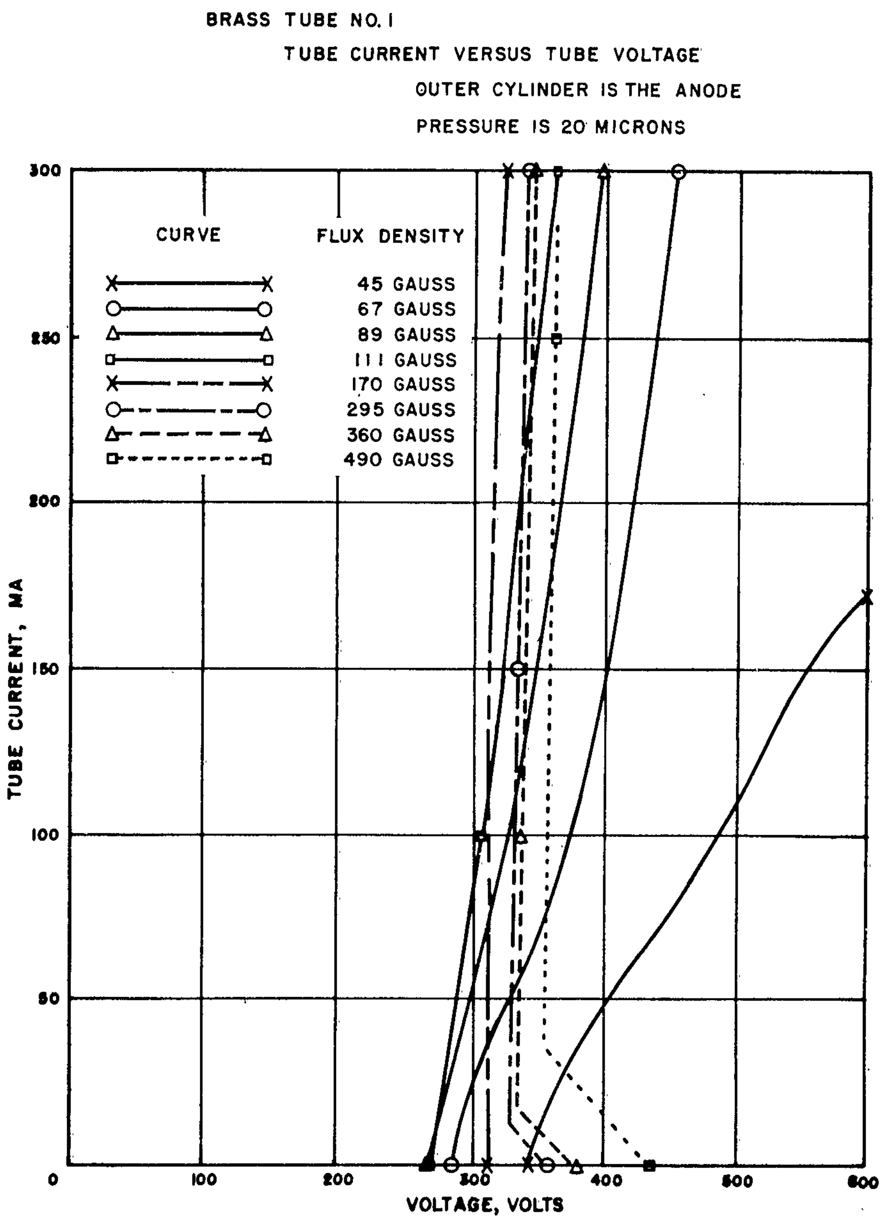
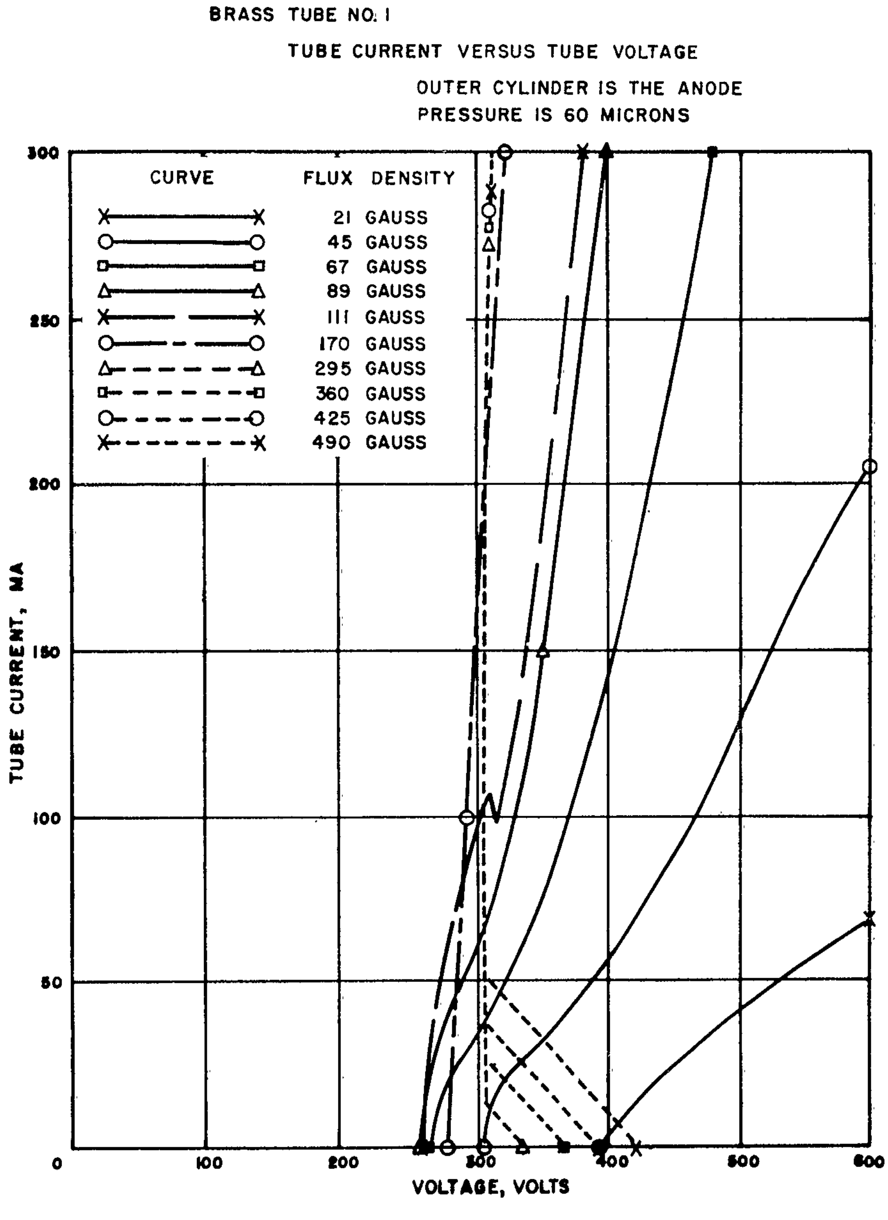

BRASS TUBE NO. I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 20 MICRONS
CURVE
FLUX DENSITY
45 GAUSS
67 GAUSS
89 GAUSS
111 GAUSS
170 GAUSS
295 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 9a



BRASS TUBE NO. I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 60 MICRONS
CURVE
FLUX DENSITY
21 GAUSS
45 GAUSS
67 GAUSS
89 GAUSS
111 GAUSS
170 GAUSS
295 GAUSS
360 GAUSS
425 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
100
200
300
400
500
600
50
100
150
200
250
300

Figure 9b

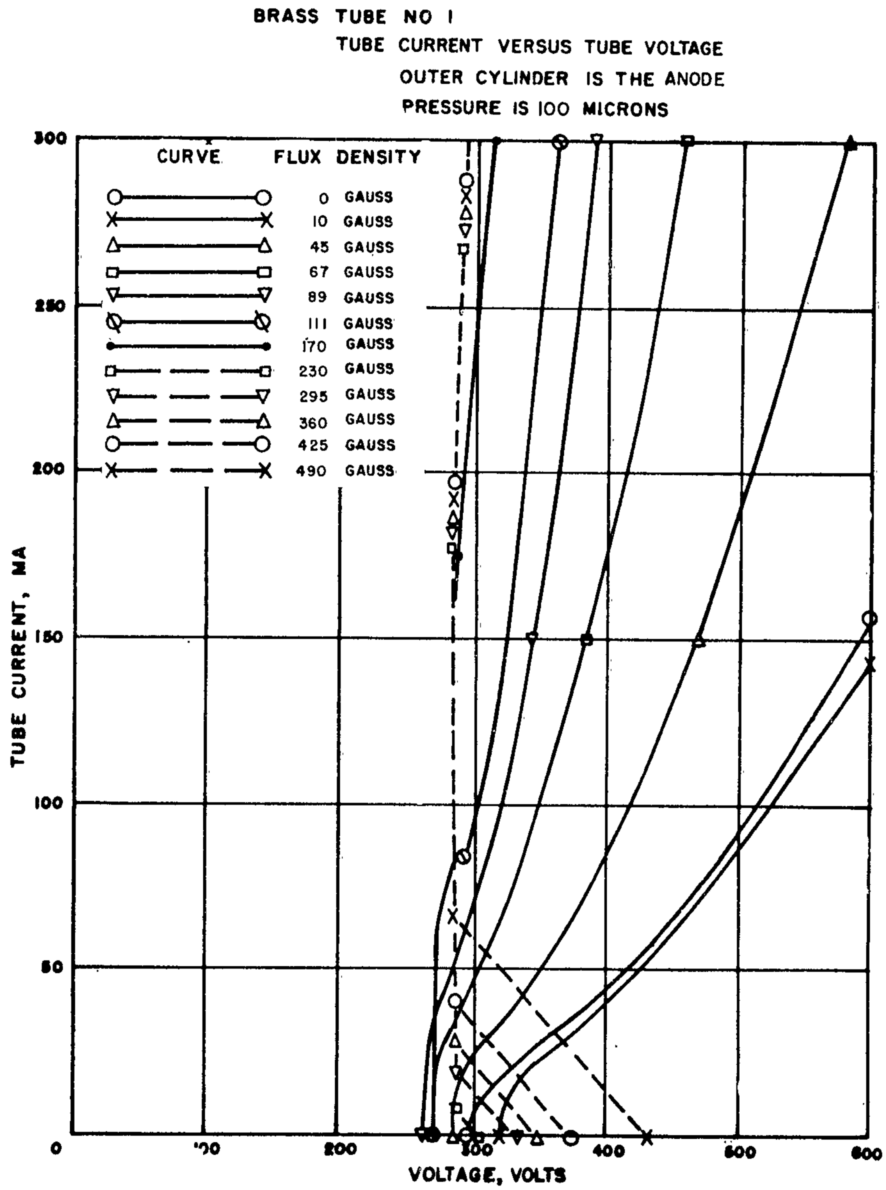

BRASS TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
CURVE
FLUX DENSITY
0 GAUSS
10 GAUSS
45 GAUSS
67 GAUSS
89 GAUSS
111 GAUSS
170 GAUSS
230 GAUSS
295 GAUSS
360 GAUSS
425 GAUSS
490 GAUSS
TUBE CURRENT, MA
300
250
200
150
100
50
0
200
300
400
500
600
VOLTAGE, VOLTS

Figure 9c

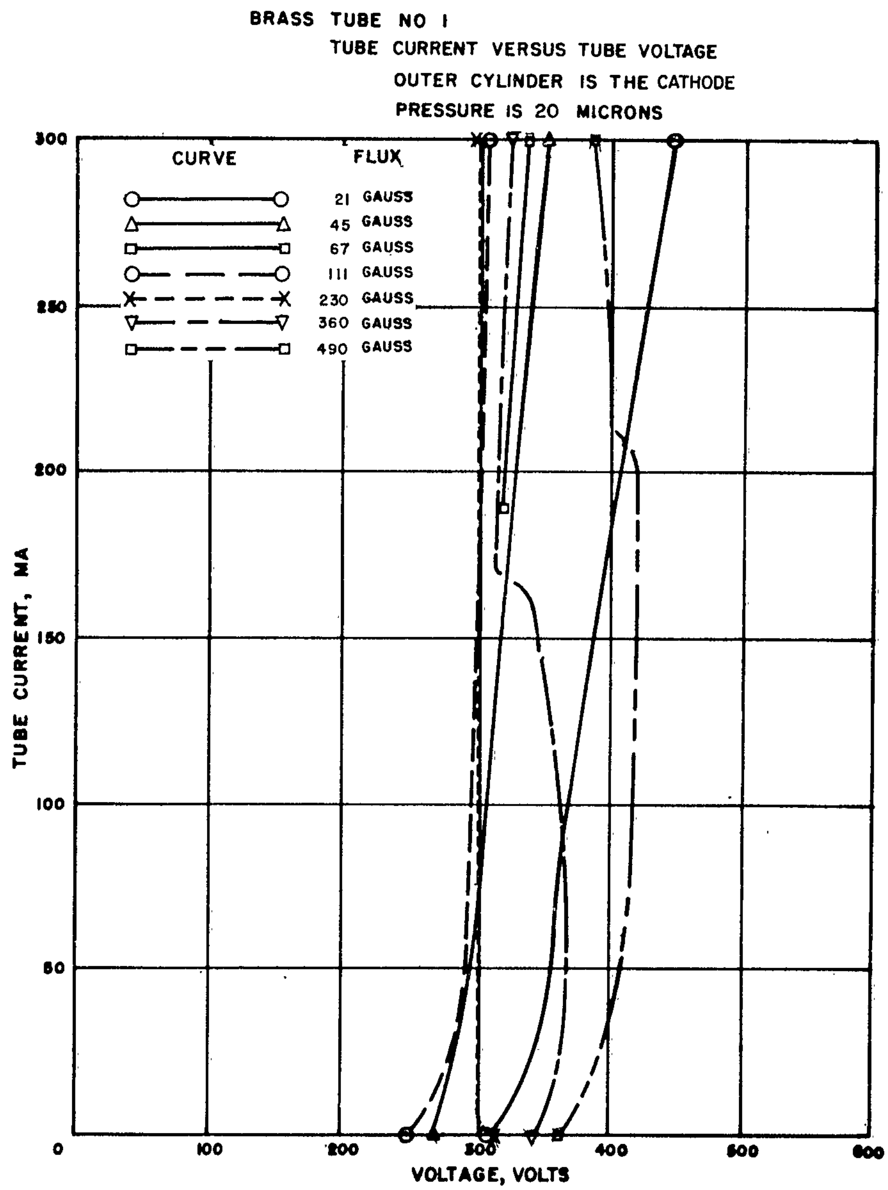

BRASS TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 20 MICRONS
CURVE
FLUX
21 GAUSS
45 GAUSS
67 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
100
200
300
400
500
600
50
150
250

Figure 10a

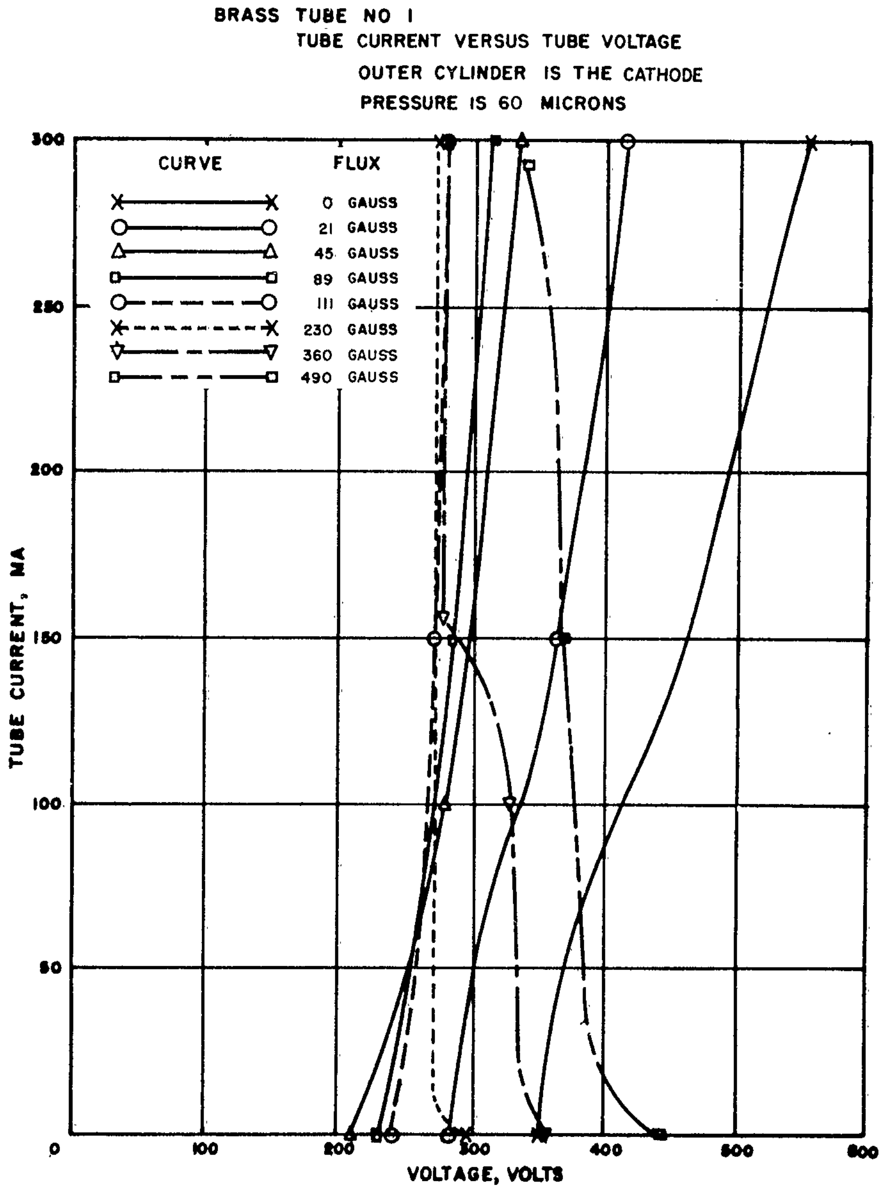

BRASS TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 60 MICRONS
CURVE
FLUX
0 GAUSS
21 GAUSS
45 GAUSS
89 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
300
250
200
150
100
50
0
100
200
300
400
500
600
VOLTAGE, VOLTS

Figure 10b

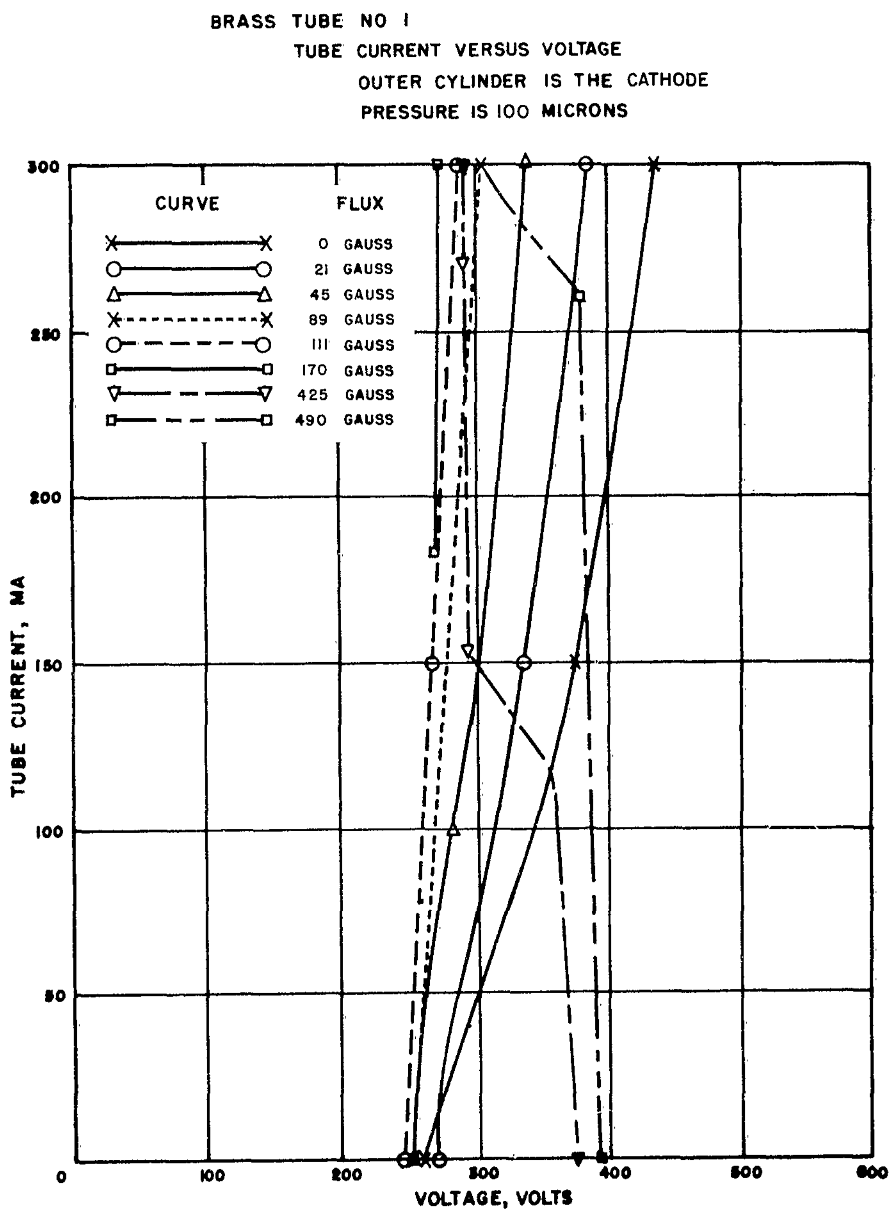
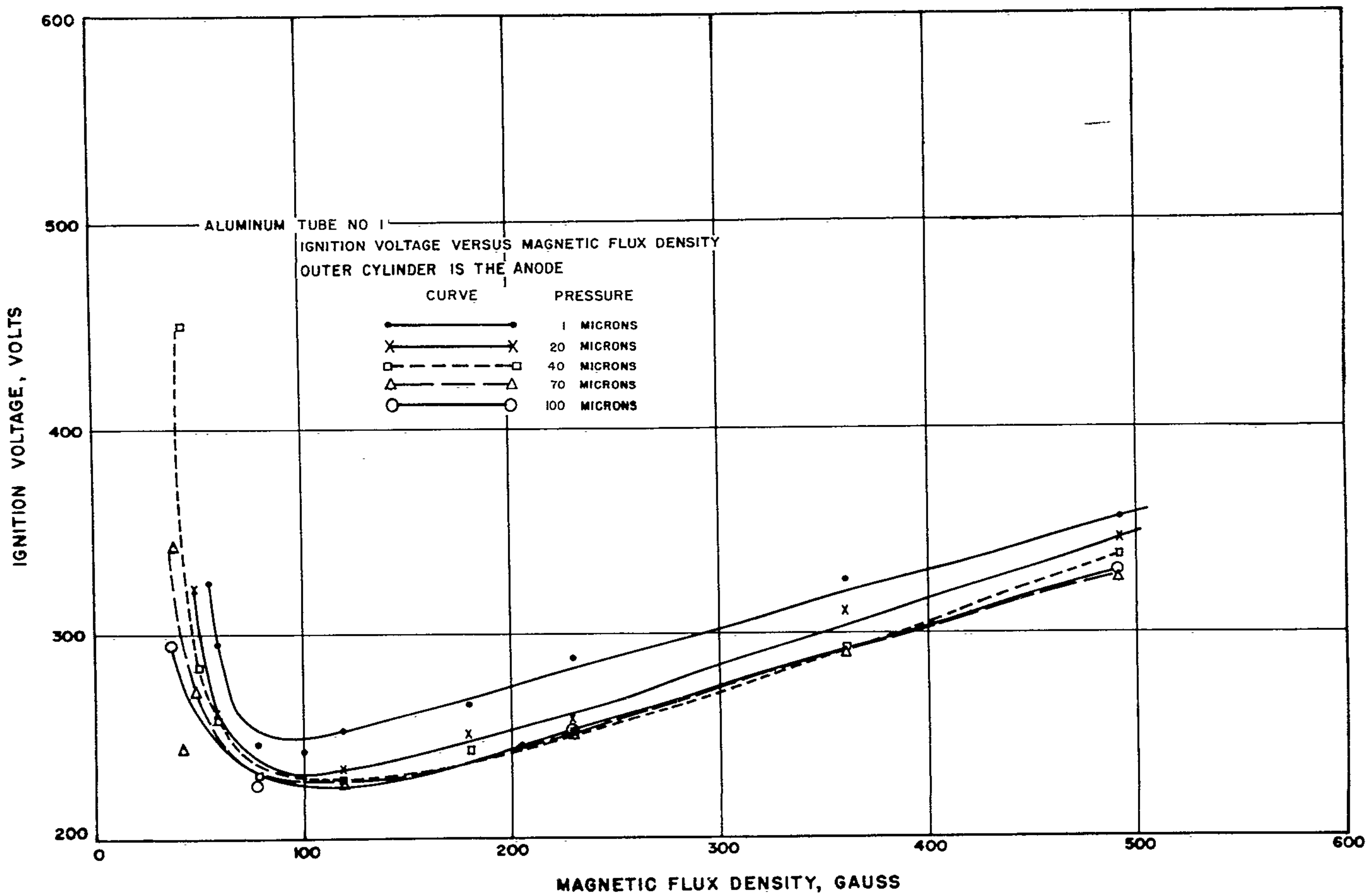

BRASS TUBE NO I
TUBE CURRENT VERSUS VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 100 MICRONS
CURVE
FLUX
0 GAUSS
21 GAUSS
45 GAUSS
89 GAUSS
111 GAUSS
170 GAUSS
425 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 10c



ALUMINUM TUBE NO 1
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
1 MICRONS
20 MICRONS
40 MICRONS
70 MICRONS
100 MICRONS
IGNITION VOLTAGE, VOLTS
MAGNETIC FLUX DENSITY, GAUSS
600
500
400
300
200
0
100
200
300
400
500
600

Figure 11

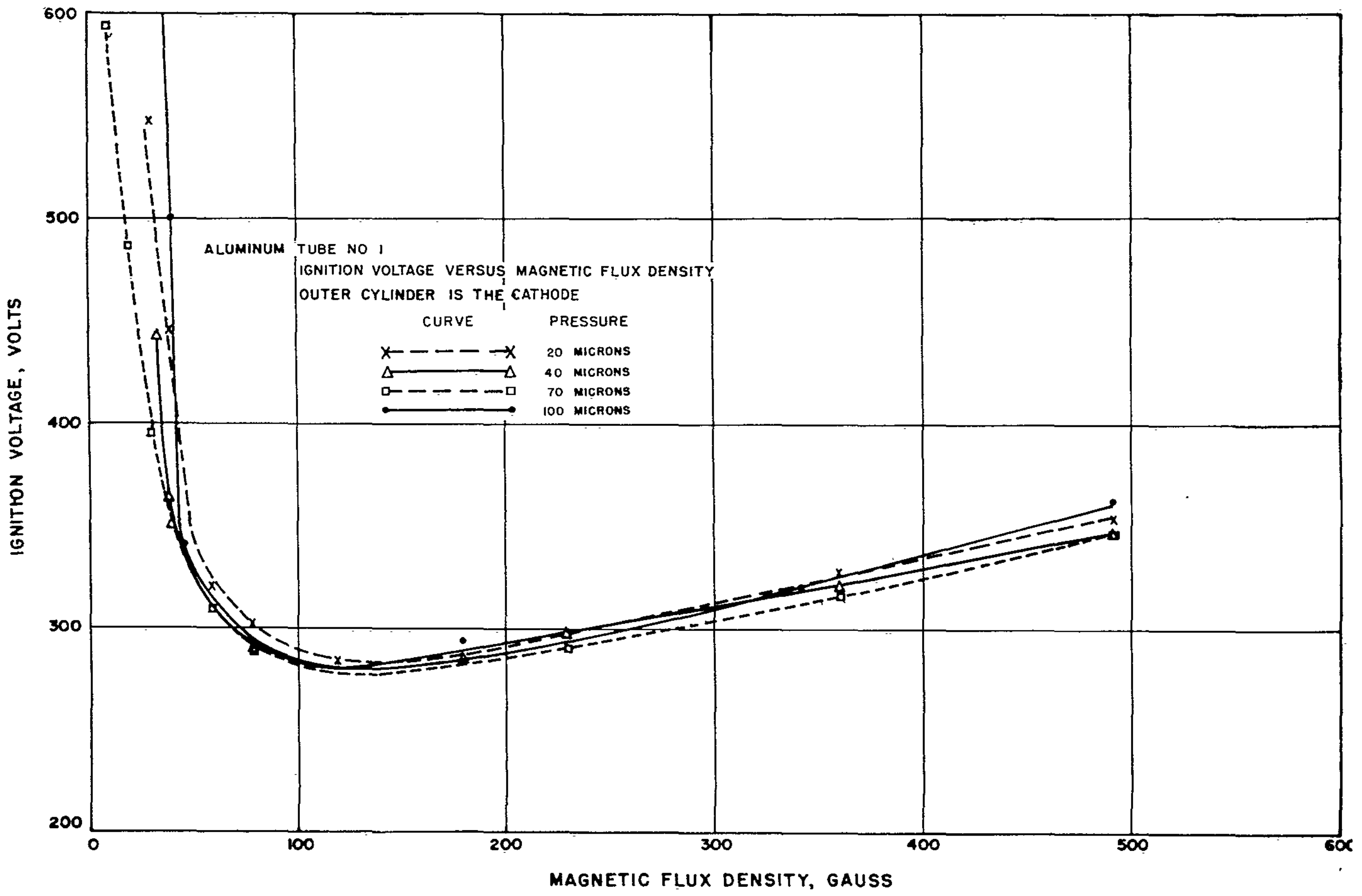

ALUMINUM TUBE NO 1
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVE
PRESSURE
20 MICRONS
40 MICRONS
70 MICRONS
100 MICRONS
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 12

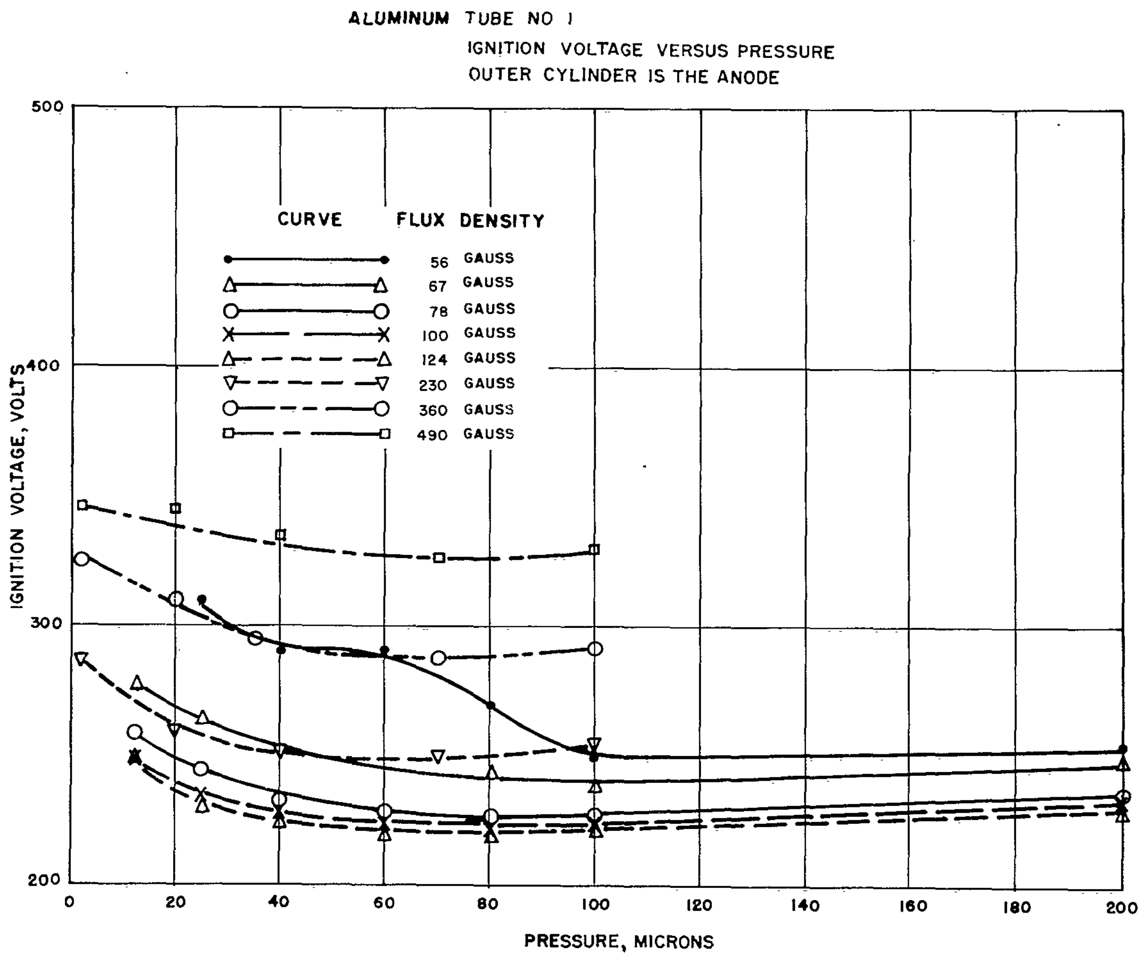

ALUMINUM TUBE NO 1
IGNITION VOLTAGE VERSUS PRESSURE
OUTER CYLINDER IS THE ANODE
CURVE
FLUX DENSITY
56 GAUSS
67 GAUSS
78 GAUSS
100 GAUSS
124 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
500
400
300
200
IGNITION VOLTAGE, VOLTS
0
20
40
60
80
100
120
140
160
180
200
PRESSURE, MICRONS

Figure 13

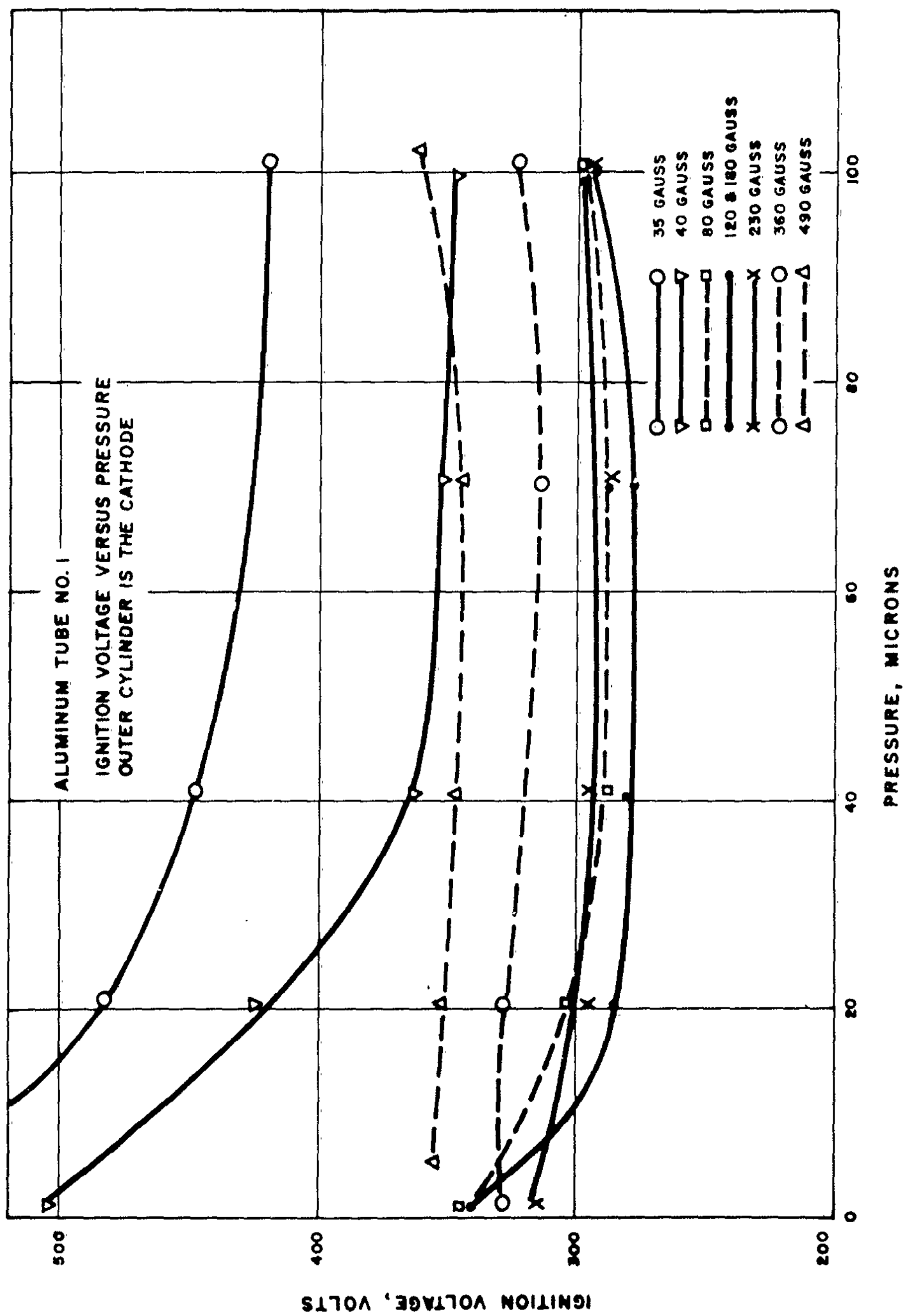

ALUMINUM TUBE NO. I
IGNITION VOLTAGE VERSUS PRESSURE
OUTER CYLINDER IS THE CATHODE
35 GAUSS
40 GAUSS
80 GAUSS
120 & 180 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
500
400
300
200
0
20
40
60
80
100
IGNITION VOLTAGE, VOLTS
PRESSURE, MICRONS

Figure 14

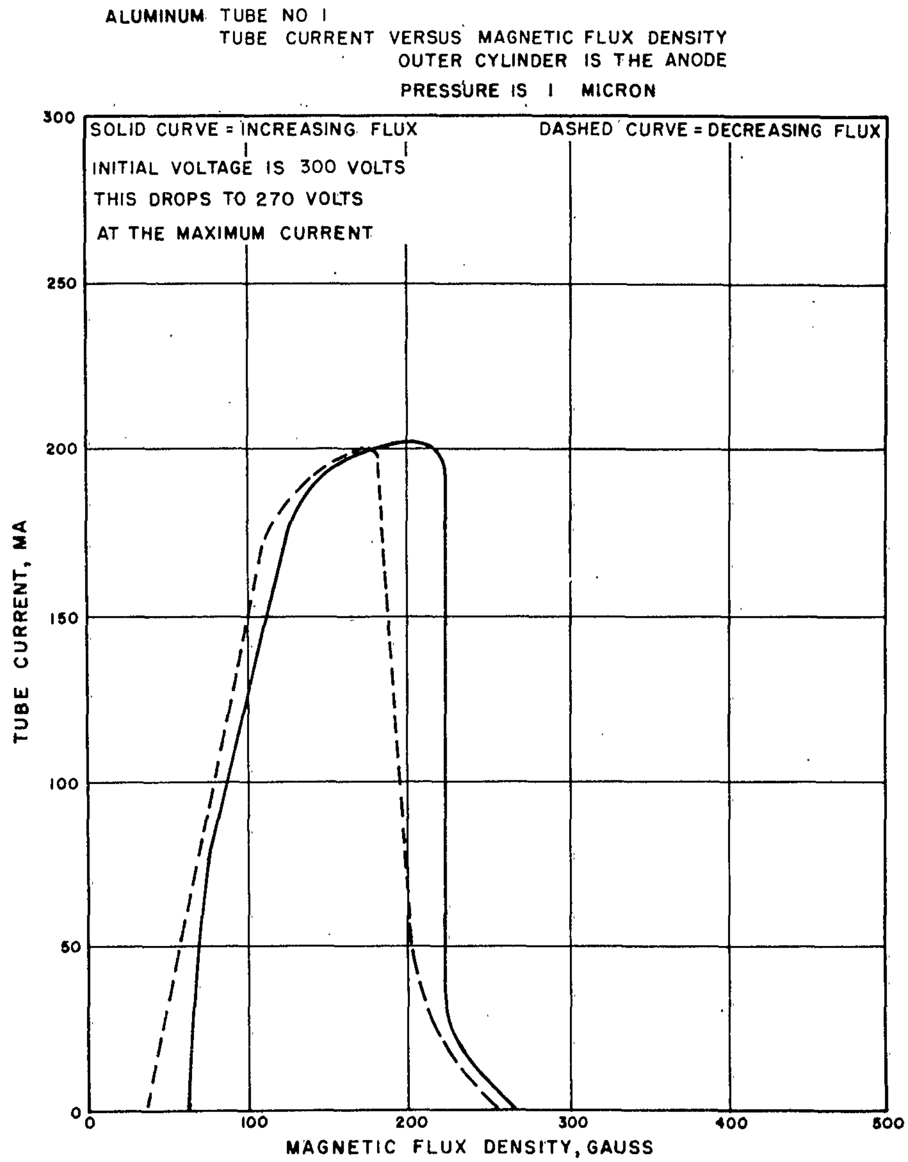

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS I MICRON
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 300 VOLTS
THIS DROPS TO 270 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
300
250
200
150
100
50
0
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 15a

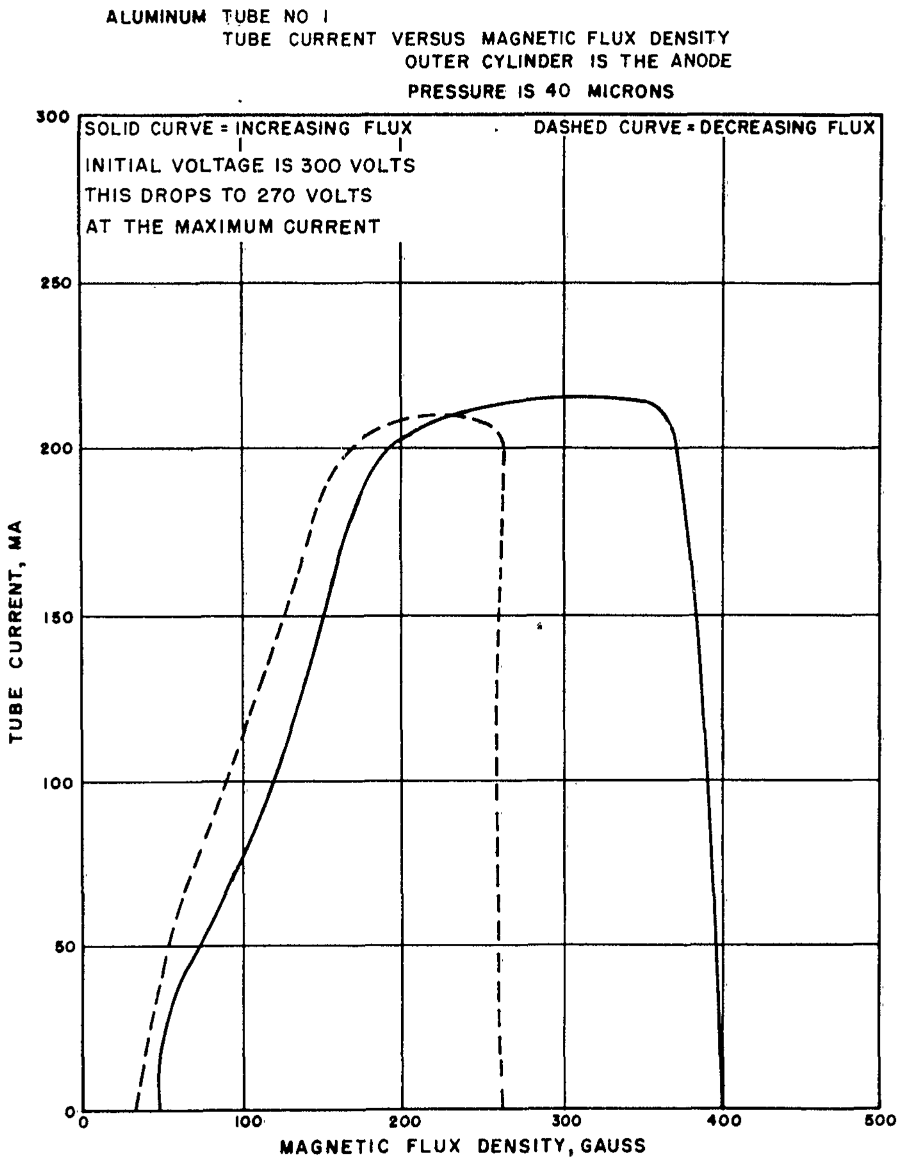
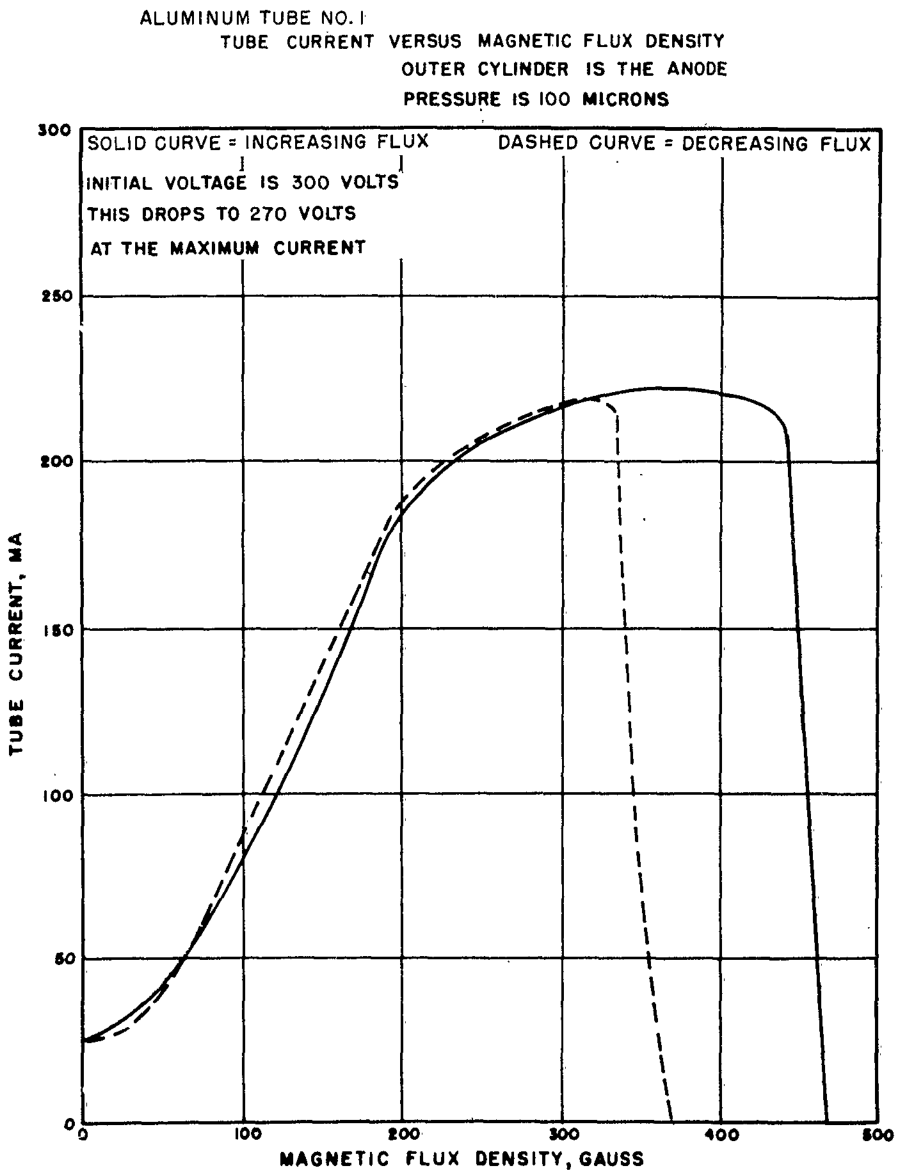

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 40 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 300 VOLTS
THIS DROPS TO 270 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 15b



ALUMINUM TUBE NO. I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 300 VOLTS
THIS DROPS TO 270 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 15c

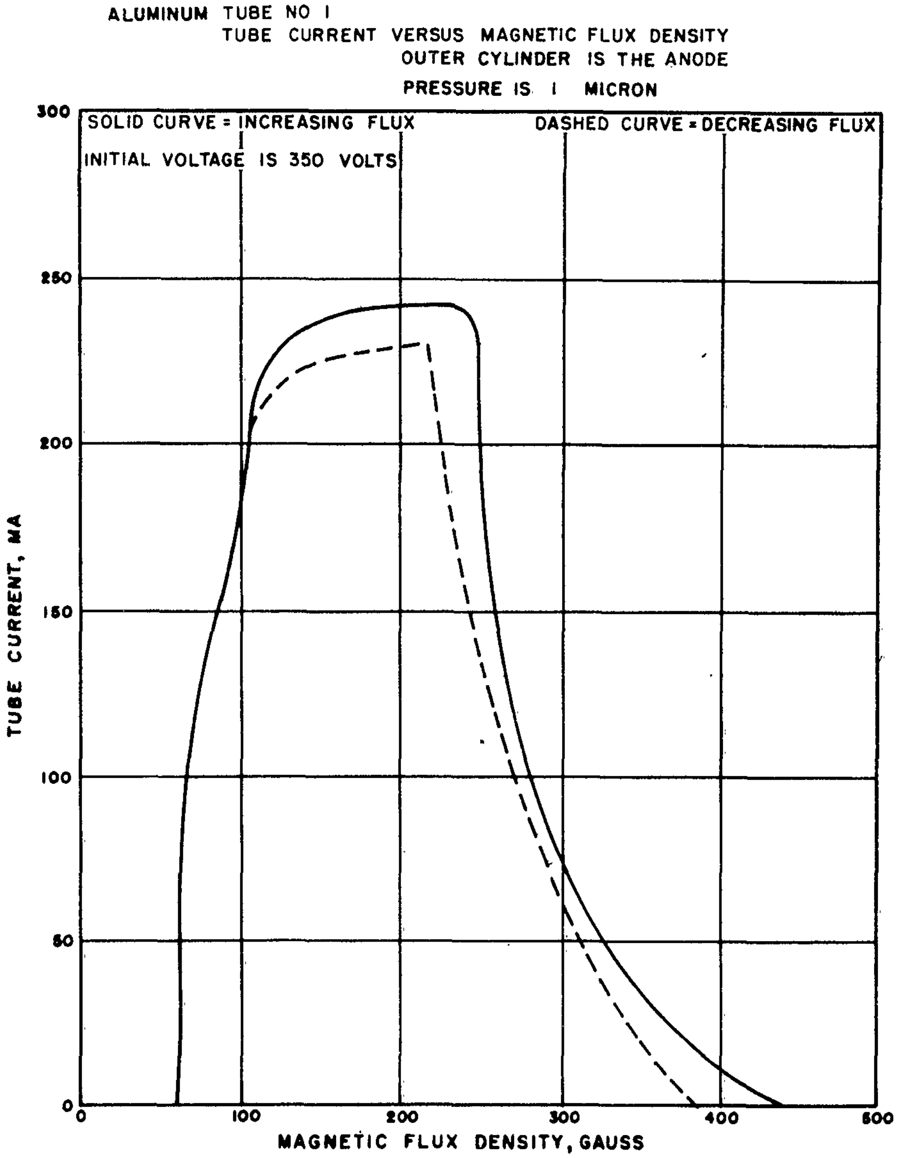

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS I MICRON
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
300
250
200
150
100
50
0
TUBE CURRENT, MA
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 15d

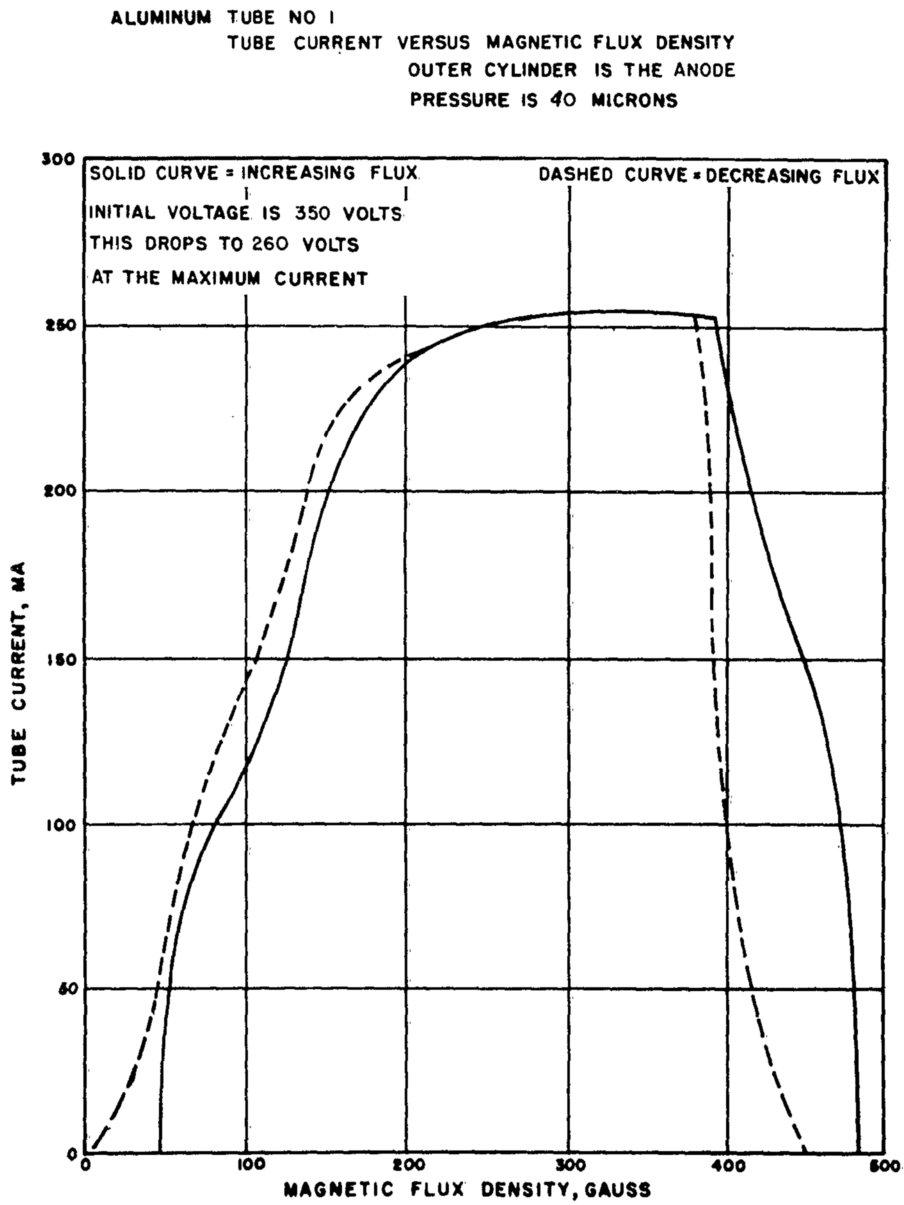

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 40 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 260 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 15e

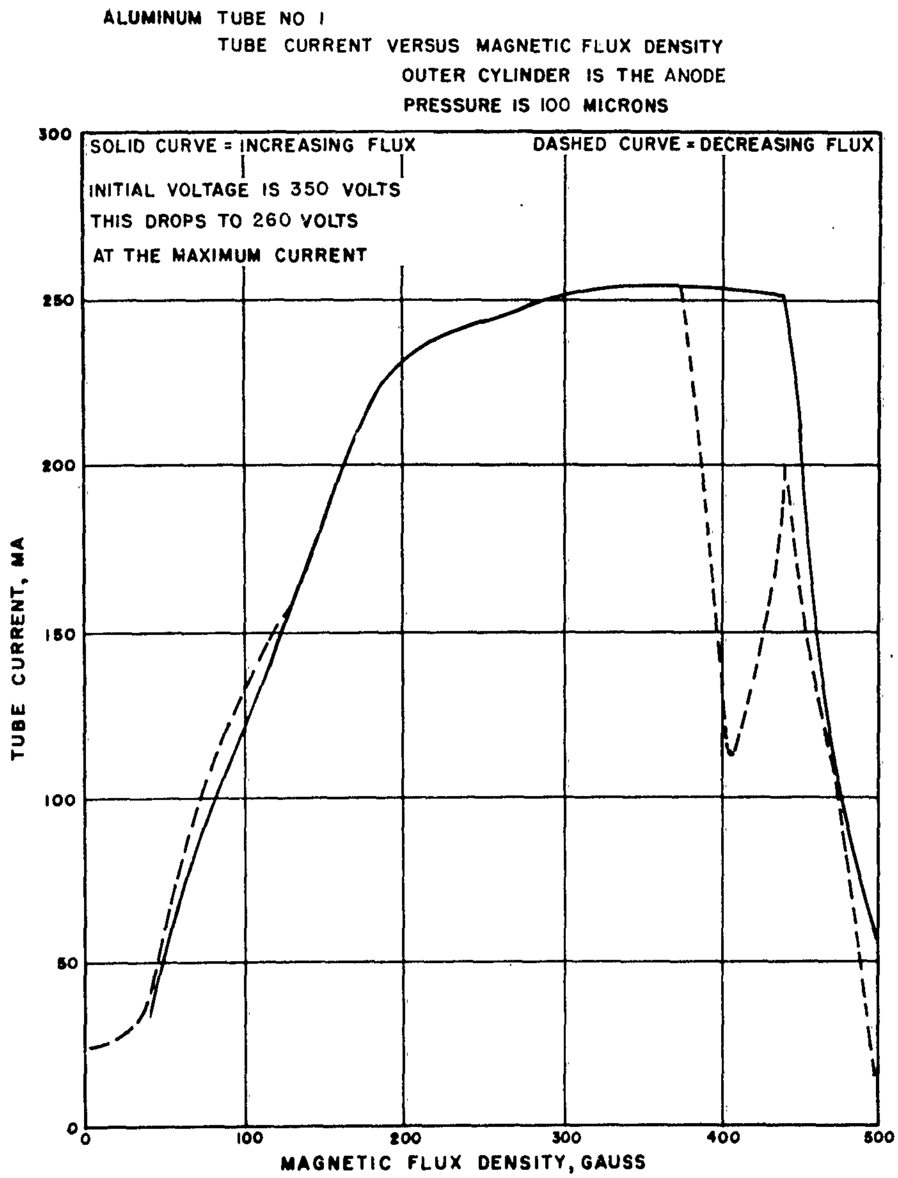

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
THIS DROPS TO 260 VOLTS
AT THE MAXIMUM CURRENT
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 15f

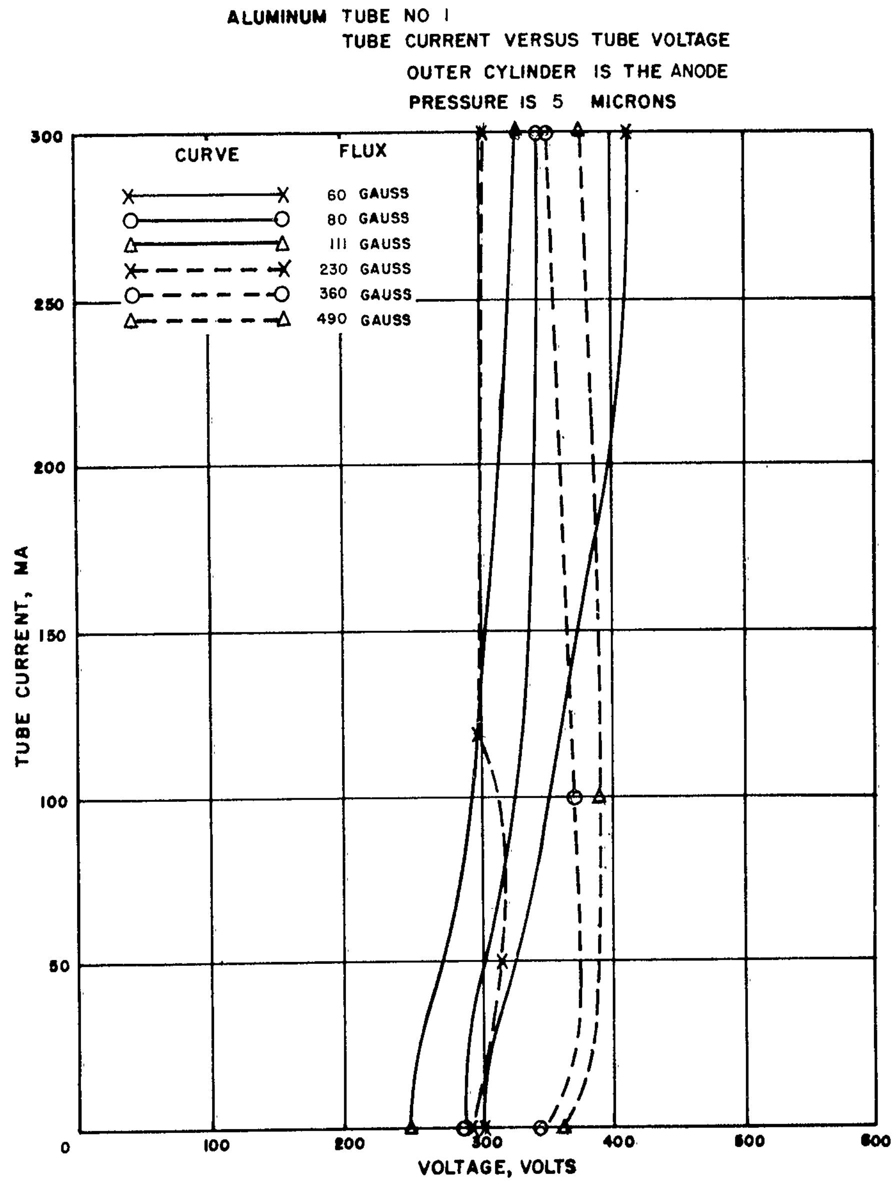

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 5 MICRONS
CURVE
FLUX
60 GAUSS
80 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 16a

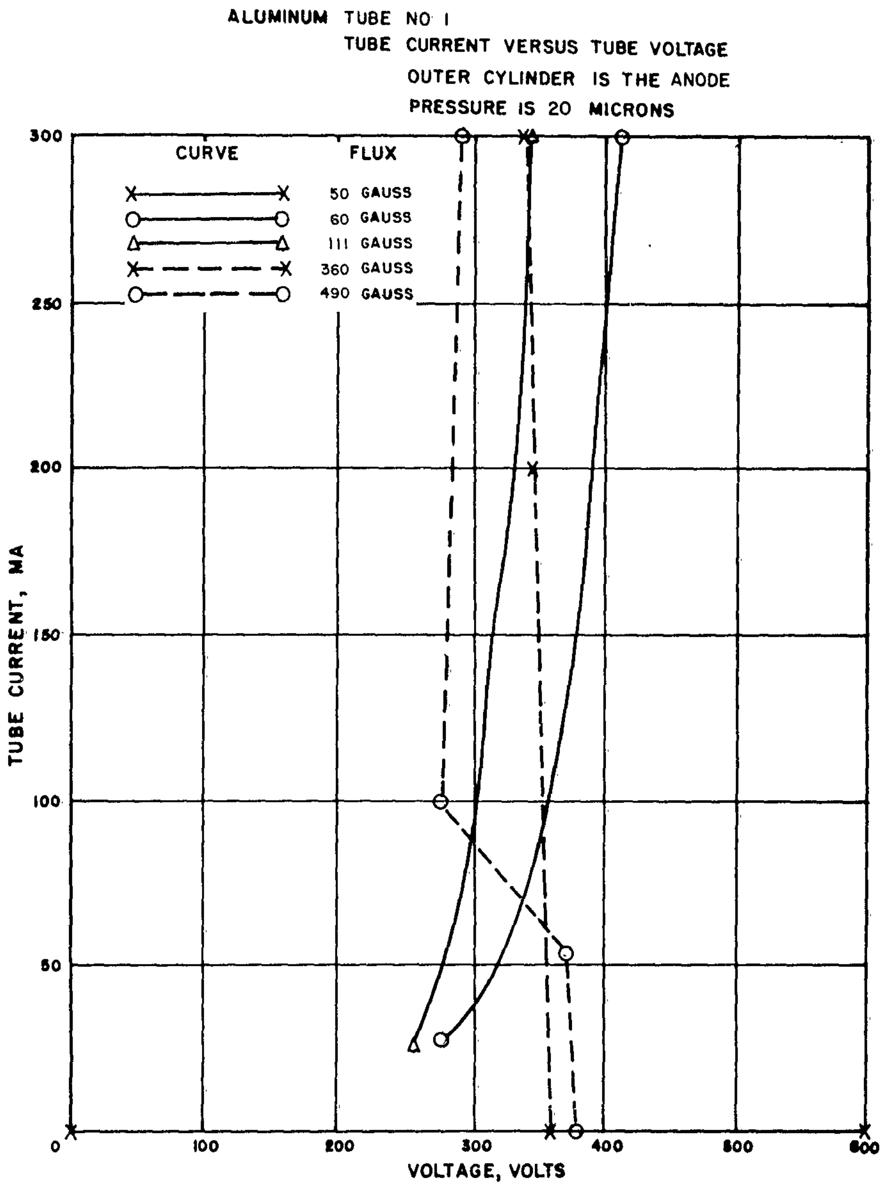
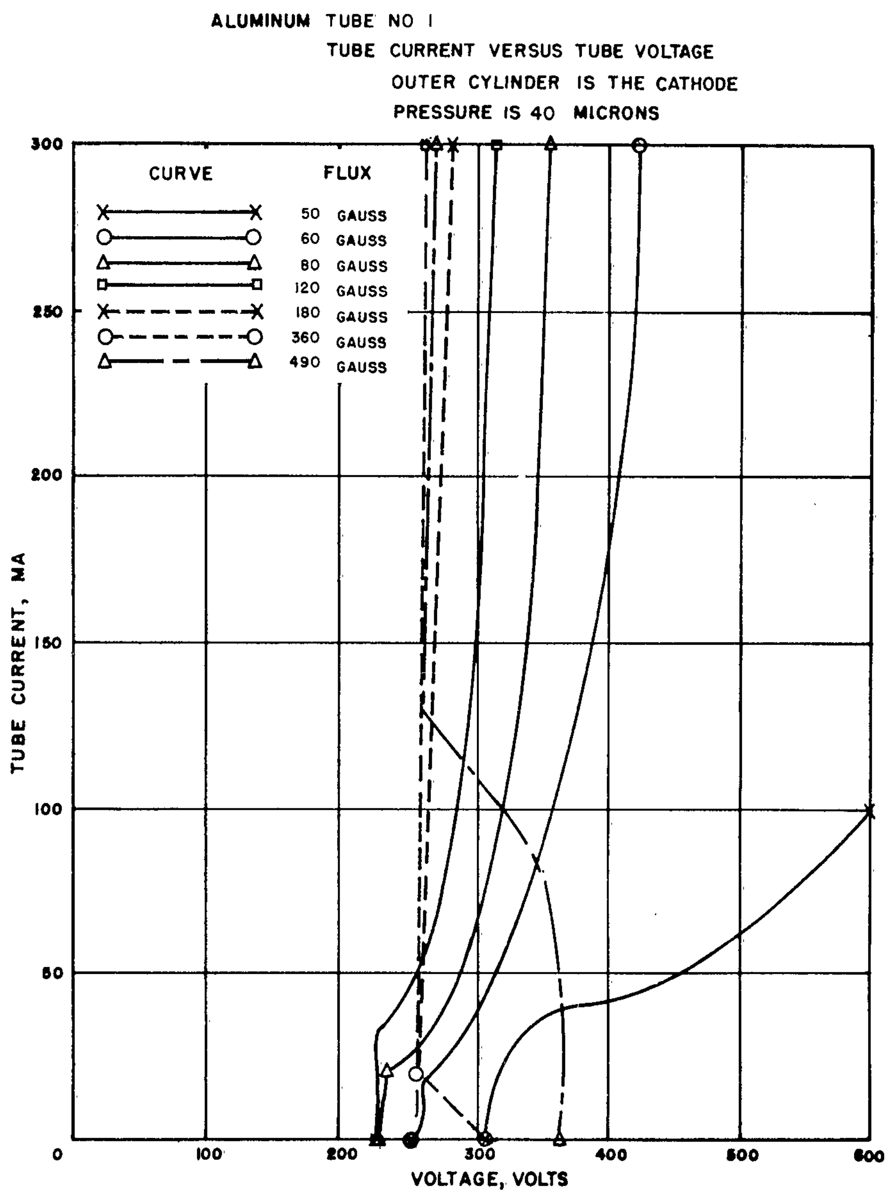

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 20 MICRONS
CURVE
FLUX
50 GAUSS
60 GAUSS
111 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
100
200
300
400
500
600
50
150
250

Figure 16b



ALUMINUM TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 40 MICRONS
CURVE
FLUX
50 GAUSS
60 GAUSS
80 GAUSS
120 GAUSS
180 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
100
200
300
400
500
600
50
150
250

Figure 16c

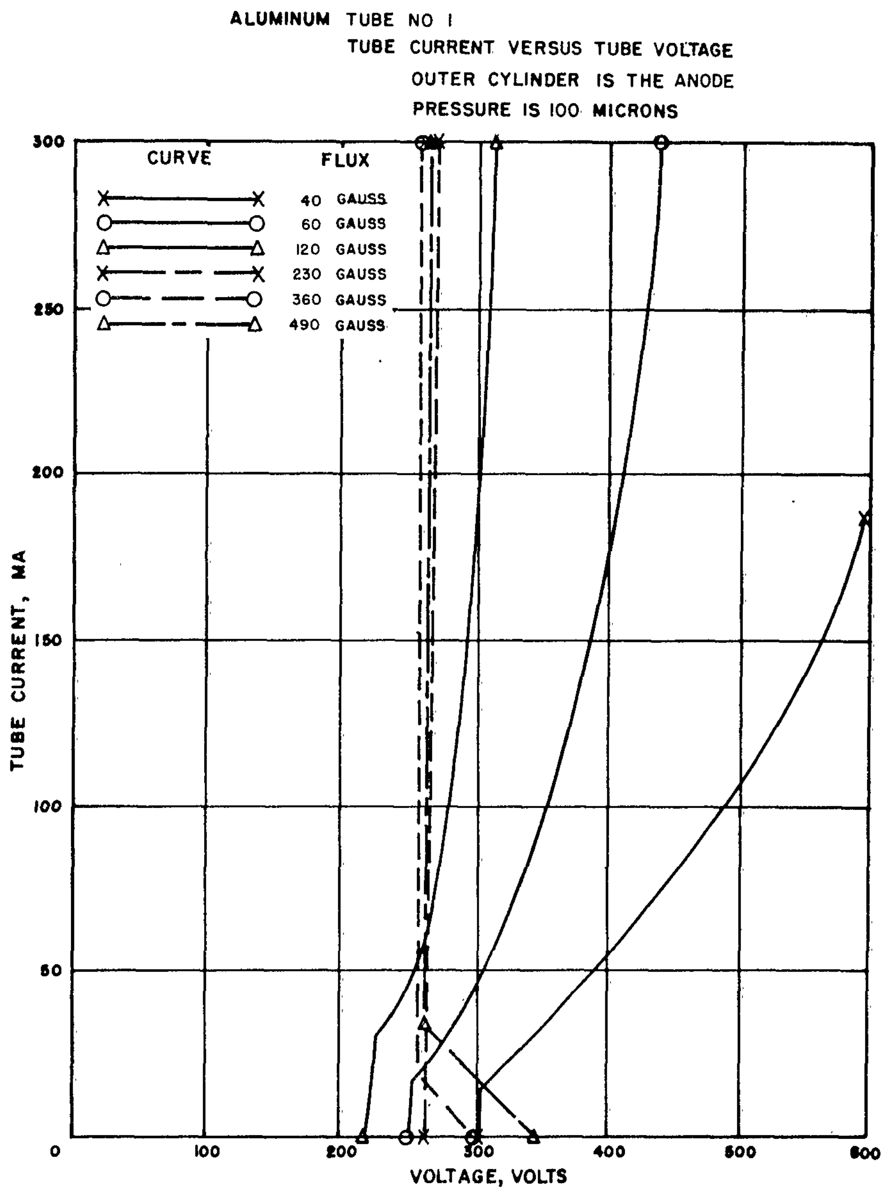

ALUMINUM TUBE NO I
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
CURVE
FLUX
40 GAUSS
60 GAUSS
120 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 16d

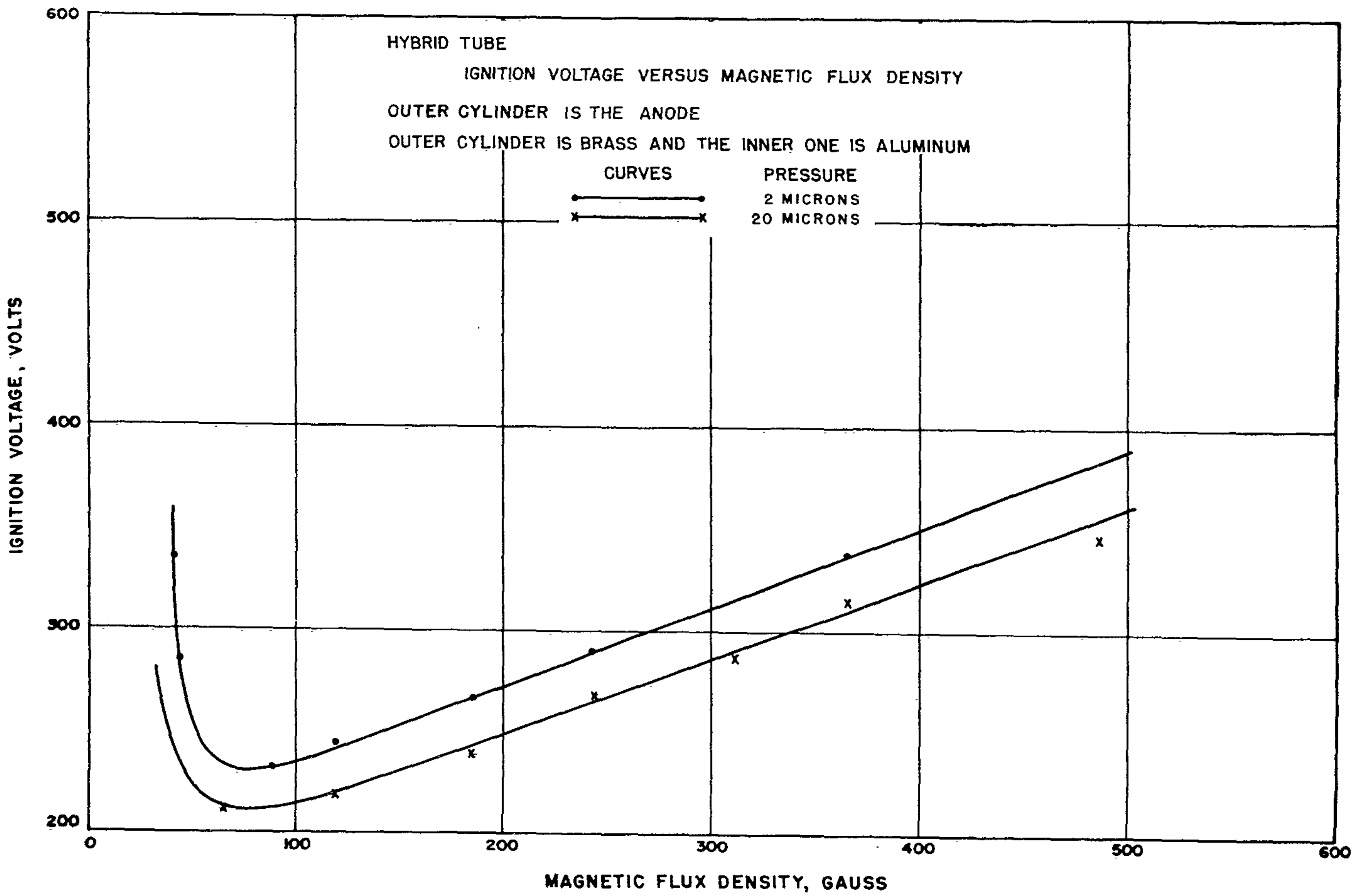

HYBRID TUBE
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
OUTER CYLINDER IS BRASS AND THE INNER ONE IS ALUMINUM
CURVES
PRESSURE
2 MICRONS
20 MICRONS
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
100
200
300
400
500
600
MAGNETIC FLUX DENSITY, GAUSS

Figure 17

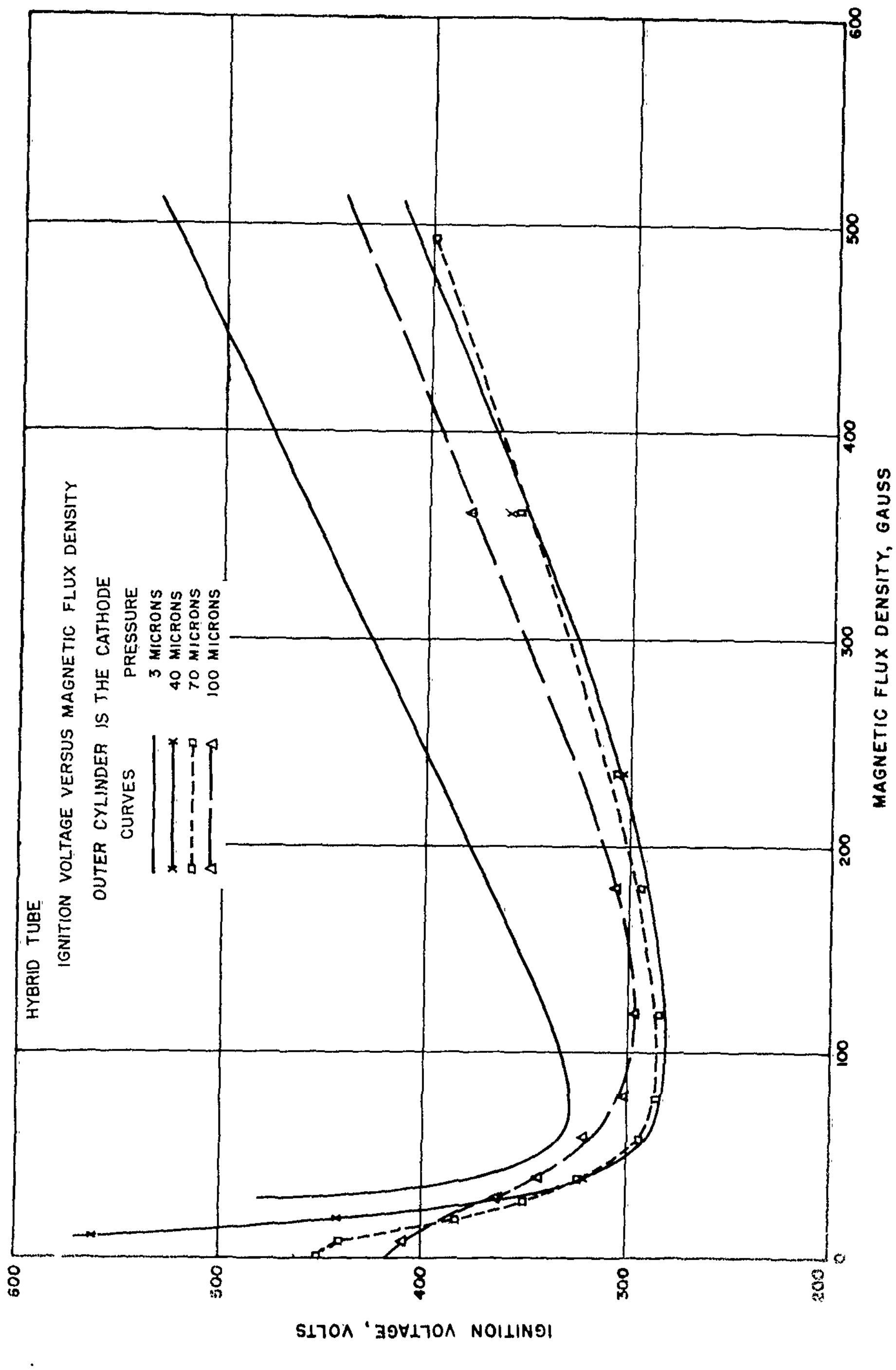

HYBRID TUBE
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVES
PRESSURE
3 MICRONS
40 MICRONS
70 MICRONS
100 MICRONS
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
MAGNETIC FLUX DENSITY, GAUSS
0
100
200
300
400
500
600

Figure 18

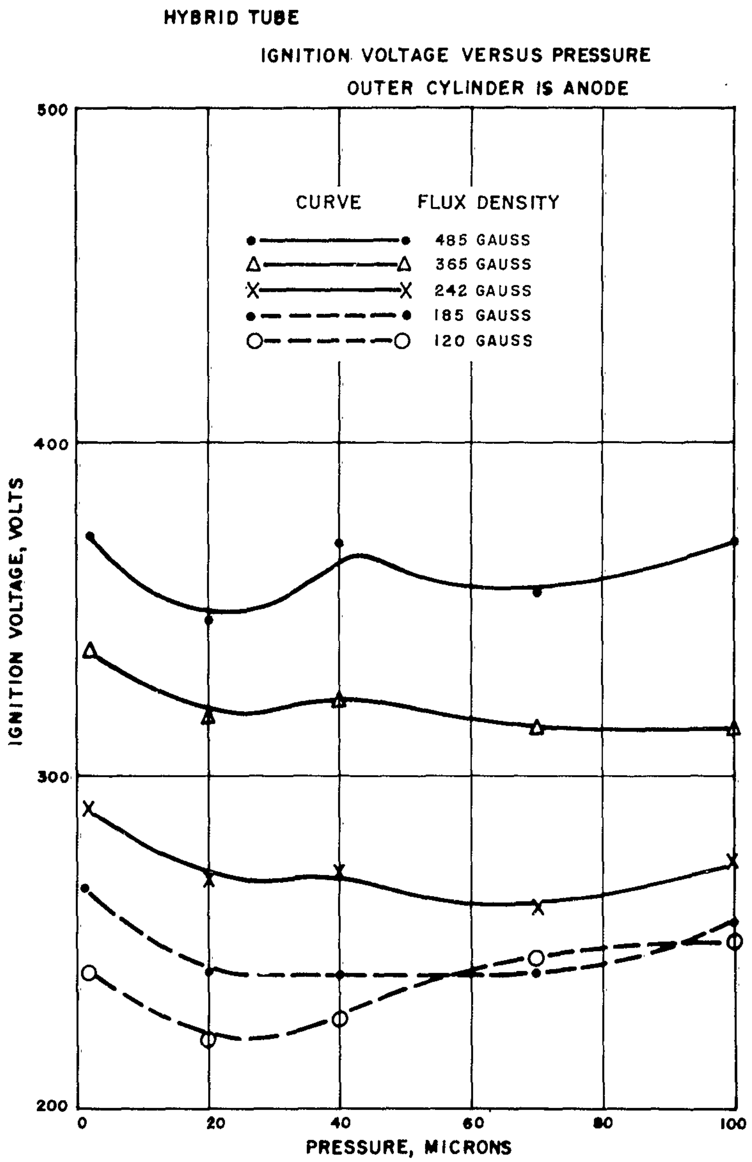

HYBRID TUBE
IGNITION VOLTAGE VERSUS PRESSURE
OUTER CYLINDER IS ANODE
CURVE
FLUX DENSITY
485 GAUSS
365 GAUSS
242 GAUSS
185 GAUSS
120 GAUSS
IGNITION VOLTAGE, VOLTS
500
400
300
200
0
20
40
60
80
100
PRESSURE, MICRONS

Figure 19

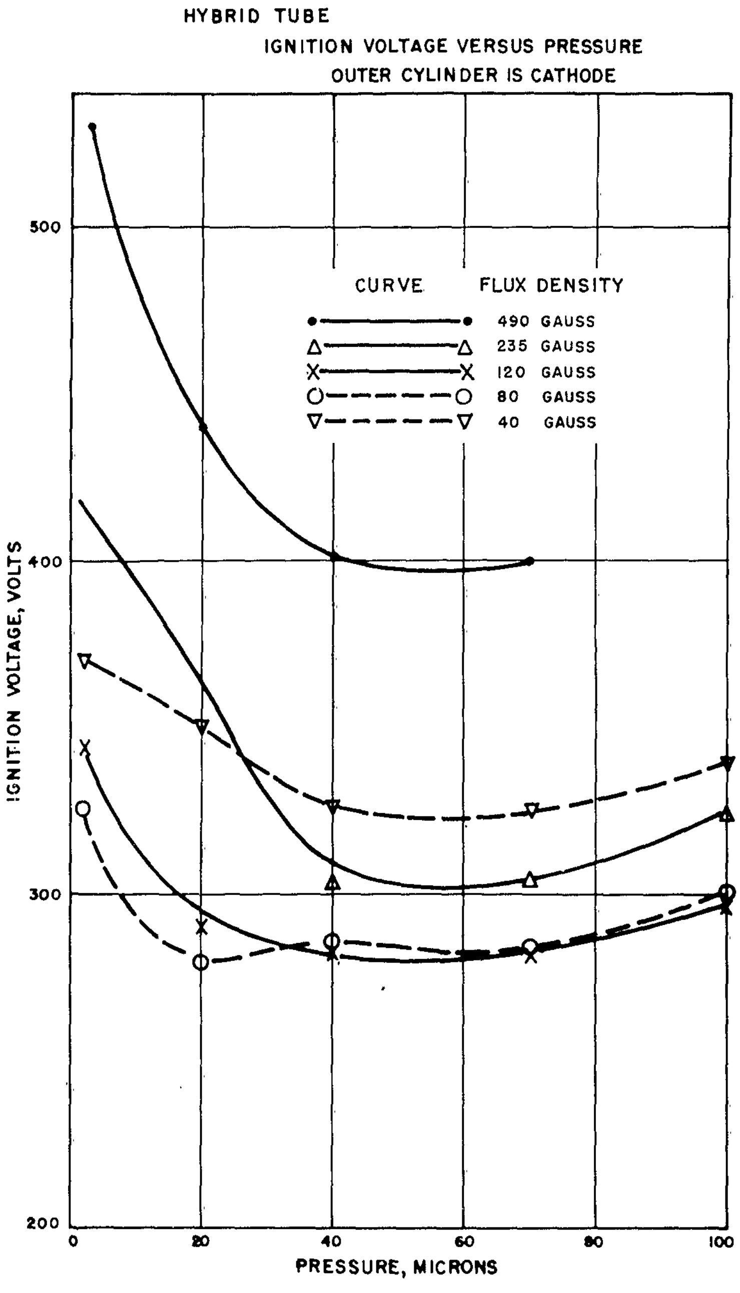

HYBRID TUBE
IGNITION VOLTAGE VERSUS PRESSURE
OUTER CYLINDER IS CATHODE
CURVE
FLUX DENSITY
490 GAUSS
235 GAUSS
120 GAUSS
80 GAUSS
40 GAUSS
IGNITION VOLTAGE, VOLTS
500
400
300
200
0
20
40
60
80
100
PRESSURE, MICRONS

Figure 20

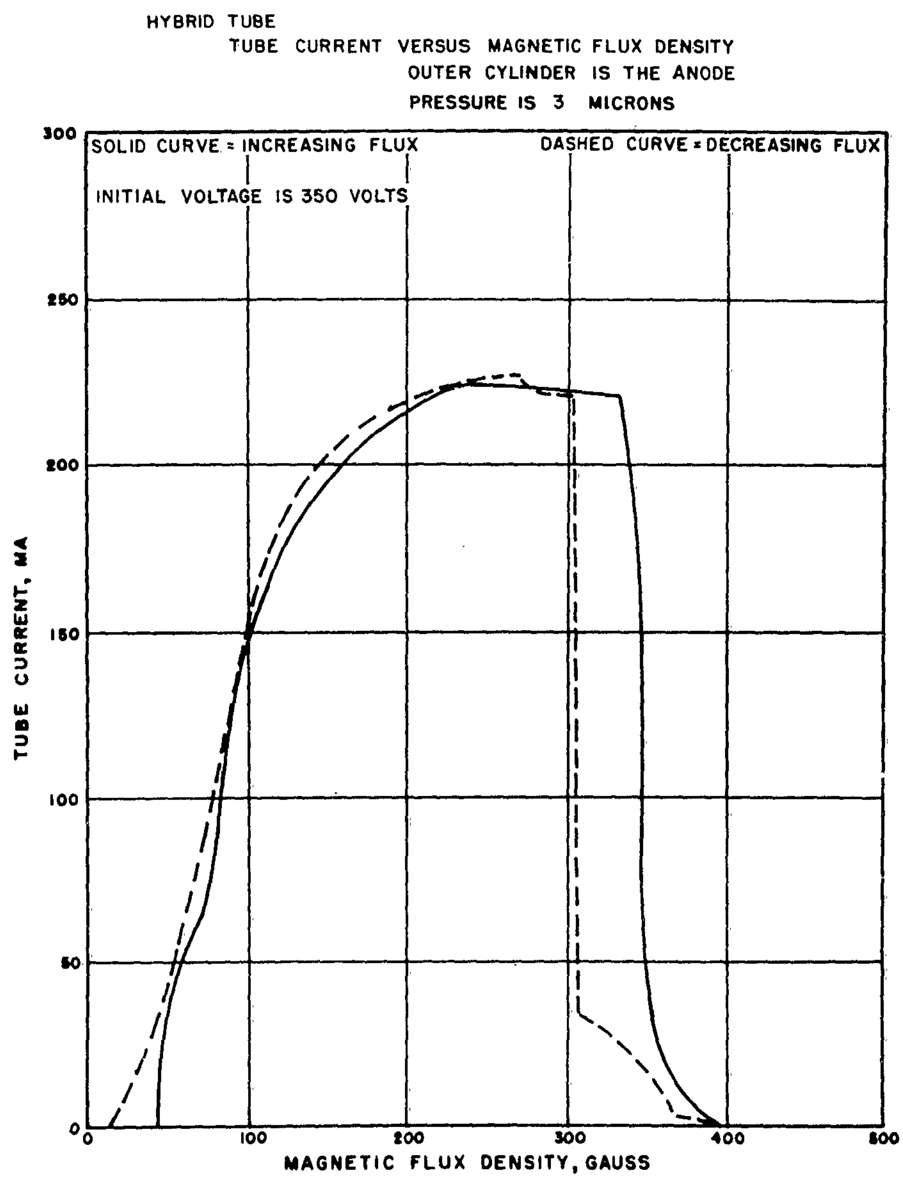

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 3 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 21a

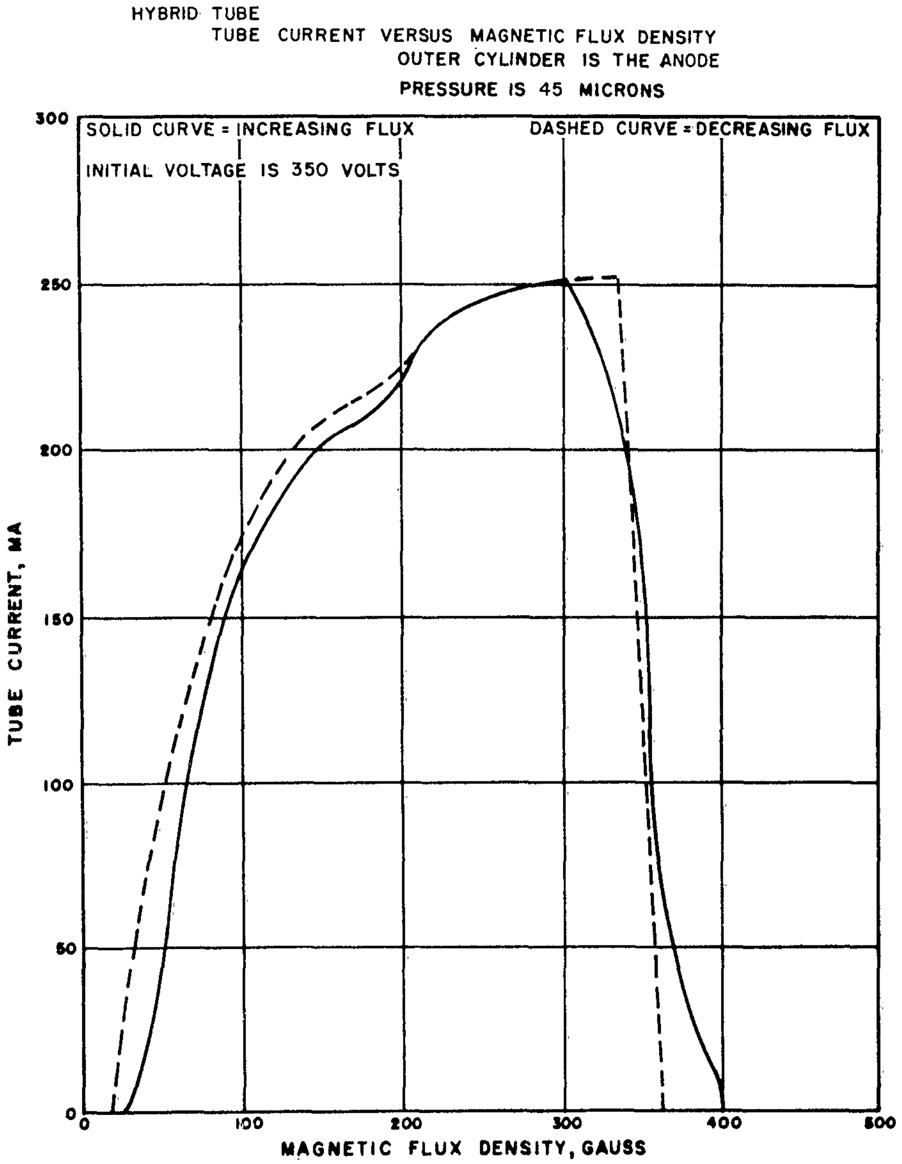

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 45 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
300
250
200
150
100
50
0
TUBE CURRENT, MA
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 21b

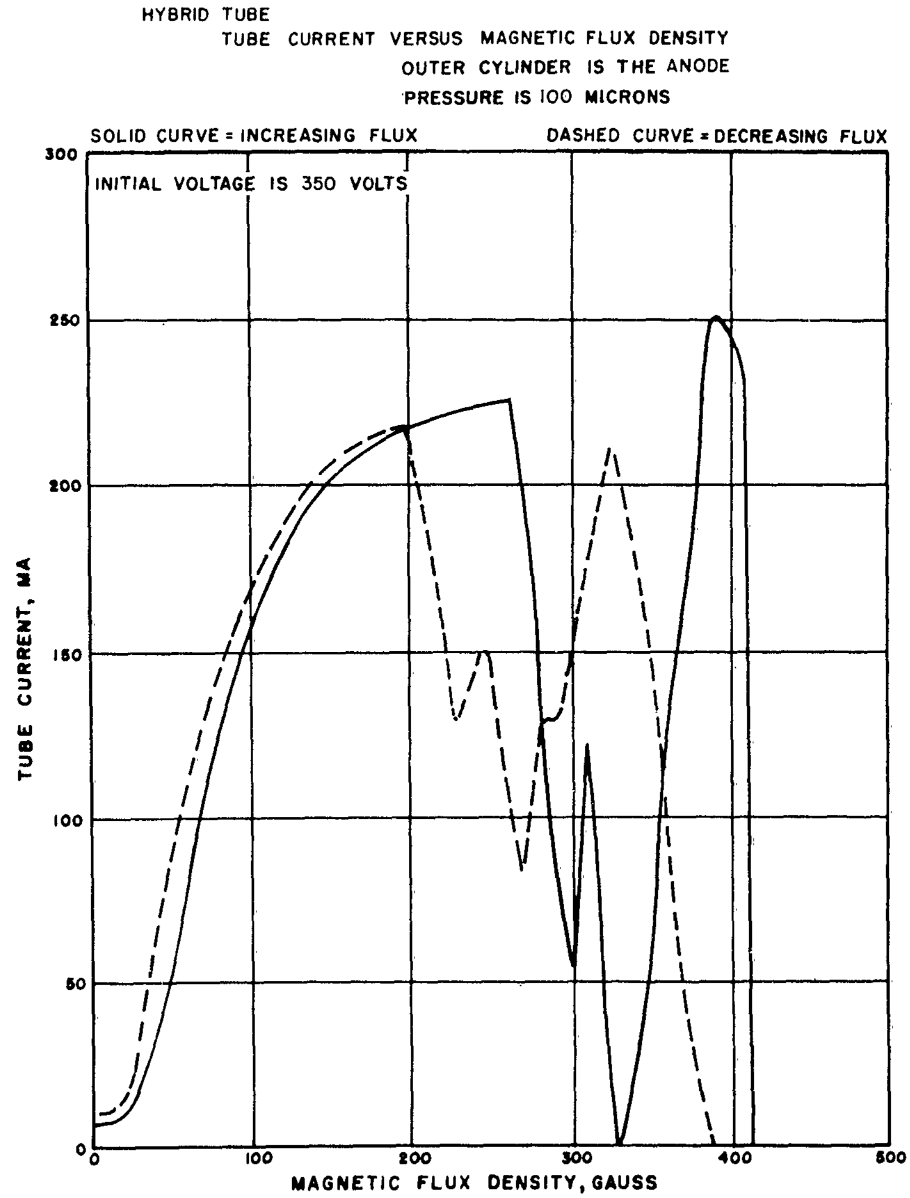

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 21c

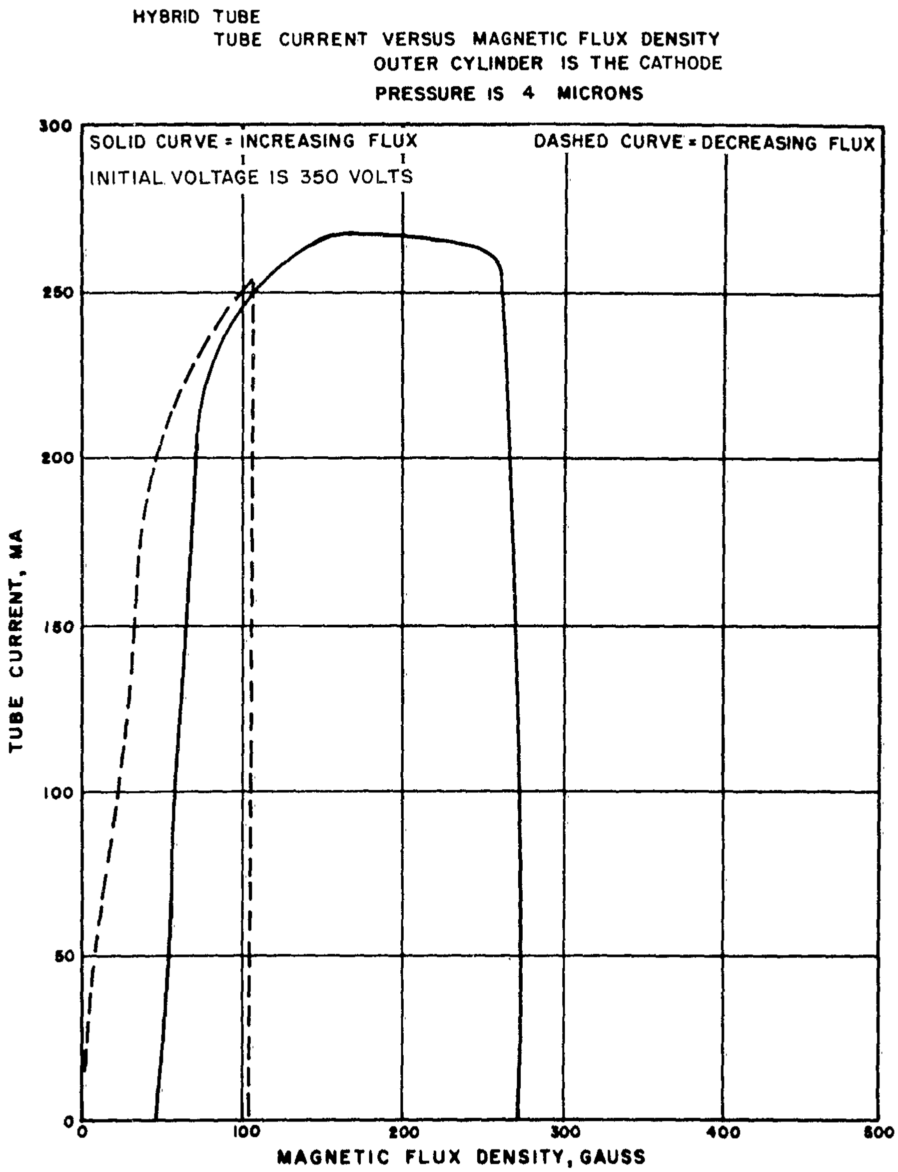

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 4 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
INITIAL VOLTAGE IS 350 VOLTS
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 22a

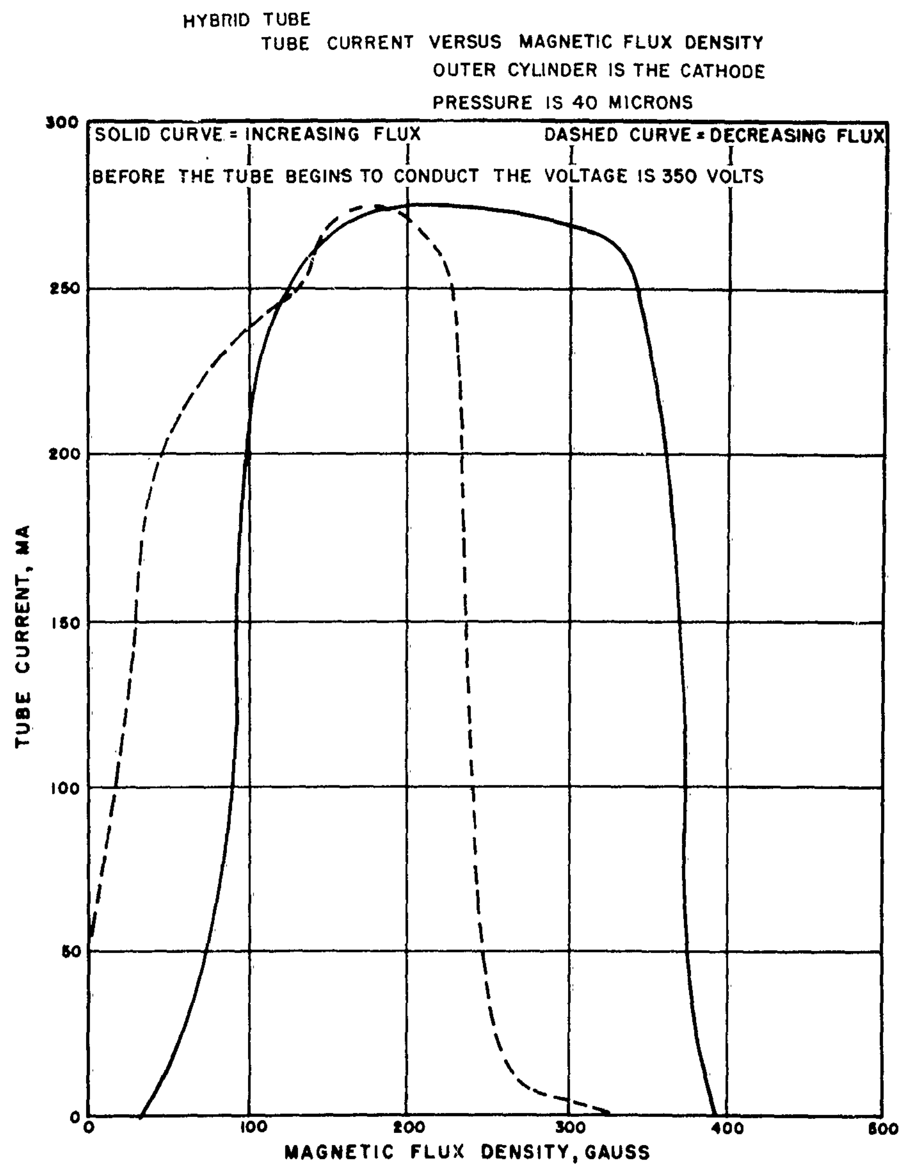

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 40 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
BEFORE THE TUBE BEGINS TO CONDUCT THE VOLTAGE IS 350 VOLTS
TUBE CURRENT, MA
MAGNETIC FLUX DENSITY, GAUSS
0
50
100
150
200
250
300
0
100
200
300
400
500

Figure 22b

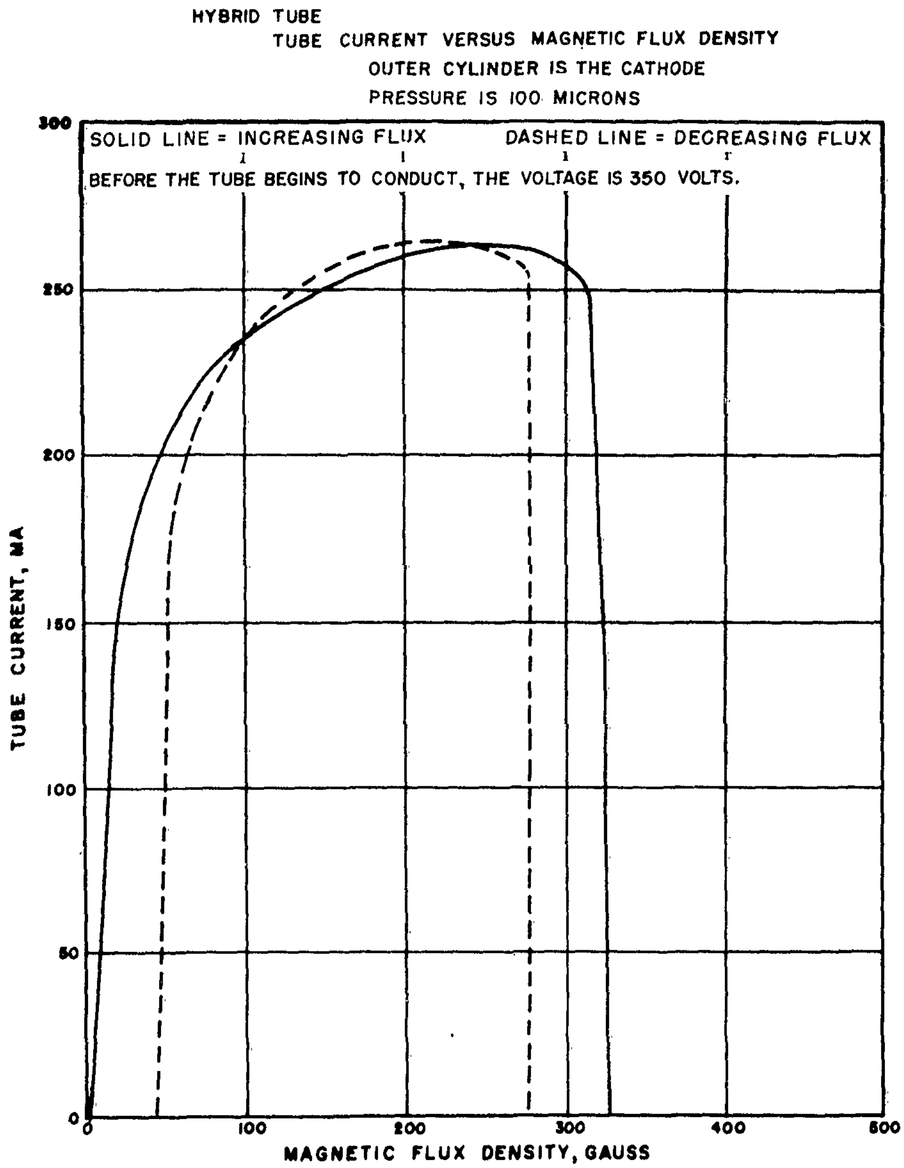

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 100 MICRONS
SOLID LINE = INCREASING FLUX
DASHED LINE = DECREASING FLUX
BEFORE THE TUBE BEGINS TO CONDUCT, THE VOLTAGE IS 350 VOLTS.
TUBE CURRENT, MA
300
250
200
150
100
50
0
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 22c

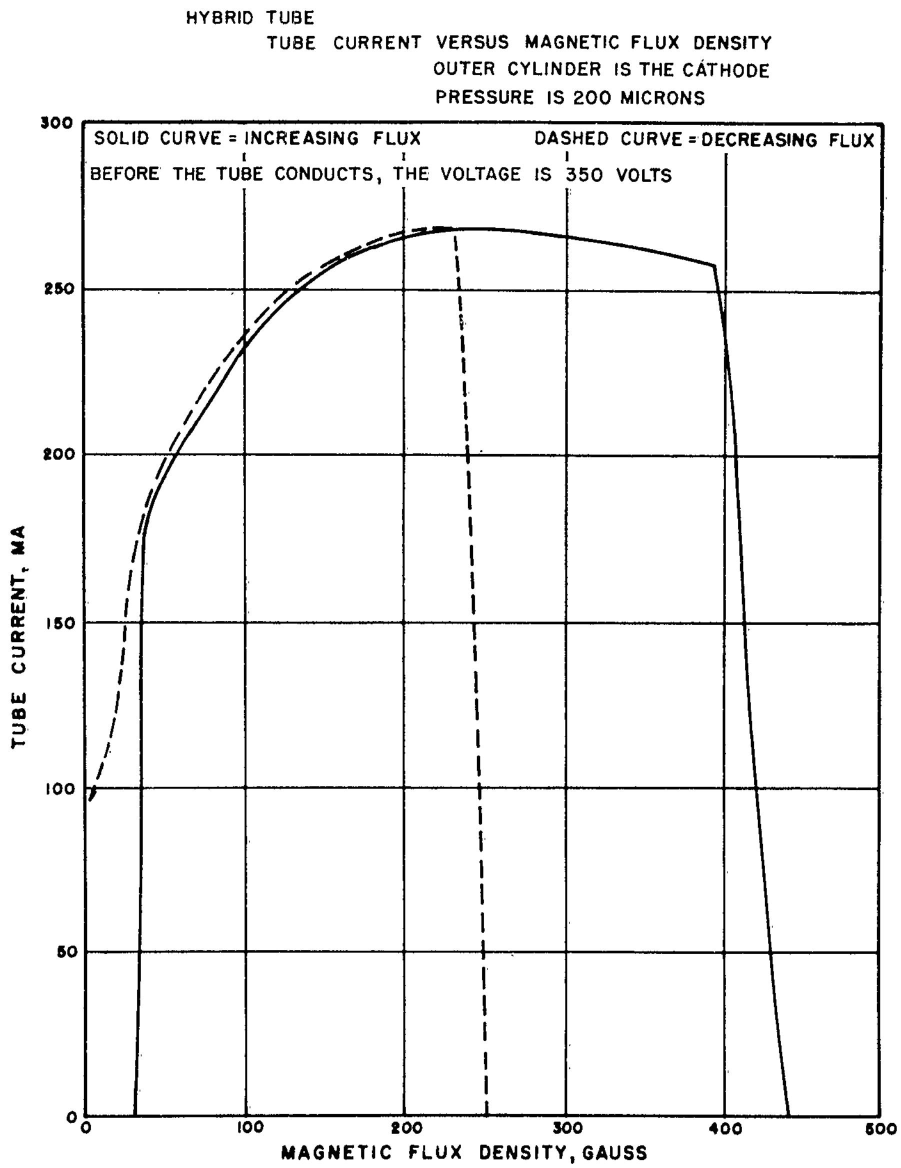

HYBRID TUBE
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 200 MICRONS
SOLID CURVE = INCREASING FLUX
DASHED CURVE = DECREASING FLUX
BEFORE THE TUBE CONDUCTS, THE VOLTAGE IS 350 VOLTS
TUBE CURRENT, MA
300
250
200
150
100
50
0
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 22d

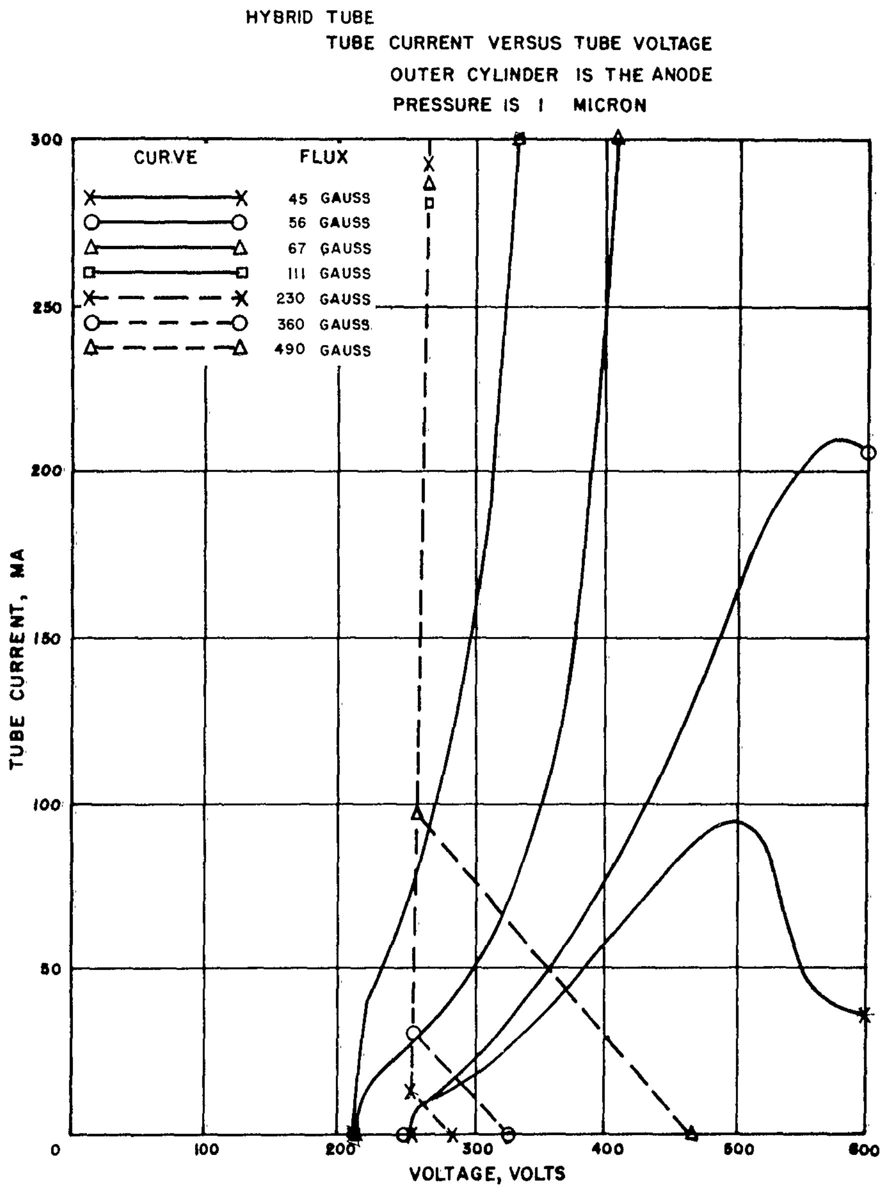

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 1 MICRON
CURVE
FLUX
45 GAUSS
56 GAUSS
67 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
0
50
100
150
200
250
300
100
200
300
400
500
600
VOLTAGE, VOLTS

Figure 23a

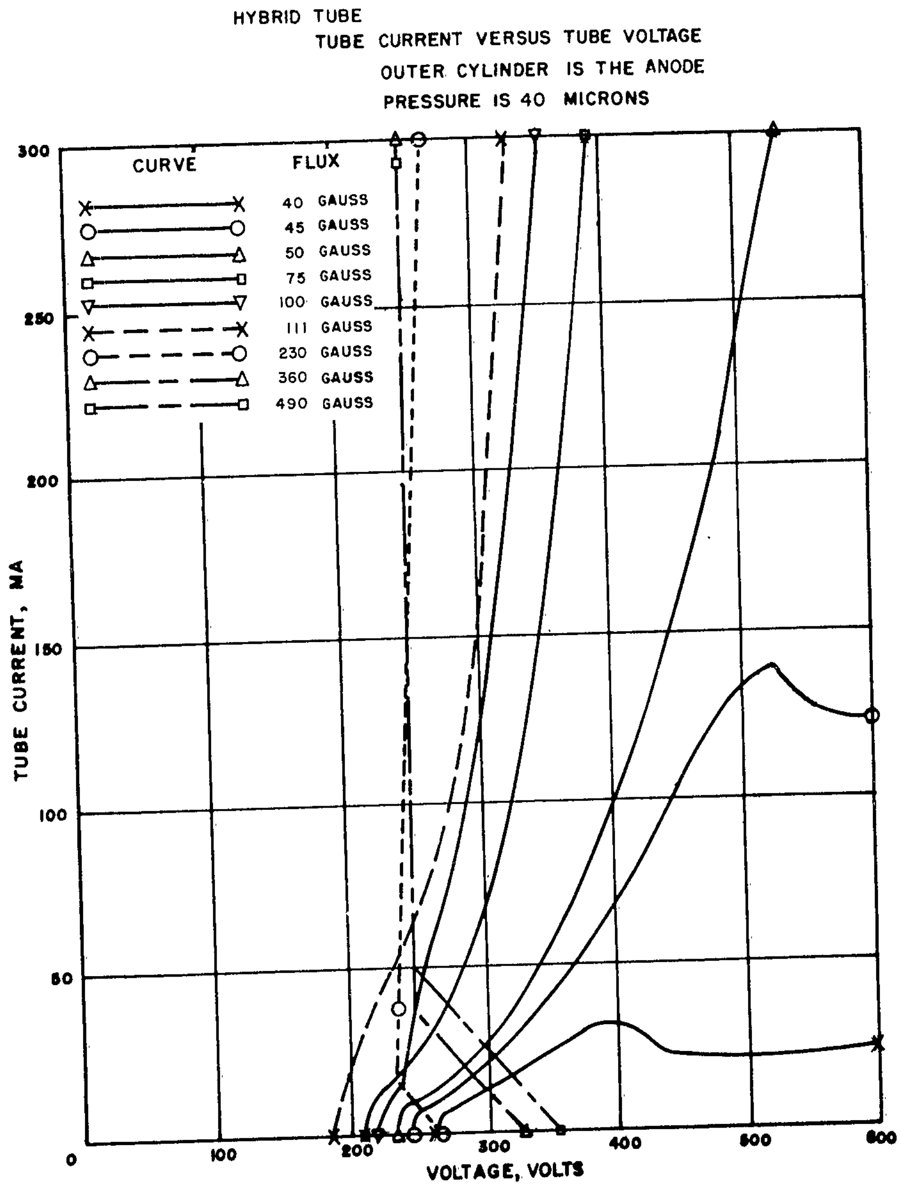

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 40 MICRONS
CURVE
FLUX
40 GAUSS
45 GAUSS
50 GAUSS
75 GAUSS
100 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
300
250
200
150
100
50
0
100
200
300
400
500
600
VOLTAGE, VOLTS

Figure 23b

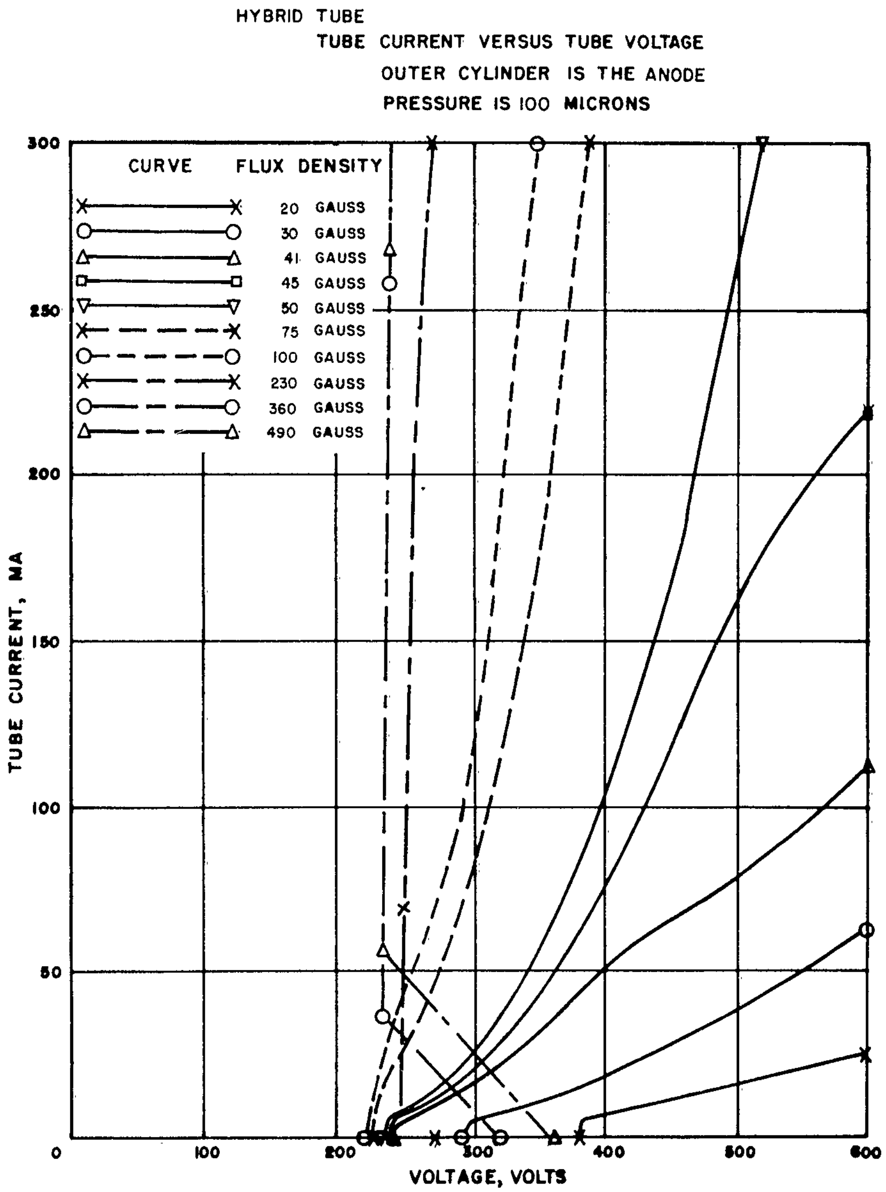

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE ANODE
PRESSURE IS 100 MICRONS
CURVE
FLUX DENSITY
20 GAUSS
30 GAUSS
41 GAUSS
45 GAUSS
50 GAUSS
75 GAUSS
100 GAUSS
230 GAUSS
360 GAUSS
490 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 23c

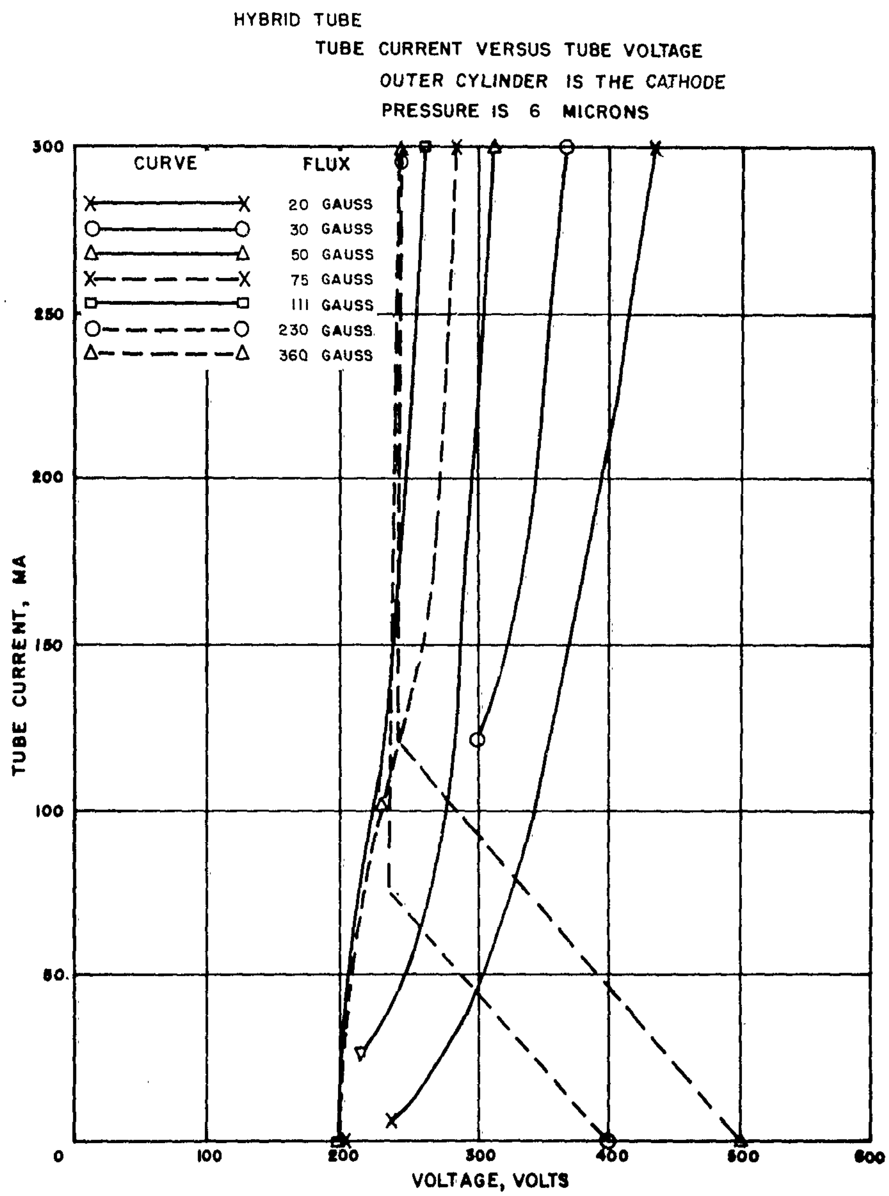

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 6 MICRONS
CURVE
FLUX
20 GAUSS
30 GAUSS
50 GAUSS
75 GAUSS
111 GAUSS
230 GAUSS
360 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
100
200
300
400
500
600
50
150
250

Figure 24a

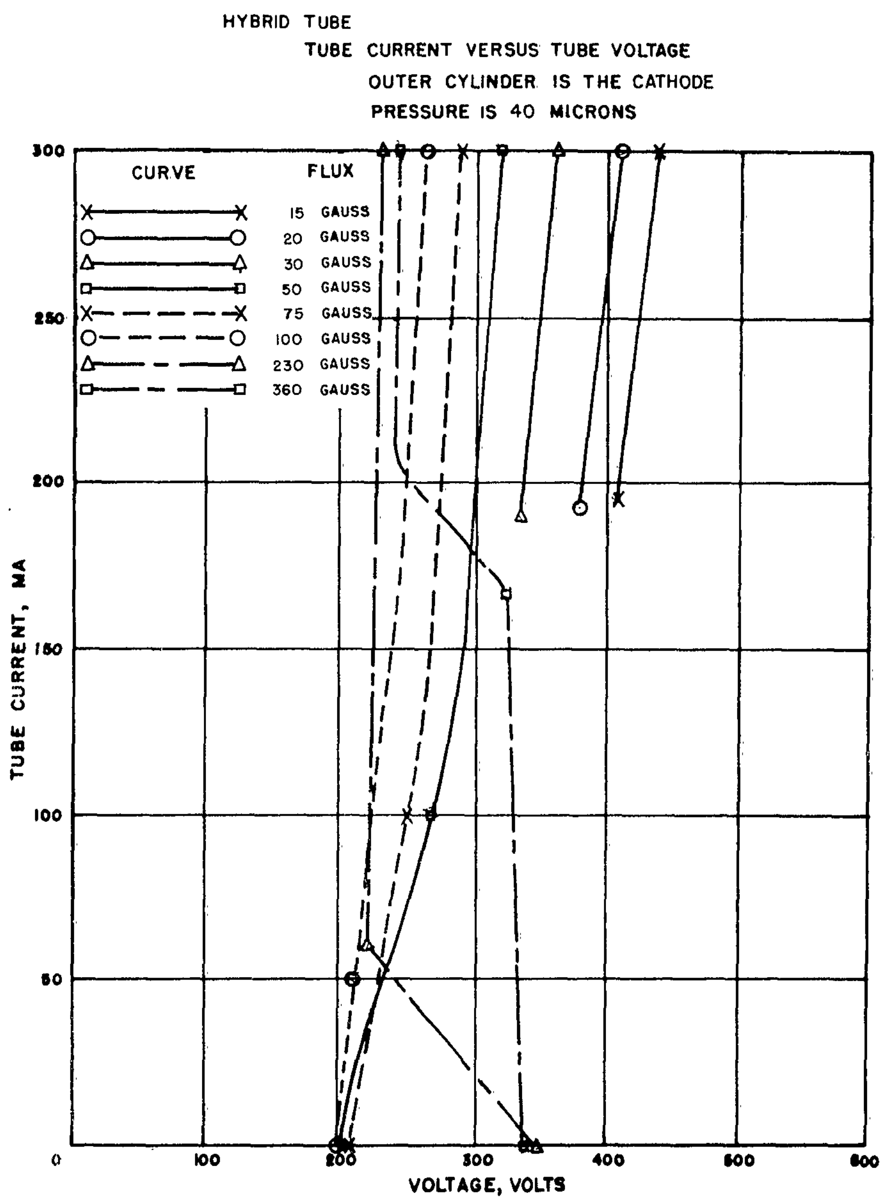

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 40 MICRONS
CURVE
FLUX
15 GAUSS
20 GAUSS
30 GAUSS
50 GAUSS
75 GAUSS
100 GAUSS
230 GAUSS
360 GAUSS
TUBE CURRENT, MA
0
50
100
150
200
250
300
100
200
300
400
500
600
VOLTAGE, VOLTS

Figure 24b

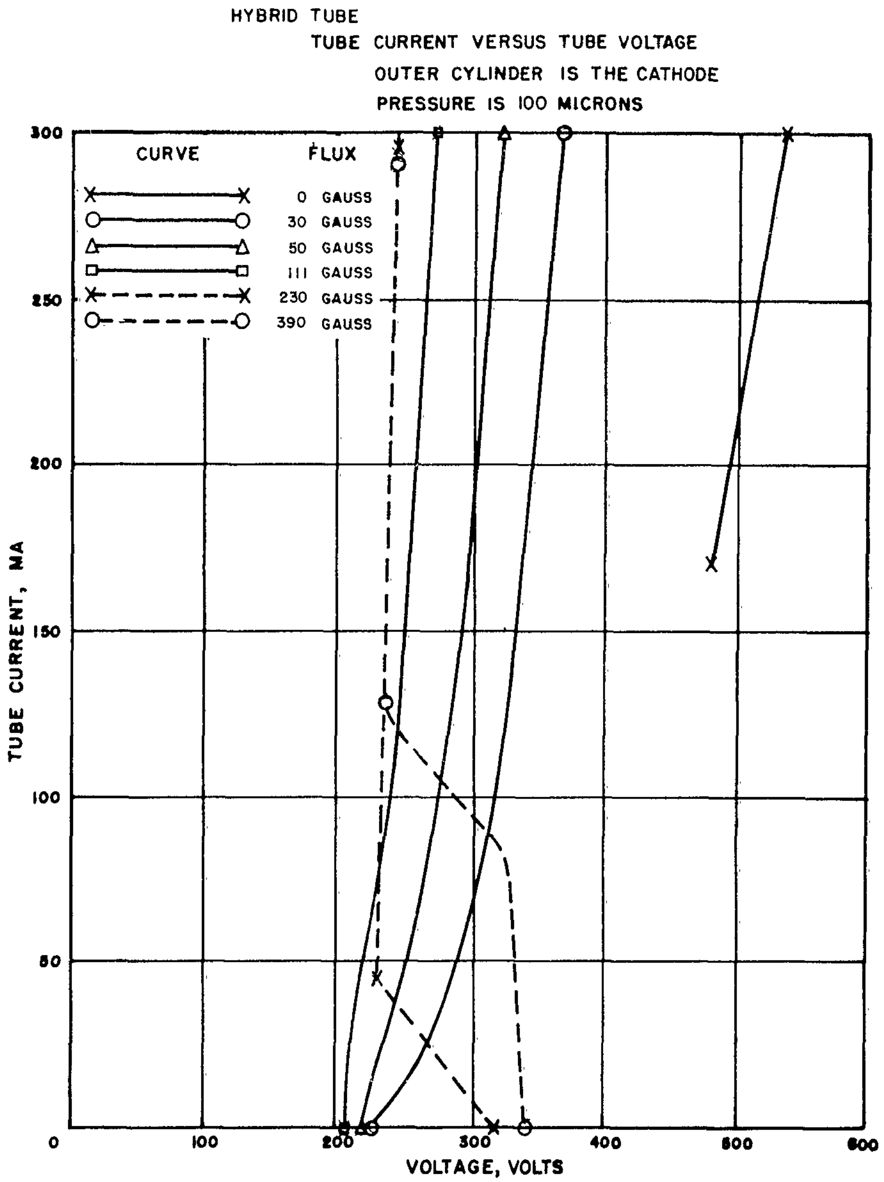

HYBRID TUBE
TUBE CURRENT VERSUS TUBE VOLTAGE
OUTER CYLINDER IS THE CATHODE
PRESSURE IS 100 MICRONS
CURVE
FLUX
0 GAUSS
30 GAUSS
50 GAUSS
111 GAUSS
230 GAUSS
390 GAUSS
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
100
200
300
400
500
600

Figure 24c

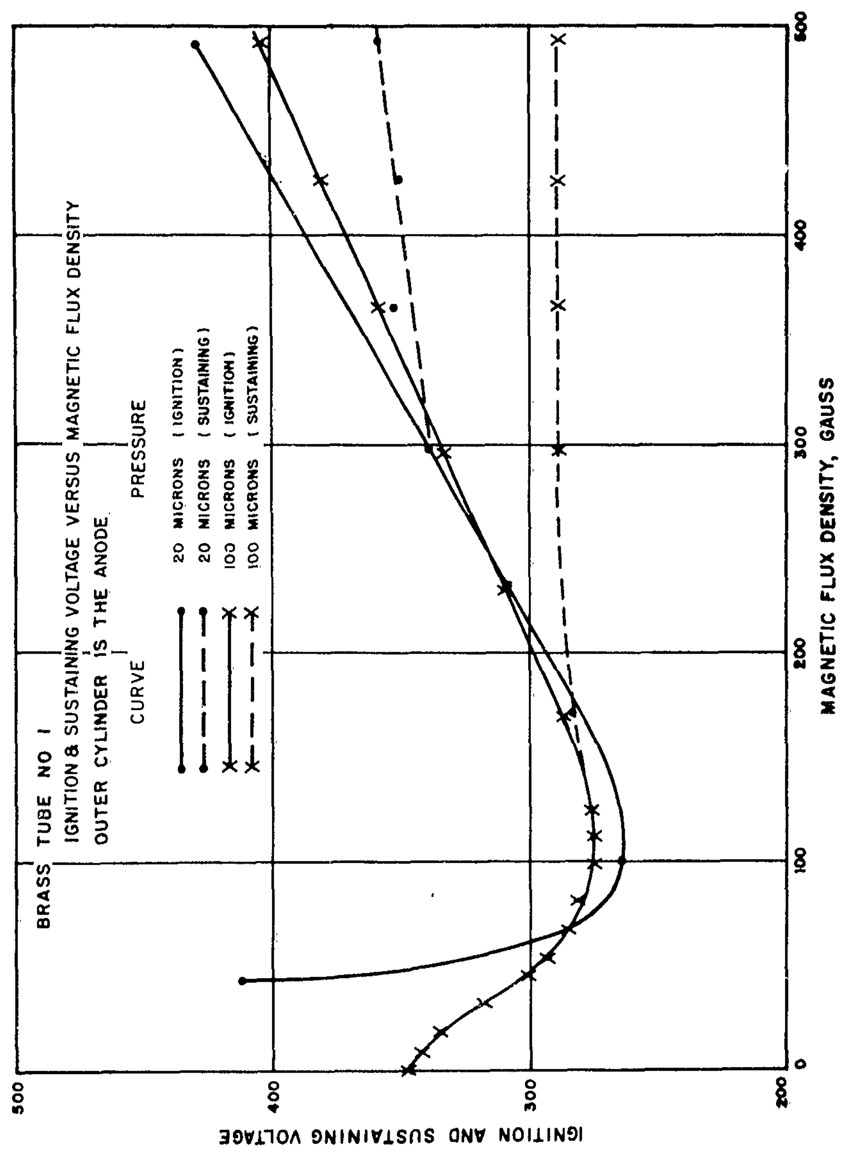
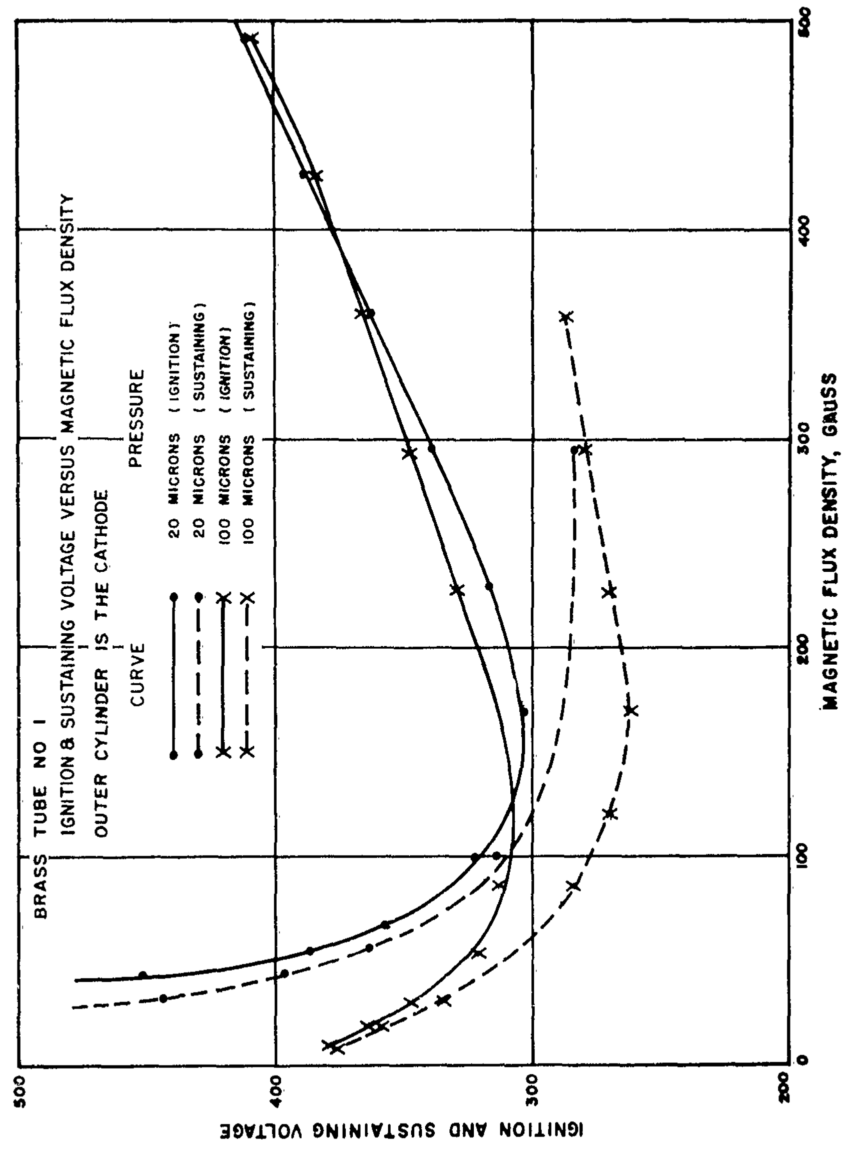

BRASS TUBE NO I
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
20 MICRONS (SUSTAINING)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
IGNITION AND SUSTAINING VOLTAGE
500
400
300
200
MAGNETIC FLUX DENSITY, GAUSS
0
100
200
300
400
500

Figure 25a



BRASS TUBE NO I
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
20 MICRONS (SUSTAINING)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
MAGNETIC FLUX DENSITY, GAUSS
IGNITION AND SUSTAINING VOLTAGE
0
100
200
300
400
500

Figure 25b

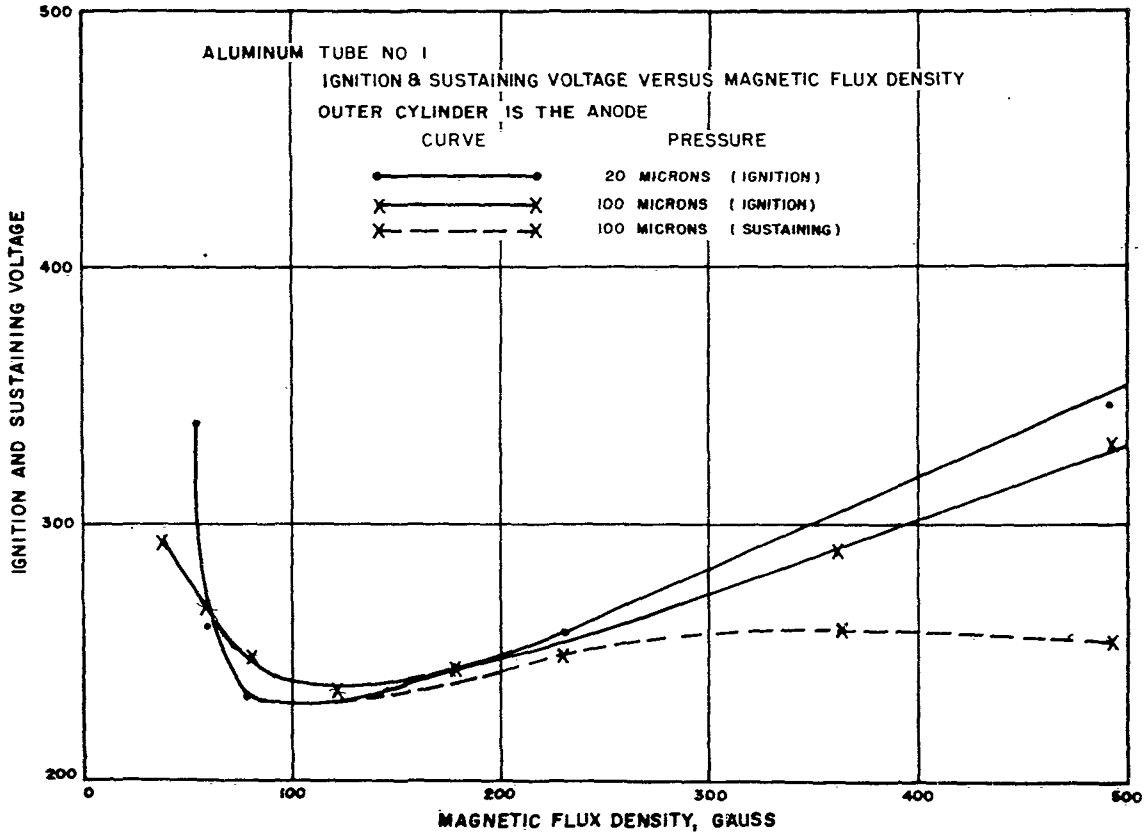

ALUMINUM TUBE NO I
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
IGNITION AND SUSTAINING VOLTAGE
200
300
400
500
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 26a

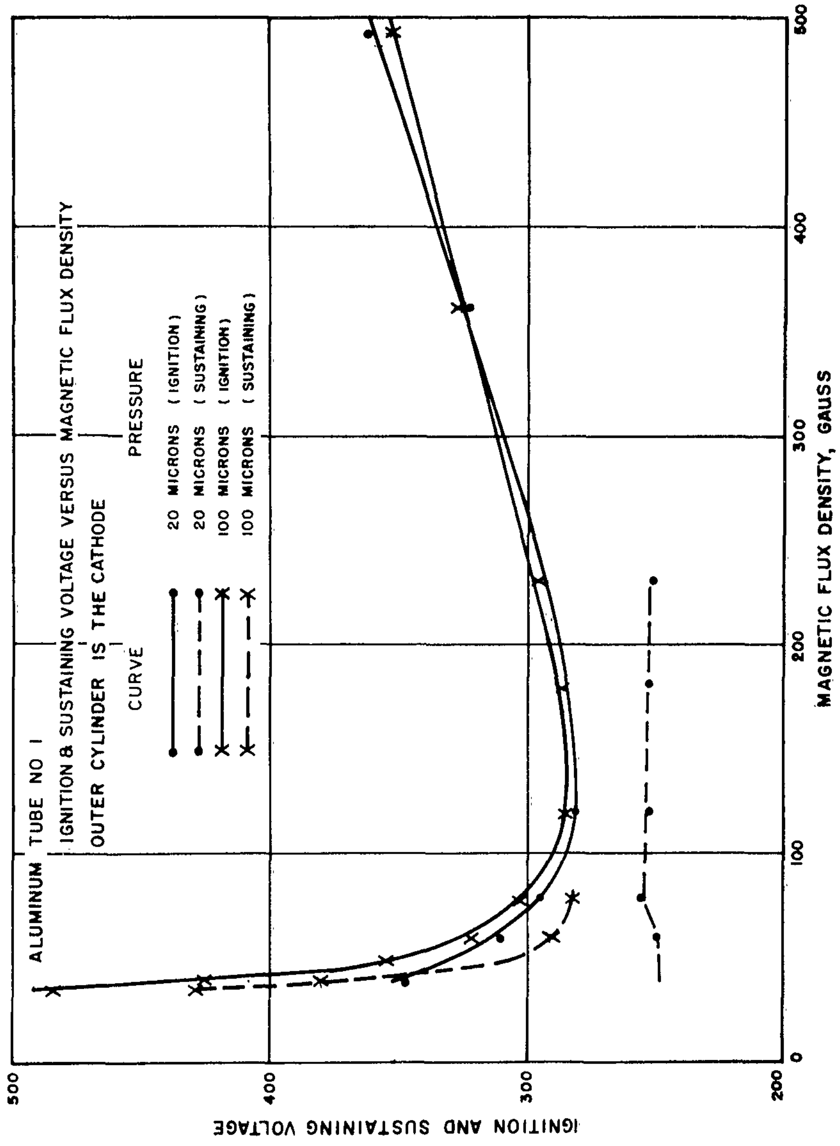

ALUMINUM TUBE NO I
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
20 MICRONS (SUSTAINING)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
MAGNETIC FLUX DENSITY, GAUSS
IGNITION AND SUSTAINING VOLTAGE
0
100
200
300
400
500

Figure 26b

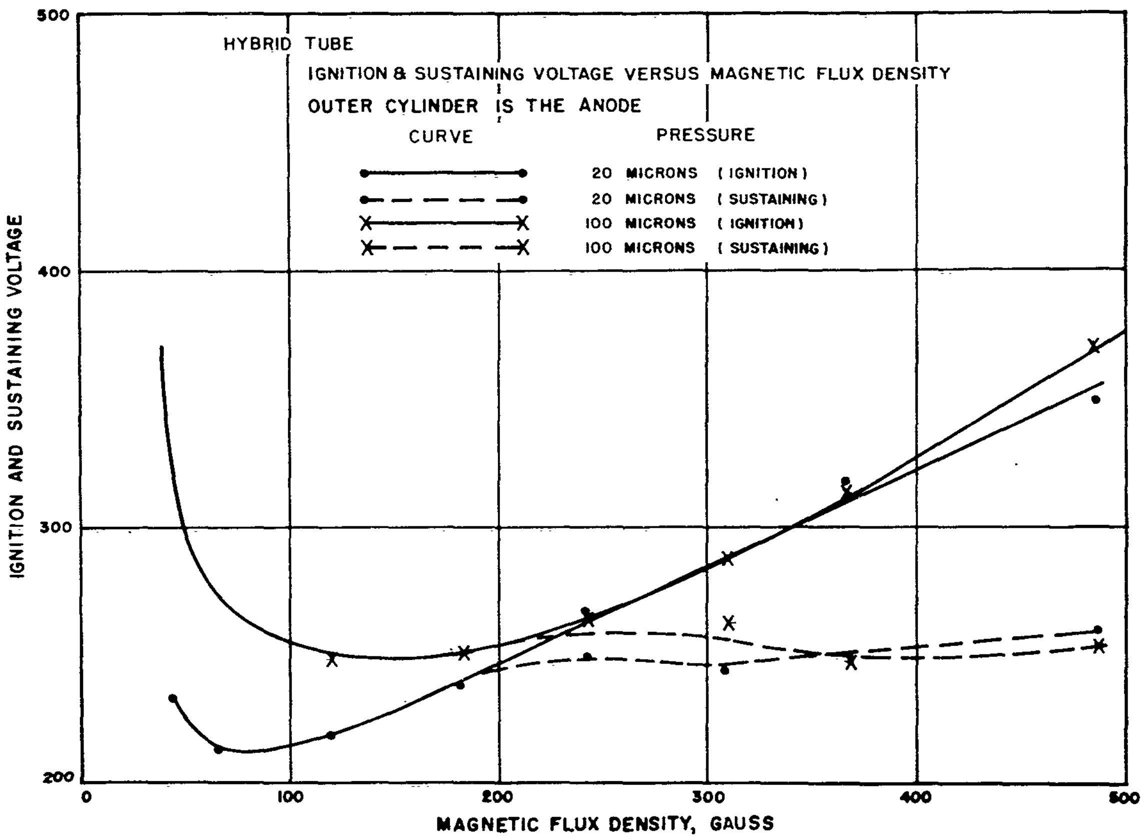

HYBRID TUBE
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
20 MICRONS (SUSTAINING)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
IGNITION AND SUSTAINING VOLTAGE
500
400
300
200
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 27a

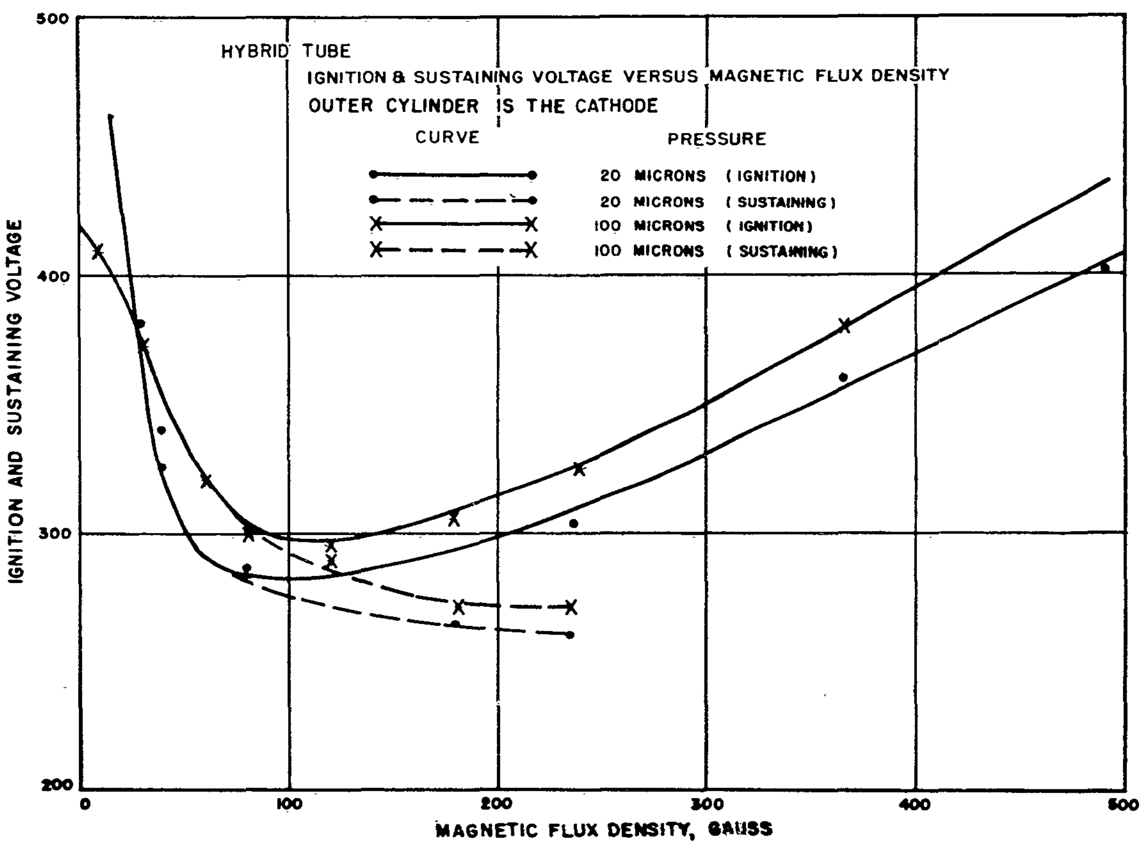

HYBRID TUBE
IGNITION & SUSTAINING VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
CURVE
PRESSURE
20 MICRONS (IGNITION)
20 MICRONS (SUSTAINING)
100 MICRONS (IGNITION)
100 MICRONS (SUSTAINING)
500
400
300
200
IGNITION AND SUSTAINING VOLTAGE
0
100
200
300
400
500
MAGNETIC FLUX DENSITY, GAUSS

Figure 27b

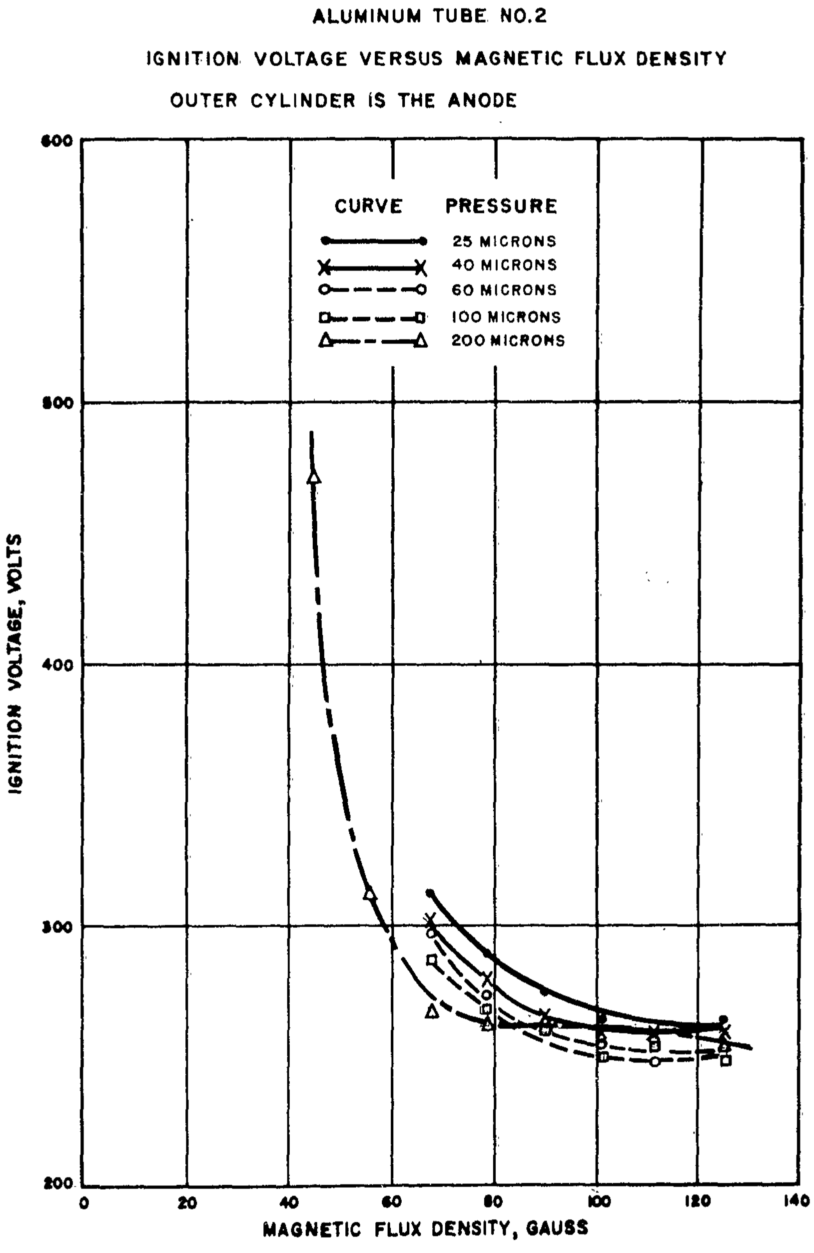

ALUMINUM TUBE NO.2
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
CURVE
PRESSURE
25 MICRONS
40 MICRONS
60 MICRONS
100 MICRONS
200 MICRONS
IGNITION VOLTAGE, VOLTS
MAGNETIC FLUX DENSITY, GAUSS
600
500
400
300
200
0
20
40
60
80
100
120
140

Figure 28

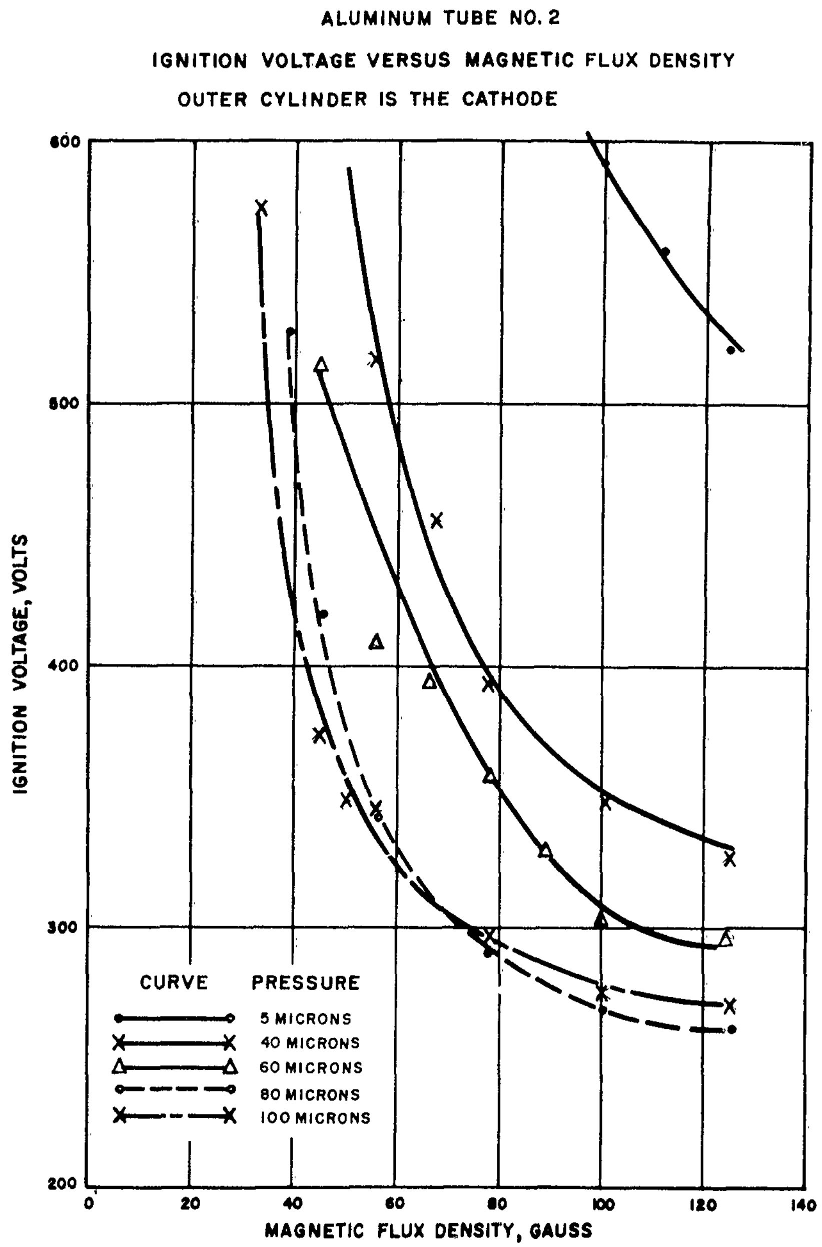
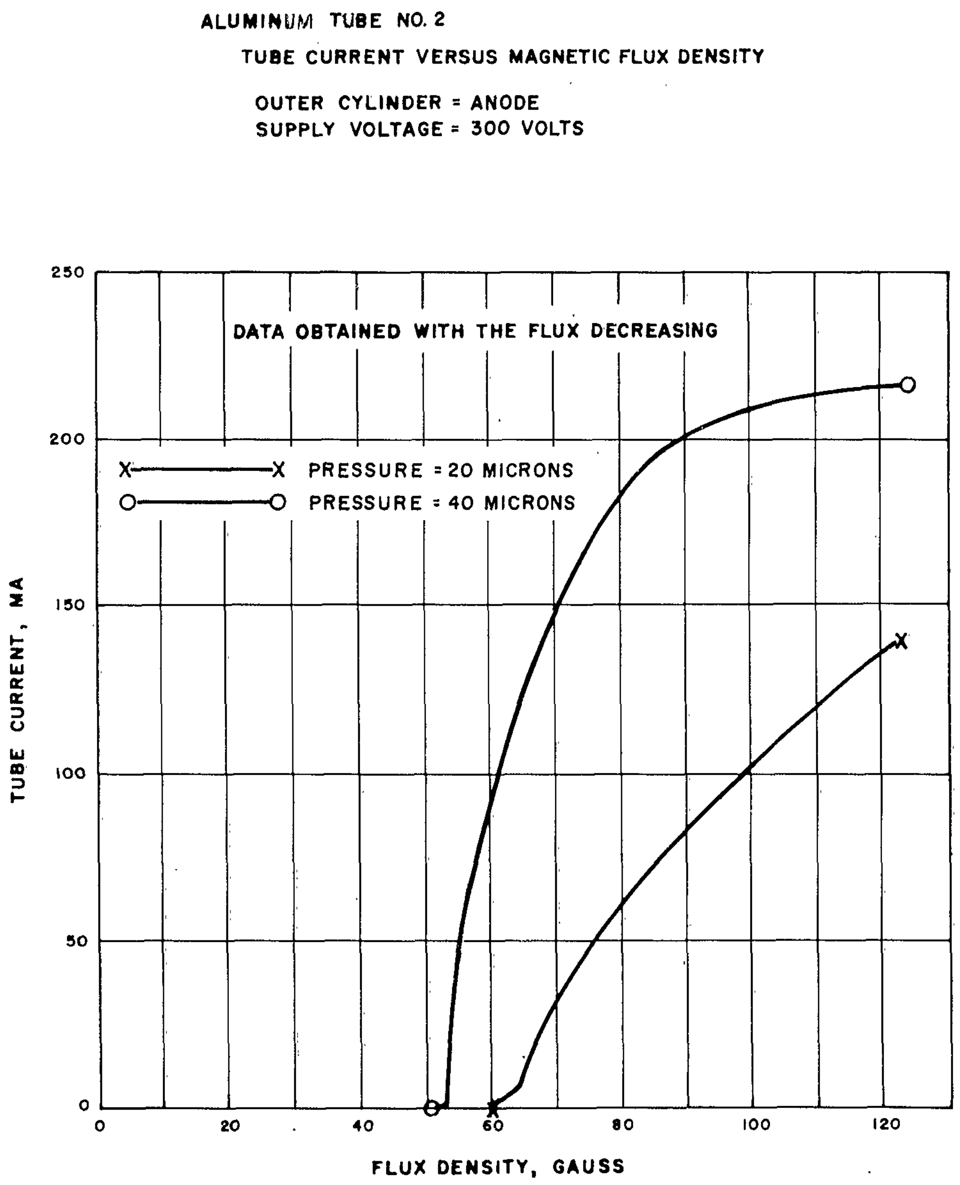

ALUMINUM TUBE NO. 2
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
20
40
60
80
100
120
140
MAGNETIC FLUX DENSITY, GAUSS
CURVE
PRESSURE
5 MICRONS
40 MICRONS
60 MICRONS
80 MICRONS
100 MICRONS

Figure 29



ALUMINUM TUBE NO. 2
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER = ANODE
SUPPLY VOLTAGE = 300 VOLTS
DATA OBTAINED WITH THE FLUX DECREASING
X———X PRESSURE = 20 MICRONS
O———O PRESSURE = 40 MICRONS
TUBE CURRENT, MA
FLUX DENSITY, GAUSS
0
50
100
150
200
250
20
40
60
80
100
120

Figure 30

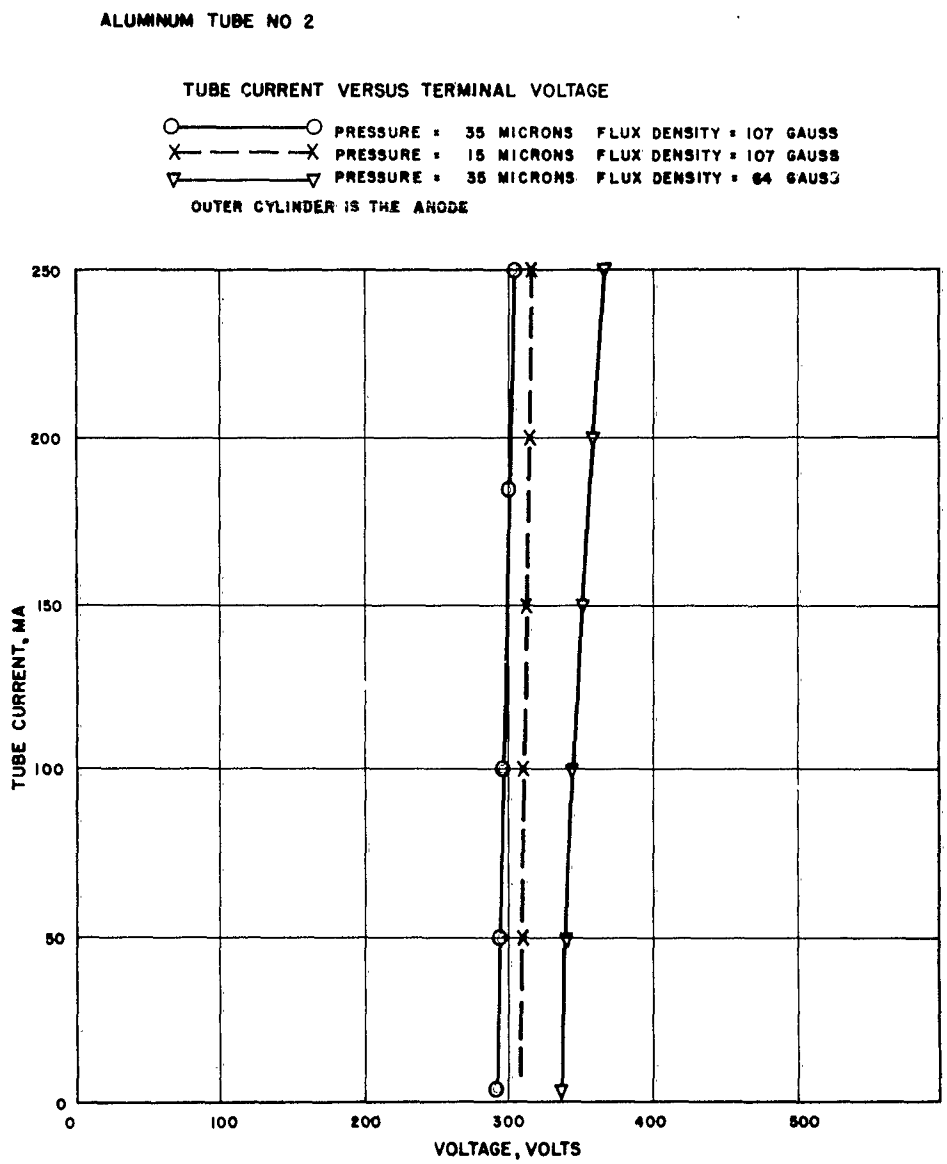

ALUMINUM TUBE NO 2
TUBE CURRENT VERSUS TERMINAL VOLTAGE
PRESSURE = 35 MICRONS FLUX DENSITY = 107 GAUSS
PRESSURE = 15 MICRONS FLUX DENSITY = 107 GAUSS
PRESSURE = 35 MICRONS FLUX DENSITY = 64 GAUSS
OUTER CYLINDER IS THE ANODE
250
200
150
100
50
0
TUBE CURRENT, MA
0
100
200
300
400
500
VOLTAGE, VOLTS

Figure 31

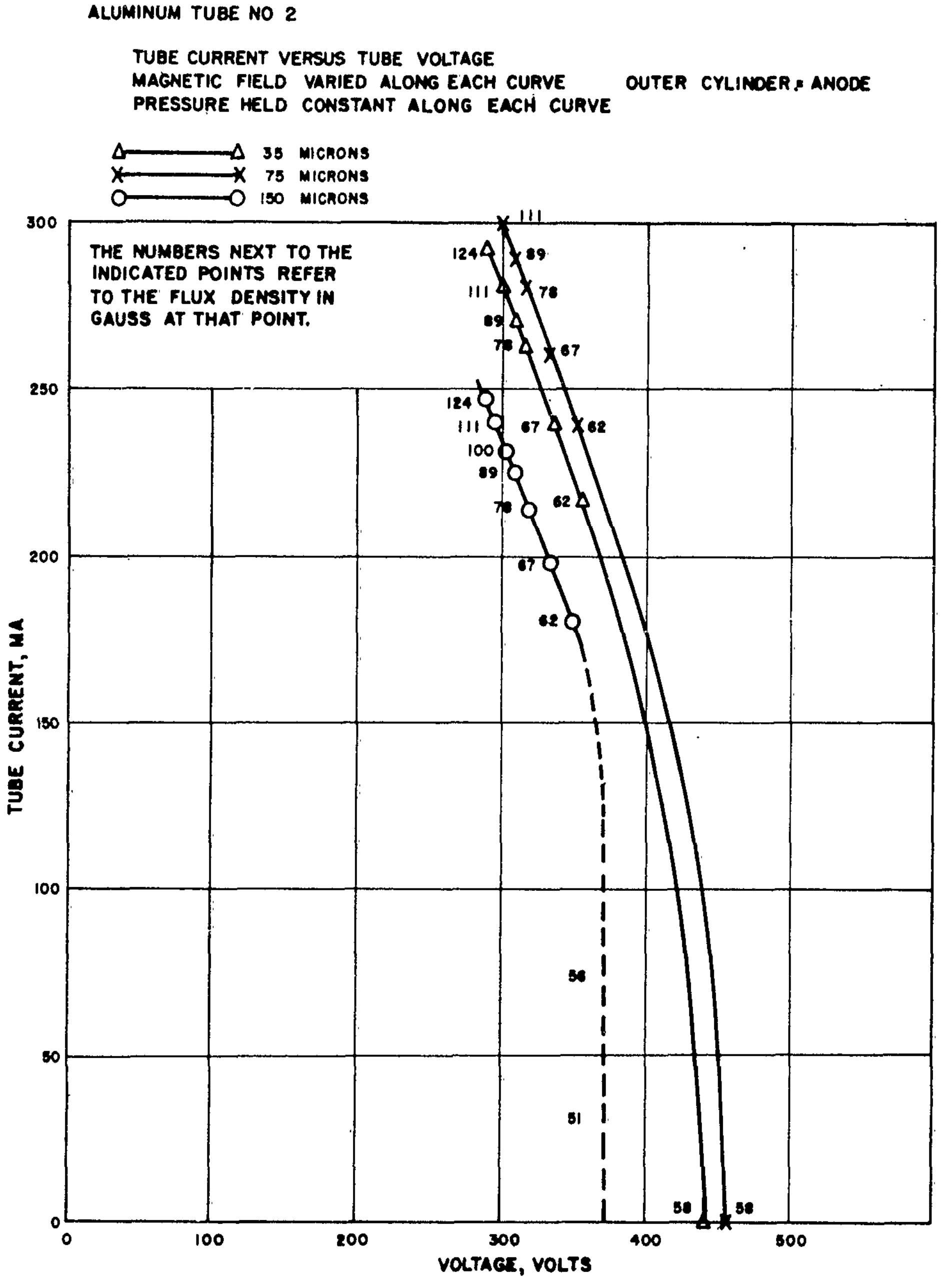

ALUMINUM TUBE NO 2
TUBE CURRENT VERSUS TUBE VOLTAGE
MAGNETIC FIELD VARIED ALONG EACH CURVE
PRESSURE HELD CONSTANT ALONG EACH CURVE
OUTER CYLINDER = ANODE
35 MICRONS
75 MICRONS
150 MICRONS
THE NUMBERS NEXT TO THE INDICATED POINTS REFER TO THE FLUX DENSITY IN GAUSS AT THAT POINT.
TUBE CURRENT, MA
VOLTAGE, VOLTS
0
50
100
150
200
250
300
0
100
200
300
400
500
111
124
89
111
78
89
78
67
124
111
67
62
100
89
78
62
67
62
56
51
58
58

Figure 32

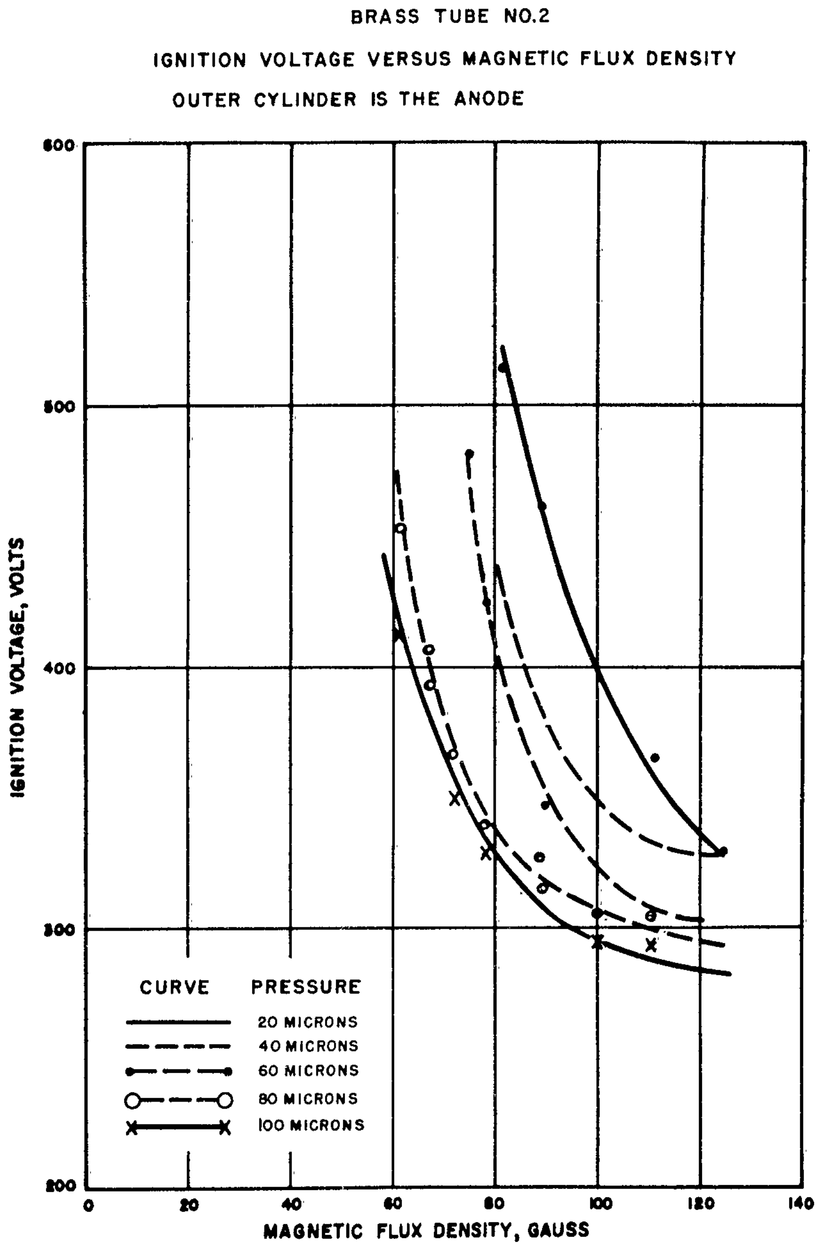
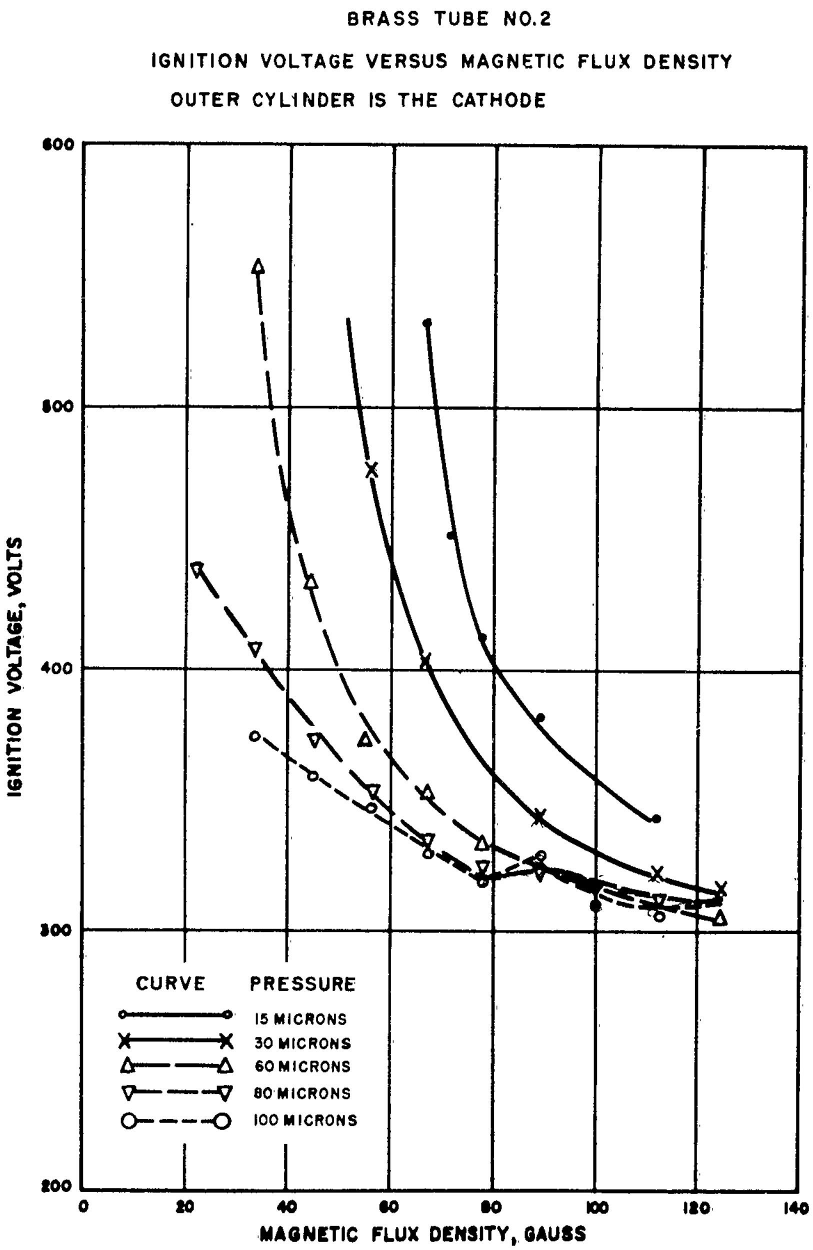
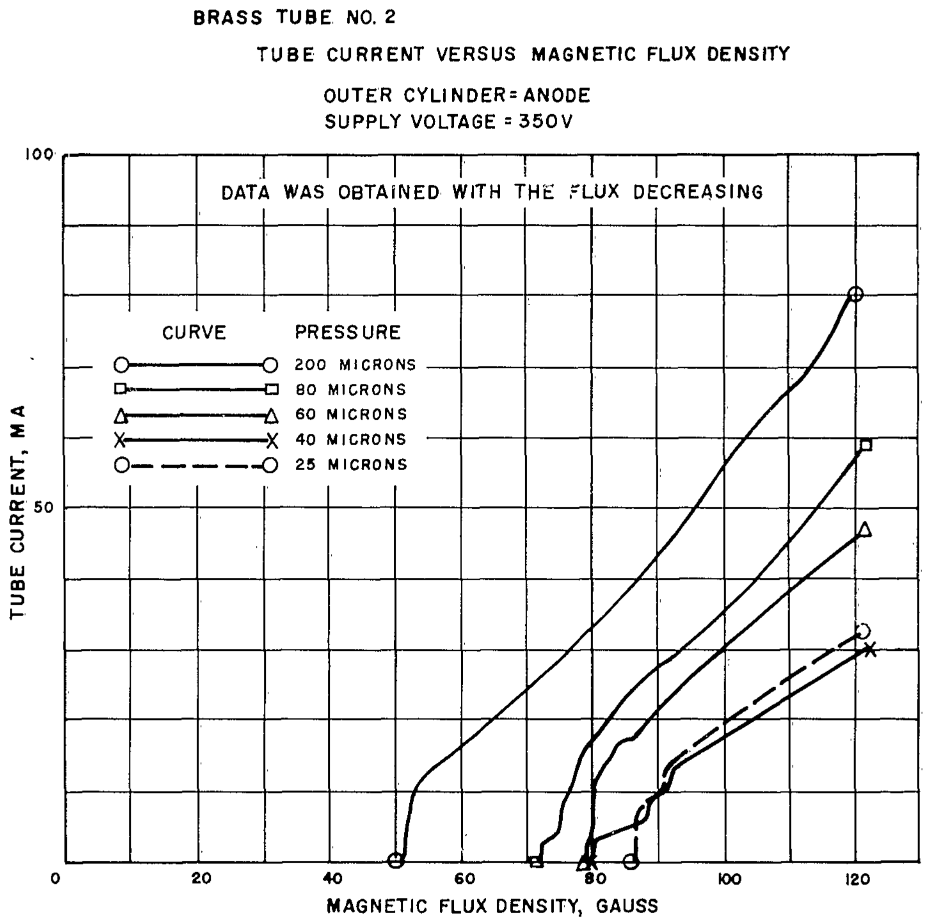

BRASS TUBE NO.2
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE ANODE
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
20
40
60
80
100
120
140
MAGNETIC FLUX DENSITY, GAUSS
CURVE
PRESSURE
20 MICRONS
40 MICRONS
60 MICRONS
80 MICRONS
100 MICRONS

Figure 33



BRASS TUBE NO.2
IGNITION VOLTAGE VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER IS THE CATHODE
IGNITION VOLTAGE, VOLTS
600
500
400
300
200
0
20
40
60
80
100
120
140
MAGNETIC FLUX DENSITY, GAUSS
CURVE
PRESSURE
15 MICRONS
30 MICRONS
60 MICRONS
80 MICRONS
100 MICRONS

Figure 34



BRASS TUBE NO. 2
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER = ANODE
SUPPLY VOLTAGE = 350V
DATA WAS OBTAINED WITH THE FLUX DECREASING
CURVE
PRESSURE
200 MICRONS
80 MICRONS
60 MICRONS
40 MICRONS
25 MICRONS
TUBE CURRENT, MA
100
50
0
20
40
60
80
100
120
MAGNETIC FLUX DENSITY, GAUSS

Figure 35

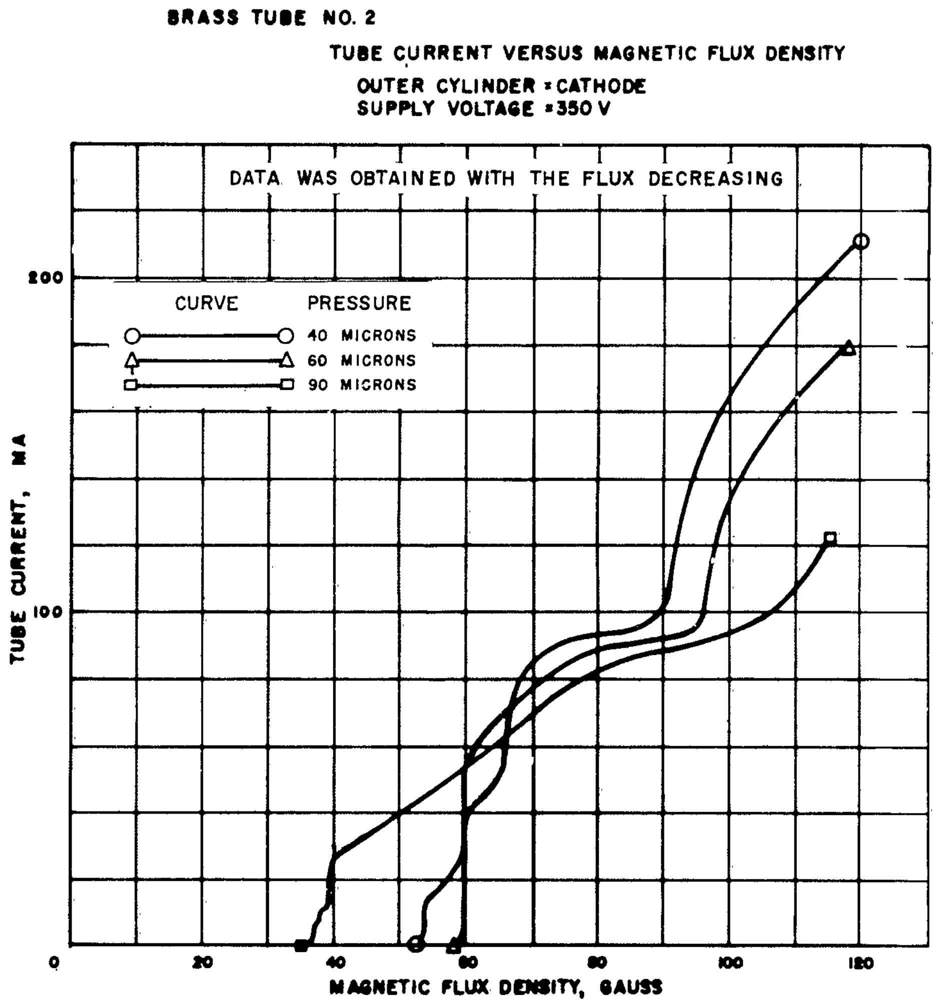

BRASS TUBE NO. 2
TUBE CURRENT VERSUS MAGNETIC FLUX DENSITY
OUTER CYLINDER = CATHODE
SUPPLY VOLTAGE = 350 V
DATA WAS OBTAINED WITH THE FLUX DECREASING
CURVE
PRESSURE
40 MICRONS
60 MICRONS
90 MICRONS
TUBE CURRENT, MA
200
100
0
20
40
60
80
100
120
MAGNETIC FLUX DENSITY, GAUSS

Figure 36

4. DISCUSSION AND SUMMARY

The results of these experiments may be summarized in the following manner:

The curves for ignition voltage versus flux density exhibit minimum points. Although the ignition voltage rises on either side of the minimum, it rises more slowly on the right of it. This effect occurs for all three tubes, and changes in polarity do not alter the basic shape of the curves. However, ignition voltages are reduced when the outer cylinders are the anodes.

At a constant field, the ignition voltage versus pressure curves also exhibit minimum points. This effect is more pronounced at low field strengths, as the voltage change with pressure is much greater. The effect is also more pronounced with the brass tube than it is with the other tubes.

These curves resemble the Paschen breakdown curve when either p or d is varied, but in this case the variables are p and B. The value of pd must be sufficiently high to maintain a discharge. The reason for this is that there must be a sufficient number of collisions between electrons and gas molecules to maintain the required degree of ionization in the interelectrode space. If the pressure is too low, the electrode spacing must be increased; if the electrode spacing is too small, the pressure must be increased.

When a transverse magnetic field is present, an electron leaving the cathode will have its path bent by the field, and, generally, if it does not make a collision, it will be returned to the cathode. Thus electron movement is confined to the region of the cathode, and may be expressed by the idea of an equivalent pressure which is higher than the pressure in the vessel. This pressure represents the fact that the electrons may now make more collisions with gas molecules than they did when the field was absent. A conclusion of the theory advanced by Somerville is that for any actual gas pressure, breakdown cannot be prevented by a transverse magnetic field.[10] The more complete analysis showed quantitatively how the pressure of a transverse field can increase the rate of ionization and lead to an increased effective gas pressure. The effect of this on the maintenance of a discharge depends on the actual gas pressure and the spark parameter pd. If the spark parameter is high, greater than that of the corresponding Paschen minimum, then the transverse magnetic field effectively increases the parameter and a higher potential is required to cause a discharge. If the spark parameter is smaller than the corresponding Paschen minimum, then the effect of the transverse field in increasing the magnitude of the parameter would enable lower voltages to initiate the discharge.[12]

Generally, the current reaches a greater maximum when the outer cylinder is the cathode. This occurs at a lower field strength than it does when the anode is the outer cylinder. The following characteristics are observed when tube current is plotted against flux density;

A. Brass Tube: The current reaches its maximum value at the lowest field strength of any of the tubes observed when the cathode is the outer cylinder. Cutoff, or the critical field, occurs at a substantially greater value and the current falls 8 to 20% between these points. The maximum is about 5 to 12% greater for this polarity, the higher figure being applicable at higher pressures. For the reversed polarity, the current reaches its maximum at slightly higher flux densities and falls 5 to 10% between the maximum and the cutoff point. The magnetic field is not able to extinguish the discharge when the pressure exceeds about 80 microns in either case.

B. Aluminum Tube: Due to extreme instability of the discharge, no data was obtained when the outer cylinder was the cathode. When the outer cylinder is made the positive terminal, the current reaches its maximum at a greater value than it does for the brass tube, and the critical field occurs soon afterwards. The critical fields occur at substantially lower values than those for the brass tube, and the field has less control of the current. The fall of current is not sharp as the field is increased.

C. Hybrid Tube: When the outer cylinder is positive, the maximum current occurs at the highest field strength observed for any of the tubes, and the critical field occurs at or near this point. The tube is quite unstable at 100 microns and fields in excess of 200 gauss. The current is considerably greater, and reaches its maximum at a much lower field strength, when the outer cylinder is negative.

The following characteristics are observed when tube current is plotted against terminal voltage:

A. Brass and Hybrid Tubes (outer cylinders are the anodes): These tubes have very poor voltage-regulating characteristics when the field strength is small. As the flux increases, the voltage change with current becomes smaller and the regulating characteristics become quite good with fields in excess of 200 gauss. In this region, changes in field strength have small effects on the terminal voltage. The hybrid tube exhibits a negative resistance characteristic for fields below 60 gauss and pressures of 40 microns or less.

B. Brass and Hybrid Tubes (outer cylinders are the cathodes): This polarity had poor voltage regulating characteristics for most fields and pressures. At low flux densities, the voltage change with current is smaller than it is for the other polarity, but it is still appreciable. Two distinct ranges of terminal voltage are observed for fields in excess of about 300 gauss. The tubes start in the higher one and as the current rises, a transition occurs. This occurs at lower currents as the pressure is increased.

C. Aluminum Tube (outer cylinder is the anode): At low pressures and high fields, this tube exhibits two regions of permissible terminal voltage. They occur at low pressures, and only one region is observed at pressures in excess of 60 microns. In this region, there is little voltage change with current, and the regulating characteristics are rather good at the higher fields.

The discharges were observed visually and the effects of the magnetic field were noted. The translucent ends of the aluminum tube hampered good observation, but it was possible with the brass and hybrid tubes. The hybrid tube behaved in a manner similar to the brass tube but no band structure appeared, possibly due to the short length of the tube.

A salmon pink glow appeared near the positive electrode at pressures on the order of 100 microns. The width of this glow narrows as the field is weakened, and widens for stronger fields. This salmon pink color is a characteristic of the positive column in air; the column's width is a function of the pressure and the electrode spacing. As the gas pressure is reduced, the negative glow and Faraday dark space appear to expand at the expense of the positive column, until at a sufficiently low pressure the positive column disappears completely.[11] The effect of increased field is to increase the effective pressure and allow the positive column to occupy more of the tube. For lower pressures, the salmon pink color does not appear even at high fields, as the pressure is too low to allow the positive column to exist.[13]

A soft bluish glow permeates the tube when the pressure is very low and little or no magnetic field is present. When a small field is applied, the light output of the tube is intensified and a band of brighter light appears near the cathode, extending nearly to the anode. As the field becomes stronger, this band of brighter light becomes narrower and confines itself about the cathode. For fields in excess of about 100 gauss, the glow sometimes splits into rings or bands of light situated at one or more positions along the length of the tube. They appeared to be several inches long, and to have a shuttle-shaped cross section. Their thickness, number, and stability varied with the strength of the field. For fields in excess of 360 gauss, they were very thin, confined very near the cathode, varied in number from two to four, and were quite unstable in location along the tube axis. Movement consisted of short jumps in which a band or ring of intense glow would jump to a new location, remain there a short time and then jump to another location. These jumps were accompanied by a transient current of small magnitude.

The glow did not split up into bands when the hybrid tube was used, but it did become very thin and bright with some instability. The short tube length probably prevented the band structure from occurring.

Good observation of the light structure of the aluminum tube was prevented by the translucent ends, but an intense glow appears near the cathode as the field is strengthened. This is quite unstable at fields in excess of 200 gauss.

When the outer cylinder is the anode, the ignition and sustaining voltages appear to be the same for fields of less than 120 gauss, while the curves separate above this point. For the brass tube, the curves separate at about twice the magnetic field for 20 microns as they do for 100 microns. Although the sustaining voltage is fairly constant with increased field at 100 microns, it rises slightly at 20 microns. The sustaining voltage is inconstant, increasing in the field strength at 20 microns as two permissible values exist, depending on the field strength. The sustaining voltage is much greater at 490 gauss than it is at half that value. The curves separate at nearly the same value for the hybrid tube and vary slightly with further increase in the field strength.

The sustaining voltage lies below the ignition voltage at all values of field strength when the outer cylinder is negative, except for the hybrid tube. In this case, the two voltages are the same for fields below 60 gauss. As the flux increases, the difference between these two voltages increases for all the tubes. Two values of sustaining voltage are possible for the hybrid tube, depending on the flux density. For 100 microns and 360 gauss, the ignition and sustaining voltages are the same. At lower fields they are considerably different.

As the field is varied from low to high values, the terminal voltage falls until the current reaches a maximum, after which it returns to its initial value as the current falls to zero for very high fields.

5. FUTURE WORK

Air was used in these experiments, and several interesting phenomena were observed. The more interesting of these occurred with the hybrid tube and they will be investigated further in the future, using a more refined technique. Experiments are also planned in which several of the noble gases and mixtures thereof will be used in a coaxial electrode geometry. The construction of these tubes will be different, allowing a higher vacuum to be attained with less possibility of contamination of the electrode surfaces. The electrodes will be either copper or aluminum, or one of each material.

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