RADC-TR-66-656
Final Report

INVESTIGATION OF VARIOUS ACTIVATOR REFRACTORY SUBSTRATE COMBINATIONS

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TECHNICAL REPORT NO. RADC-TR-66-656
January 1967

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Air Force Systems Command
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FOREWORD

This final report was prepared by J. H. Affleck and W. T. Boyd of General Electric Company, Schnectady, New York, under Contract AF30(602)-3395. project number 5573, task number 557303. RADC project engineer is Anthony S. Cardello (EMATP).

This report has been reviewed and is approved.

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ABSTRACT

An investigation was conducted under Air Force Contract No. AF 30-(602)-3395, Supplemental Agreement No. 3, to continue the study of various thin-film refractory substrate combinations capable of producing high current density in dispenser cathodes. In comparing these cathodes, emphasis was placed on techniques for measuring fundamental properties of the systems -- in particular, the Richardson work function and temperature coefficient of the work function. Oscilloscope and computer techniques were utilized in determining the work function of several commercial and experimental dispenser cathodes.

Dispenser cathodes were evaluated in beam testers, with current densities in excess of 30 amperes/cm^2 demonstrated.

A simple emission microscope provided a means of comparing the emitting surfaces of various cathodes.

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EVALUATION

The purpose of this program was to study and evaluate the thermionic properties of various activator-substrate combinations on cathode systems to determine the current density capability of each system.

In the course of the study techniques of cathode fabrication, combinations of various materials, emission measurements, work function measurements, poisoning causes and effects, evaporation, sublimation, life tests and comparisons with off-the-shelf cathodes were performed. The work has significantly contributed to providing a broader understanding of the emission mechanism of high current cathodes, the problem associated with emitter evaluation and testing, the effects of environment and operational conditions on the cathode in practice.

During the investigation dispenser type cathodes were developed which have a work function characteristic which approach that of an oxide coated cathode and it was also shown that the work function is effected by reacting barium oxide with refractory oxides.

It is generally conceded that the dispenser cathode will not replace an oxide cathode in short duty cycle, pulsed conditions, however in D-C conditions or long duty cycle operation, where high current densities are important, it is considered that these cathodes will find increased utility. In a barium-strontium-tungstate cathode test, 30 amperes per cm^2 D-C was achieved at saturated emission levels.

This work has contributed to the state-of-the-art in cathode research. The various techniques for fabrication and measurement of emission have resulted in the award of four patents, and three others are awaiting issue as of this date. The information derived from this effort has lead to other investigations into the tungstate cathode and justifies the expenditure of Air Force funds in this area.

Anthony S. Cardello

ANTHONY S. CARDELLO
Project Engineer

Section I
INTRODUCTION

For purposes of perspective, the information presented in this document constitutes a logical extension of previous work conducted under Air Force Contracts No. AF 19(604)-4093, AF 19(628)-279, AF 30(602)-2947, and AF 30(602)-3395. As a result of the entire investigation seven patents have been filed and allowed, four of which have been issued under the following U.S. patent numbers: U.S. 3,176,180; U.S. 3,229,147; U.S. 3,243,637; U.S. 3,243,638. The remaining three, although allowed, have not been issued to date.

The work described herein is a continuation of Air Force Contract No. AF 30(602)-3395, under Supplemental Agreement No. 3, and supplements Technical Report No. RADC-TR-65-100 which covered an investigation by the Microwave Tube Business Section of the General Electric Tube Department for the Rome Air Development Center.

The primary purpose of this investigation has been to study the thermionic properties of various activator-substrate combinations (cathodes) that might be capable of producing high current densities. To this end, various aspects of the problem have been examined during the course of the program, including the techniques of cathode fabrication, materials combinations, emission measurements, poisoning tests, evaporation rates, life tests, and practical demonstration of cathodes in tubes.

This work has contributed to an understanding of the emission mechanism of high current density cathodes, the problems associated with emitter evaluation and testing, and the general effects of environment. Such factors are of particular interest in the practical application of high current density emitters.

Section 2
SUMMARY

The results obtained during this program can be summarized as follows:

1. Oscilloscope techniques demonstrated that the space-charge break-away point in a 2/3 power plot of an I-V characteristic does not correspond to zero field emission. Therefore, work functions cannot be determined from these curves.

2. A computer technique was developed to provide a rapid analysis of emission data.

3. Work functions were determined and compared for four commercial and three developmental dispenser cathodes. These results were described in relation to the structure of the cathodes.

4. Cathodes were evaluated in various beam testers, using both pulsed and d-c operation. A barium-strontium-tungstate cathode produced nine hours of d-c emission in excess of 30 amperes/cm^2.

5. A simple emission microscope demonstrated the patchy nature of the surfaces of several dispenser cathodes.

Section 3
GENERAL DISCUSSION

For approximately the past fifty years, there have been many new advances in the development of electron tubes. These advances have resulted from a combination of theoretical considerations, inventions, innovations, and the ability of the tube designer to fabricate a device that was operable. Obviously, this would not have been possible had there not been new advances and developments in that area of science commonly known as "tube techniques"; principally, this field covers materials and processes, the joining of materials, chemical cleaning, vacuum techniques, and thermionic emitters.

As tube designs have improved in frequency, power output, and life, there has been an increasing demand for continued improvement in the tube techniques field. For example, in the area of thermionic emitters, as the frequency of operation of a tube doubles, the cathode current must be quadrupled.[1] As a consequence, current density requirements for thermionic emitters in microwave devices are much higher than those normally associated with receiving or cathode-ray tubes. At this point in time, there is a need for emitters capable of delivering well in excess of 10 amperes/cm^2 continuously.

The widely used oxide-coated cathode cannot supply current densities continuously in excess of 1 to 2 amperes/cm^2.[2,3] It was for this fact alone that the dispenser-type cathode was developed and received so much attention.

The dispenser cathode has been described[4] as a system that gains its electron emission by virtue of material dispensed to its surface. The dispensed material, usually an electropositive element, is presumed to form a thin film or monolayer over the cathode surface, thereby producing a dipole layer and lowering the potential barrier by an amount $\Delta\phi$. There is evidence, however, to indicate that this is a highly idealized description.[5,6,7] Although there are emitting areas covered only by a monolayer, it is also probable that there are areas covered with many monolayers or not covered at all. Moreover, it is possible that the principal source of emission may be from the barium material in the matrix pores, which may vary in thermionic activity. Recent published data[6] suggests that only 18 percent of the surface area of a dispenser-type cathode determines the saturated emission. The remainder either is not emitting, or it is contributing only in a very small way to saturated emission. The complexity of such a surface makes it difficult to characterize an emitter precisely.

A major objective of this program has been to measure the properties of systems potentially capable of producing high current densities. In order to make a meaningful evaluation of the emission properties of various dispenser cathode systems, it was necessary to compare them on the basis of some fundamental property common to all systems and independent of geometry, field, anode, and environmental effects. This property is the work function characteristic.

Section 4
EMISSION MEASUREMENT TECHNIQUES

In considering the evaluation of a cathode in terms of emission, one must recognize the diversity of opinions and practices in existence. There is a general laxity in applying theory to practical measurements, often leading to discrepancies in data taken on the same system. Performance data is also frequently reported without sufficient clarification as to how it was obtained or how it compares with other data obtained in a completely different manner. This matter has been brought before the American Society for Testing and Materials, Committee F-1, Subcommittee I on Cathode Materials, where consideration is being given to a recommended practice to be followed in the evaluation of a thermionic emitter.

The problem is not simple, especially where high current density cathodes are concerned. To make effective a measurement of work function, it is necessary to know the zero field emission density (I_o) and the cathode temperature (T). The determination of I_o is somewhat dependent upon the ability of the anode to dissipate power without affecting the cathode.

The Schottky method[8] usually requires a rather high anode potential in order to establish saturated emission and zero field emission. The product of high potential and high current densities leads to power levels that are difficult to handle and can result in a number of phenomena that may influence emission measurement.

The retarding potential method[9] similarly requires a high potential to establish the saturated emission level at high current densities. By lowering cathode temperature and emission to the proper level, zero field measurements may be made by either the Schottky or retarding potential method, and the effective work function can then be readily determined. However, the effective work function is measured only in a certain temperature range and its actual value under high current density operation is determined by an extrapolation of the effective work function to the higher temperatures and higher current densities. Some objections may be raised in determining the effective work function in this manner since measurements were not made at the temperature of operation or at a current density in excess of 1 amperes/cm^2.

One approach, frequently used as an alternate method, is to measure the I-V characteristic, make a 2/3 power plot of the data, and look for the point where the data departs from the Child-Langmuir law, which is:

$$I_s = 2.33 \times 10^{-6} \frac{V^{3/2}}{d^2} \text{ amp/cm}^2$$

where:
I_s = the space charge current density (amp/cm^2)
V = anode voltage (volts)
d = anode-cathode spacing (cm)

This method contains a number of problems that could result in misleading information. First, it is difficult from an ordinary plot of data to determine the point of departure from the space-charge line. To illustrate this point, Figure 1 includes three curves: Curve III represents the space-charge emission line, and Curves I and II represent the I-V characteristics of two diodes with different geometries, cathodes, and thermionic emission.

From Curve I, the saturated emission line is often extrapolated back to the point A where a value for the saturated emission is obtained. This value is frequently used in the Richardson equation to determine the work function. However, point A is not the point where Curve I departs from

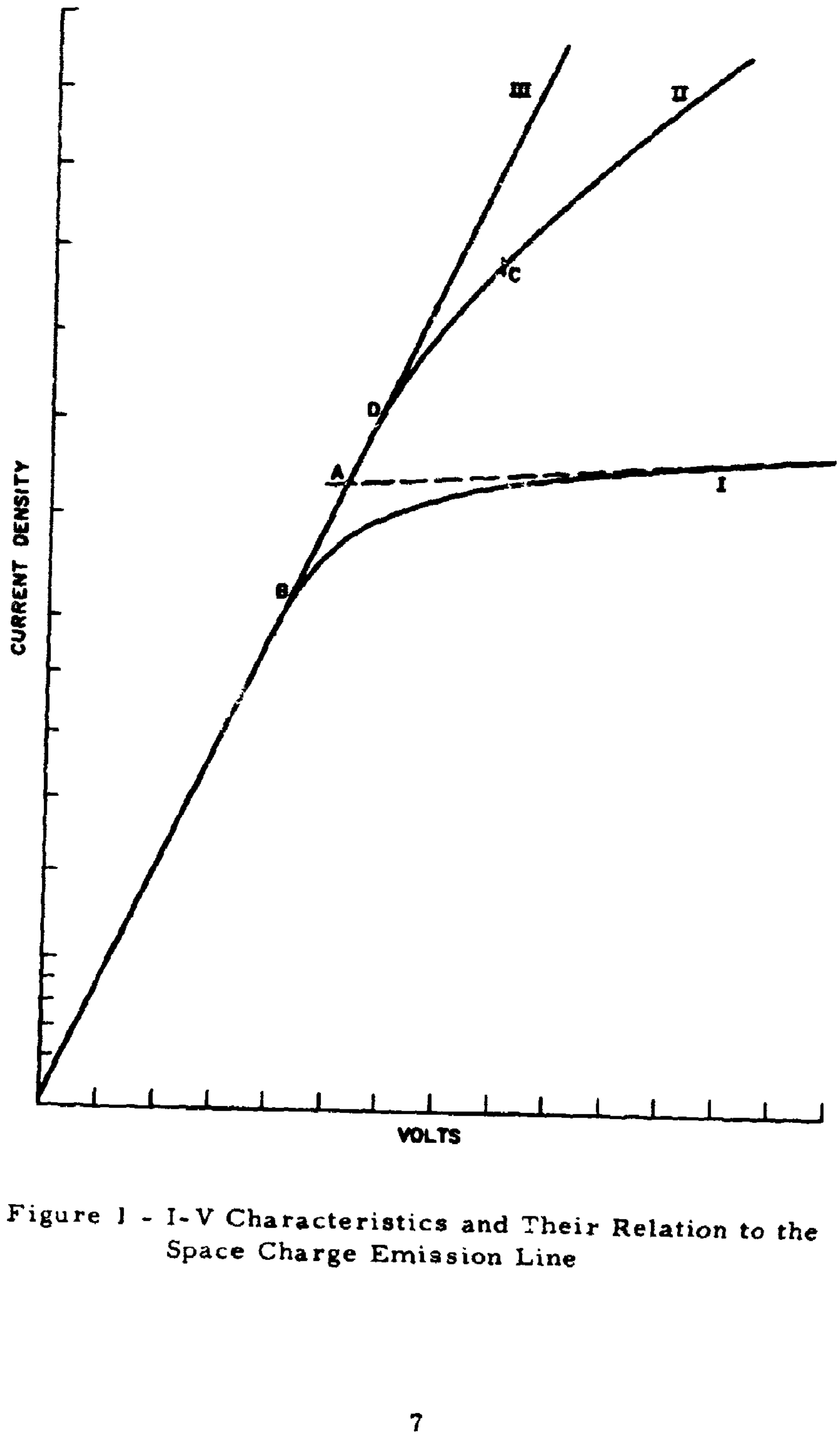

Figure 1 - I-V Characteristics and Their Relation to the Space Charge Emission Line

Curve III; it is more probable that it lies in the region of point B -- at least to the extent that it can be ascertained by visual inspection.

In Curve II, the saturated emission is less well defined. Again, it has been the practice of some investigators[10] to choose a point, such as C, where the curve has departed from the space charge line by 10 percent. Visual inspection of the data makes the determination of the actual breakaway point more difficult in this case.

A more sensitive and accurate method of detecting the point of departure would be to take the derivative of the curve and note where $\frac{dI}{dV}$ reaches a maximum, or where $\frac{d^2I}{dV^2}$ equals zero (see Figure 2). This provides a better and more meaningful way to compare cathodes in identical tube structures. Such data, however, should not be used to determine the work function or be compared with zero field emission data.

In an effort to prove this point, several refinements have been made in the analysis of the I-V characteristic, using the circuit shown in Figure 3. A 300-volt ramp is applied to the tube under test. Since the voltage ramp increases linearly with time, the scope sweep is calibrated against the ramp so that the X-axis of the scope trace is proportional to the voltage applied to the tube. The Y-axis is obtained from the voltage drop across the viewing resistor and is proportional to the current flowing in the tube. A Tektronix 536 X-Y oscilloscope was used with Type "T" plug-in unit to generate the X-axis sweep and the sawtooth signal to drive the voltage-ramp generating circuit shown in Figure 4. A Type "O" plug-in unit was used to perform the necessary operations on the signal to the Y-axis. The Type "O" unit is basically a pre-amplifier with two operational amplifiers. The versatility of this unit permits the scope to display three important curves. First, the I-V characteristic is displayed. Secondly, by adjusting the first operational amplifier to differentiate, a curve is obtained showing $\frac{dI}{dV}$

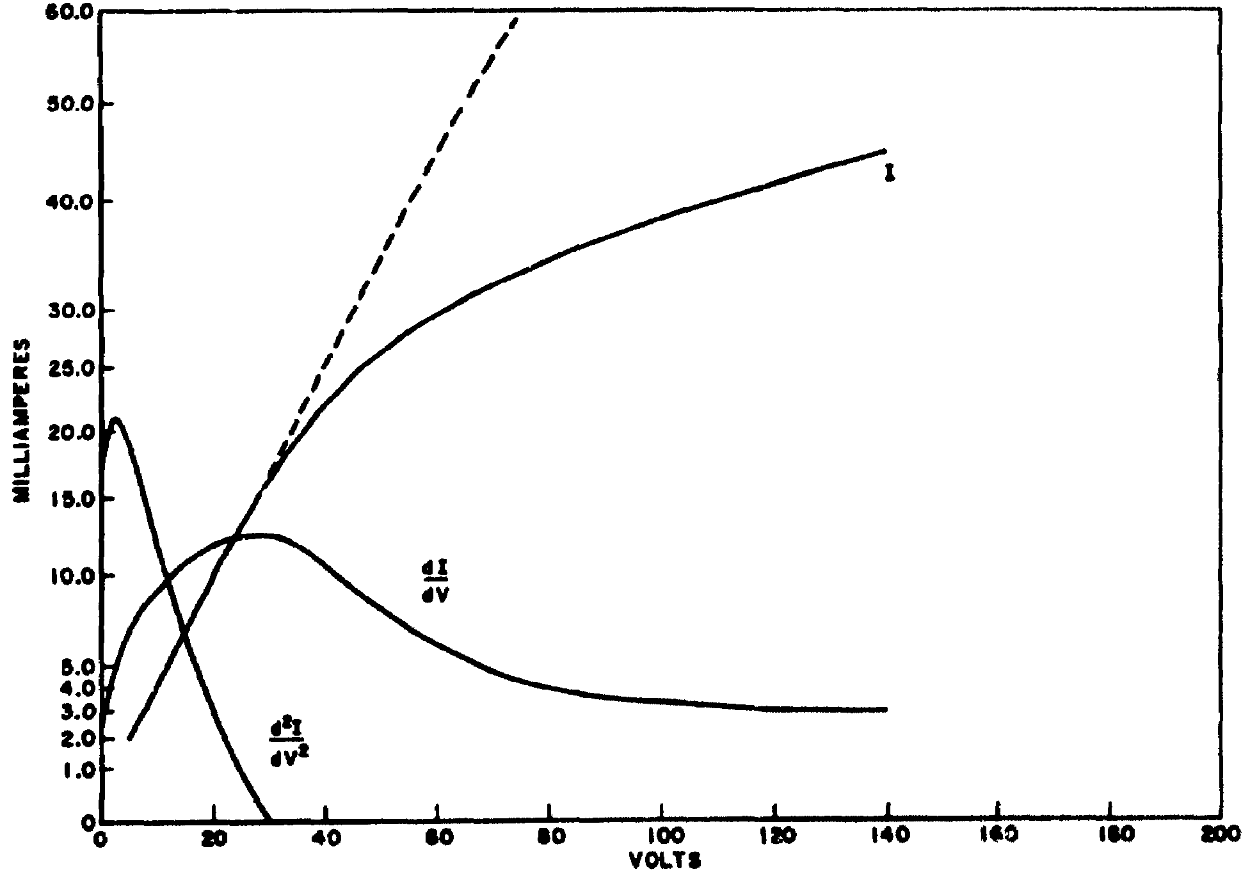

Figure 2 - Typical I-V Characteristic With First and Second Derivative Curves

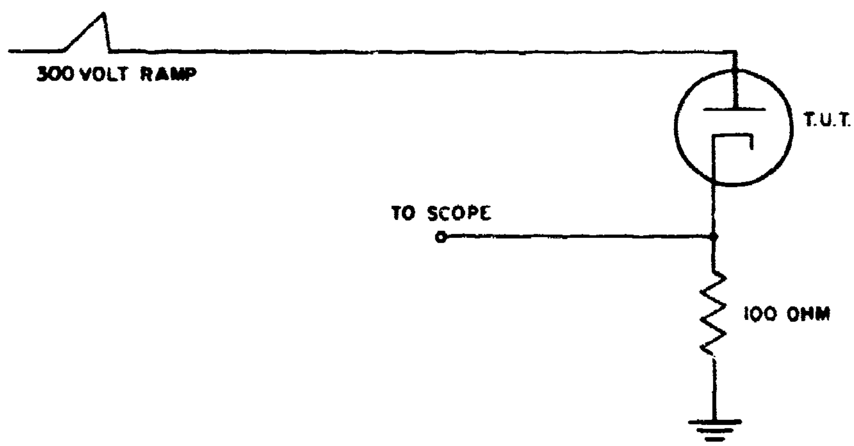

Figure 3 - Circuit Used in Analyzing I-V Characteristics

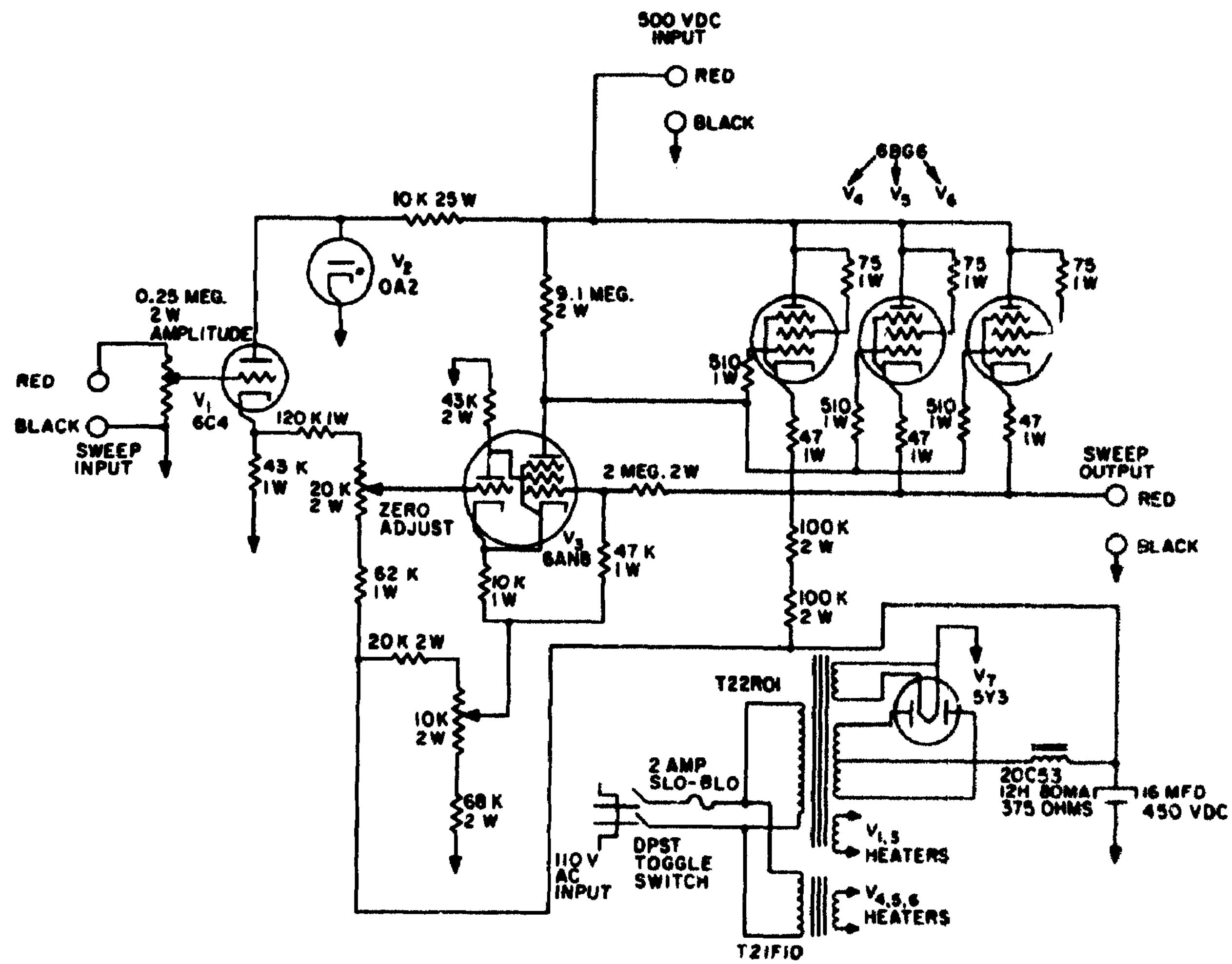

Figure 4 - Ramp Generator Circuit

versus V; the maximum of this curve gives the point of inflection on the I-V characteristic, or the point at which the curve departs from the space-charge characteristic. And last, the second operational amplifier is modified so as to display log I versus V; this may be used as a retarding potential curve, although somewhat limited in the retarding region. An extrapolation of the saturated and retarding portions of the curve serves as a good measure of zero field emission.

These three curves are usually recorded on film by making a multiple exposure, thus recording all the data necessary for analysis, as shown in Figure 5. Taking data at several temperatures for various cathode systems, it has been found that the breakaway point from the space-charge curve does not coincide with the zero field measurements. Depending upon the uniformity of the emitting surface and the geometry of the diode, this point may be higher or lower than the zero field emission -- and only a fortuitous circumstance if they happen to be equal.

Typical data is presented in Table I for two systems, where I_o = zero field emission and I_{sp} = breakaway point from the space-charge line.

In the case of the dispenser system, I_{sp} is about a factor of 2 lower than I_o, while in the oxide-cathode system, the I_o value is slightly higher.

Obviously, where discrepancies of this kind exist, there is little basis for comparing the two systems in terms of the "space-charge breakaway" point. Since the breakaway point is extremely dependent upon geometry -- i.e., spacing and parallelism -- it should be recognized that the data is pertinent only to a given system.

The effect of electrode spacing on the breakaway point is clearly demonstrated in Figures 6, 7, and 8, which show diode test results from an independent study. The figures show I-V characteristics of a tungstate

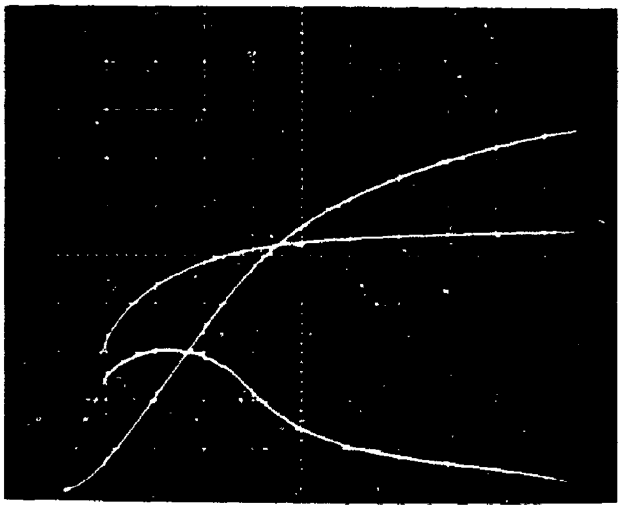

Figure 5 - Multiple Exposure Showing I, dI/dV, and Log I vs. V

Table I - Comparison of Zero Field Emission and Space Charge Departure Point

Barium-Strontium-Tungstate Cathode System

T (^{o}K)	I_o (Amps)	I_{sp} (Amps)
985	0.70×10^{-2}	0.36×10^{-2}
1031	2×10^{-2}	0.95×10^{-2}
1106	5×10^{-2}	2.3×10^{-2}
1125	7.5×10^{-2}	5×10^{-2}
1181	7.8×10^{-2}	1.8

Oxide-Coated Cathode System

T (^{o}K)	I_o (Amps)	I_{sp} (Amps)
624	3×10^{-4}	1×10^{-3}
748	2×10^{-3}	2.8×10^{-3}
666	0.38×10^{-3}	0.28×10^{-3}

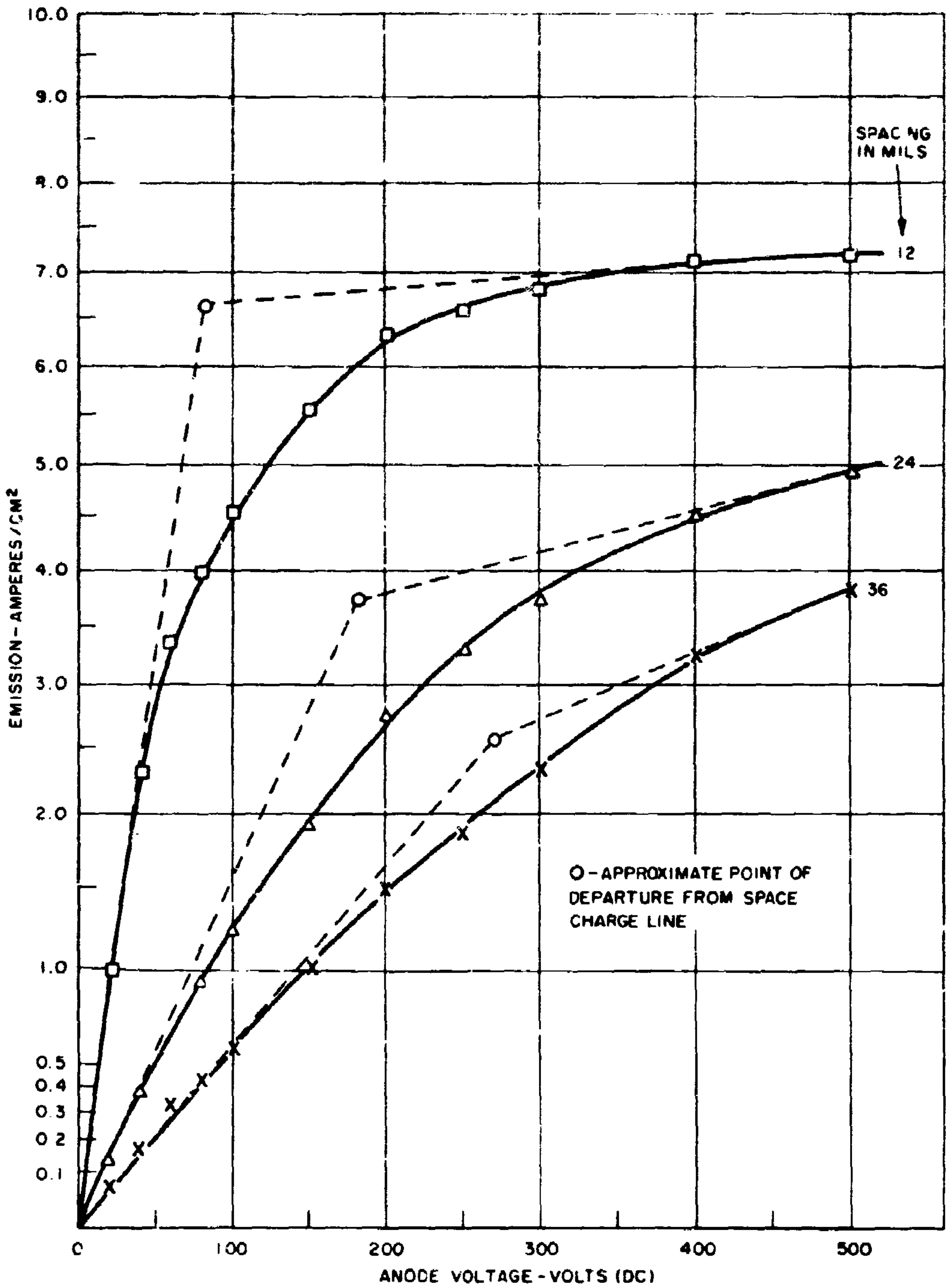

Figure 6 - Electrode Spacing Effect on Tungstate Cathode Emission at 951°C

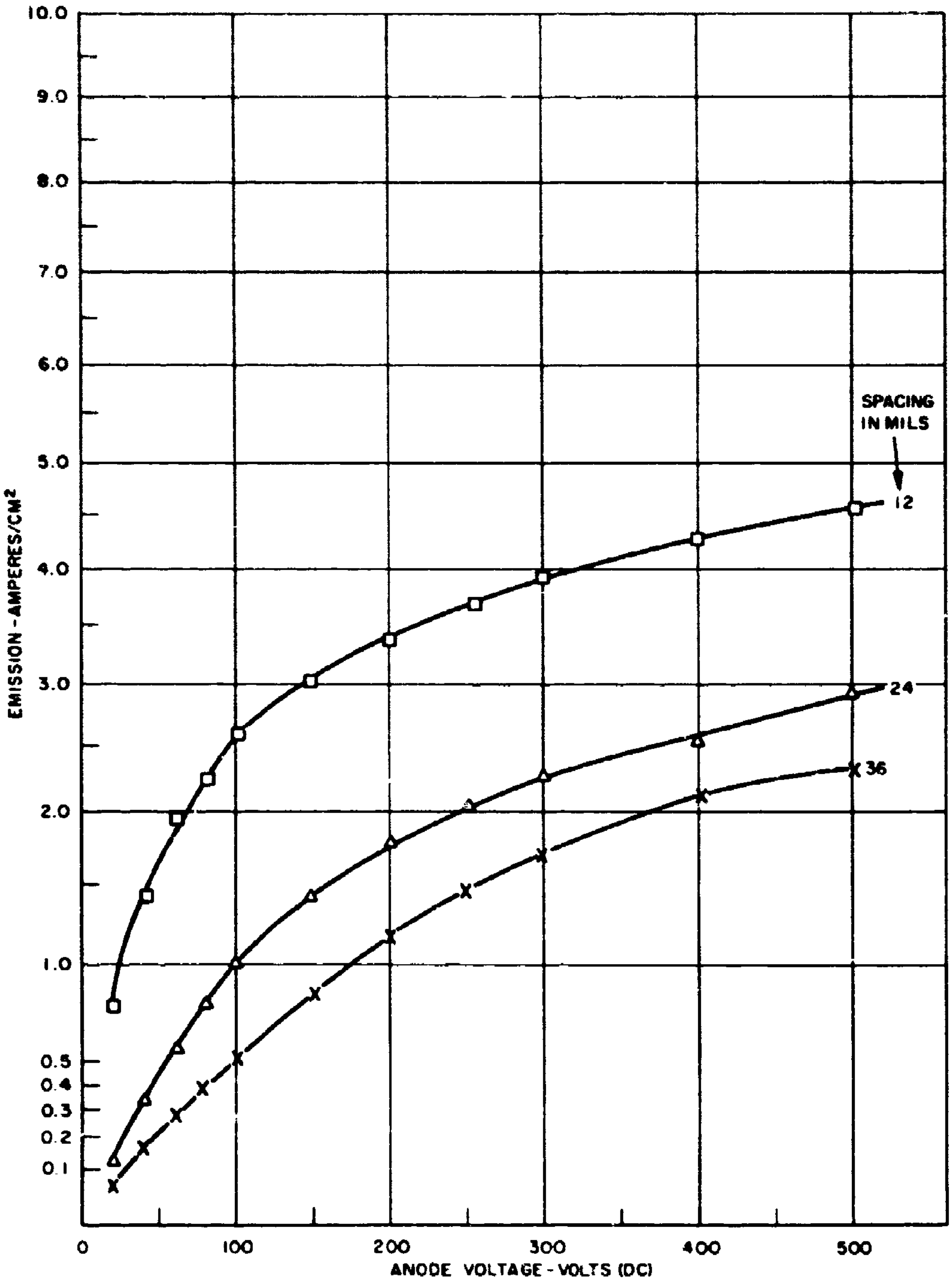

Figure 7 - Electrode Spacing Effect on Tungstate Cathode Emission at 902°C

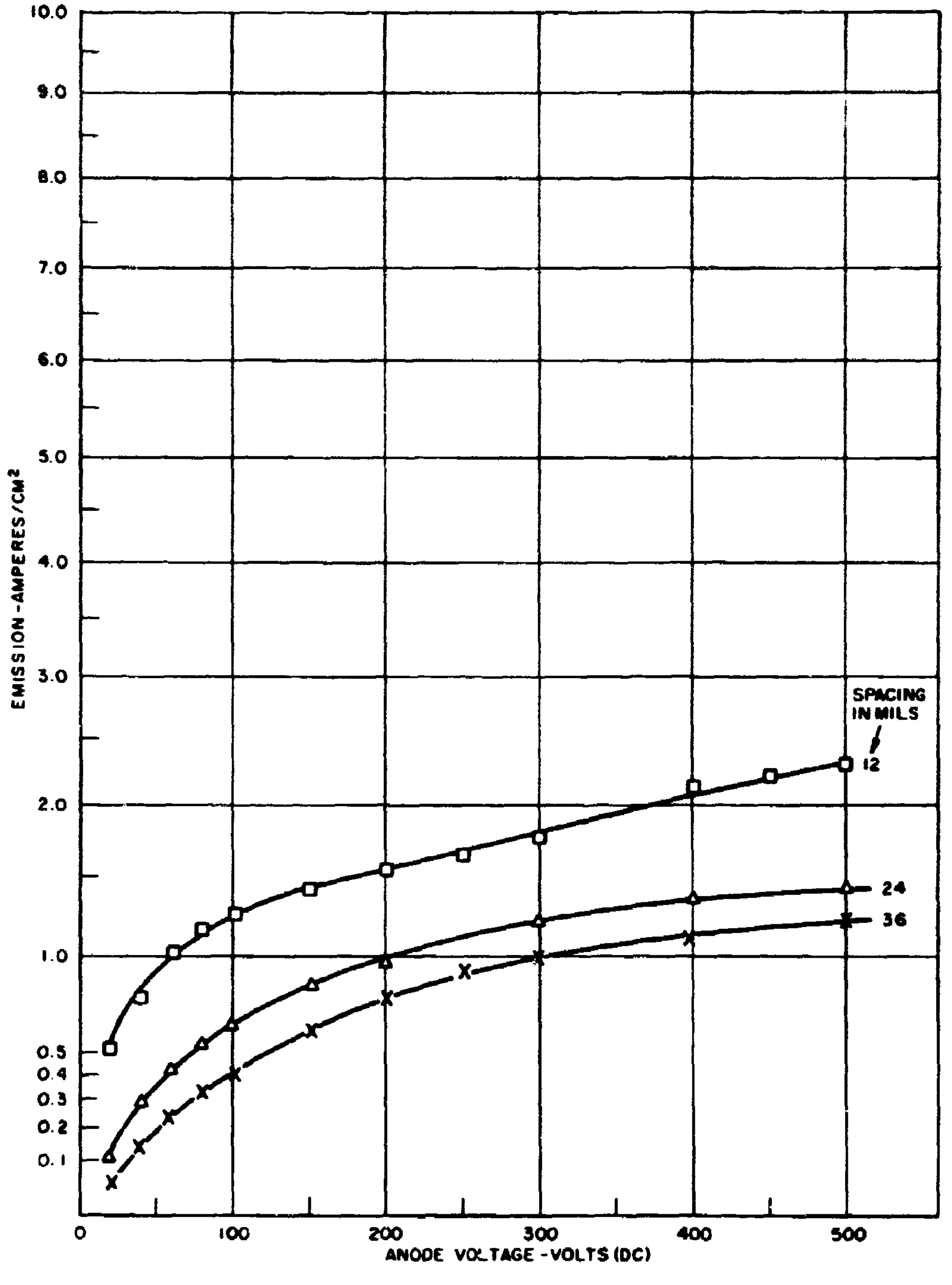

Figure 8 - Electrode Spacing Effect on Tungstate Cathode Emission at 852°C

cathode, measured in a diode structure containing a movable water-cooled anode. For each of the three figures, the I-V plots were obtained under identical conditions, except for a variation in electrode spacing. The temperatures were determined by means of a thermocouple and adjusted for electron cooling at each point. In Figure 6, an approximate point-of-departure from the space charge line is indicated for each curve. If one did not know that all of the curves in Figure 6 were obtained from the same cathode, he would erroneously conclude that the close-spaced cathode was a much better emitter than those with wider spacings: Obviously, this was not so.

Similar objections to the interpretation of I-V data have been raised by W. B. Nottingham[11] in the Handbuck der Physik. An alternate recommendation suggested by Nottingham requires the use of a universal limiting curve. This method permits the determination of zero field emission, but again, as with other methods, is only applicable at low current densities.

To evaluate different thermionic emitters and to make comparisons between data obtained from different laboratories and systems, it is necessary that a basic property be measured. For this reason, throughout this work the policy has been to measure the effective work function at various temperatures, and determine the temperature coefficient of the work function (α) and the Richardson work function (ϕ_o) so that the work-function characteristic could be presented in the following form:

$$\phi = \phi_o + \alpha T$$

Knowing ϕ_o and α, then for a given temperature (T), the effective work function may be determined. Effective work function is the important parameter, for it enables the tube designer to assess the maximum emission from a cathode and the temperature necessary to achieve the emission required.

Similar information may be obtained if the Richardson work function (ϕ_o) and the emission constant (A) are known, but it is not nearly as convenient to use.

Another technique that has been found convenient, rapid, and extremely useful involves a computer analysis of the data obtained from emission tests. Standard programs are available for performing a regression analysis and are accessible through the General Electric Time Sharing Computer Program and a General Electric 235 computer.

For example, zero field emission (I_o) values were obtained for cathodes at different temperatures (T). Knowing I_o and T, the effective work function was determined with the aid of the Tables of Effective Work Function.[12] The effective work function and temperature data are then fed into the computer on punched tape, and a linear regression analysis is made, resulting in the following data.

Table II - Computer Analysis of Work Function Data

0 Data 1
1 Data 985, 1.75, 1031, 1.755, 1106, 1.80, 1125, 1.81, 1181, 1.815

RUN

LINREG 11:30 SCH MON 6/06/66

LINEAR: Y=A+B*X WITH A = 1.36777 and B = 3.85252 E-4

COEFFICIENTS: CORREL = .962798 DETERM = .92698

COMPARISON OF ACTUAL Y'S WITH Y'S ESTIMATED FROM EQUATION:

X-ACTUAL	Y-ACTUAL	Y-ESTIM	DIFFER	PCT-DIFF
985	1.75	1.74724	-2.75634 E-3	-.157505
1031	1.755	1.76497	9.96524 E-3	.56782
1106	1.8	1.79386	-6.14087 E-3	-.341159
1125	1.81	1.80118	-8.82108 E-3	-.487353
1181	1.815	1.82275	7.75302 E-3	.427164

TIME: 2 SECS.

The result is essentially the equation for the best line to fit the data. The Constants (A) and (B) are the values for the Richardson work function (ϕ_o) and the temperature coefficient of the work function (α), respectively. The percent difference between the actual ϕ and the estimated ϕ is less than ± 0.6 percent.

This analysis can be made in less time than it takes to make a plot of the data and provides considerably more accuracy in fitting the curve to the data. Similar analyses have been worked out in determining I_o from a Schottky plot and fitting a curve to the logrithmic function, such as the evaporation rate.

These techniques of measurement and analysis permit the attainment of a more objective result than has been possible in previous work.

Section 5
EXPERIMENTAL RESULTS

WORK FUNCTION DETERMINATION

To form a basis for comparing the properties of dispenser cathodes developed on this program with other systems, the work-function characteristic was measured as previously described and expressed in the following form:

$$\phi = \phi_o + \alpha T \text{ volts}$$

The data for a number of systems is given in Table III.

Table III - Comparison of Work-Function Characteristics

System	$\phi = \phi_o + \alpha T$	ϕ at 1250°K
Philips "B"	$1.53 + 5.7 \times 10^{-4}$ T	2.24
Spectra Mat LS-311	$1.47 + 5.8 \times 10^{-4}$ T	2.10
Semicon S-80	$1.55 + 4.3 \times 10^{-4}$ T	2.09
Semicon Sembo	$1.66 + 3 \times 10^{-4}$ T	2.03
Barium Orthosilicate	$1.60 + 2.9 \times 10^{-4}$ T	2.07
Barium Yttriate	$1.47 + 4.7 \times 10^{-4}$ T	2.06
Barium Strontium Tungstate	$1.36 + 3.8 \times 10^{-4}$ T	1.84

The Philips "B" cathode consists of a 17 percent porous tungsten matrix impregnated with barium calcium aluminate in the form of $5\,BaO \cdot 3\,CaO \cdot 2\,Al_2O_3$. This system is reported[13] to consist of a monolayer of Ba/BaO on tungsten that is continually replenished by the dispensing action of the matrix. It is further claimed that the $5BaO \cdot 3CaO \cdot 2Al_2O_3$ composition forms a eutectic so that there is no excess BaO.

This is not the case in other barium-aluminate cathodes. For example, the Semicon S-80 cathode uses an impregnate of $4BaO \cdot CaO \cdot Al_2O_3$ which results in an excess of BaO.[14] It is, perhaps, because there is excess barium oxide in the matrix, either deliberately or accidently, that the effective work-function values are lowered.

The Spectra Mat LS-311 cathode consists of a 90-percent dense tungsten body impregnated with barium calcium aluminate.[15] The work function characteristic agrees well with other barium-calcium-aluminate systems. It was observed, however, that below 1250°K the work function increased, which suggests that, as a result of the density of the matrix at lower temperatures, it is more difficult to maintain a uniformly covered surface.

After the cathode was activated, it was turned off for 72 hours. When the cathode was operated after this quiescent period, the emission was very low and several hours of normal operation were required before it recovered completely. The pressure in the system during these tests was always less than 5×10^{-9} torr, and a water-cooled anode was used to minimize anode effects.

The Semicon S-80 cathode previously mentioned -- which is an 80-percent dense tungsten matrix impregnated with barium calcium aluminate in the molar ratio of 4:1:1 -- was subjected to similar tests to determine whether the cathode degraded during an off or quiescent period. No detectable degradation was observed.

The only other commercial cathode tested was the Semicon "Sembo" cathode. This system has a 60-percent dense tungsten matrix, and the emissive material is "similar" to the "S" type cathode.[16] The measured current densities were slightly lower than expected. The emission level of this system occurred only at a temperature 40°C lower than a "standard" dispenser cathode -- not at 100-200°C as anticipated.

Cathodes developed on this program such as the barium-orthosilicate and barium-yttriate systems have work-function characteristics similar to the aluminate systems. Some improvement may be made by simply increasing the ratio of barium oxide in the impregnant. This apparently adds emission sites to the pores of the cathode, presumably to the pore ends which contribute more to the total emission than do monolayer regions. The recent work of Jansen, Venema and Weekers[6] demonstrates in a quantitative way that only a fraction of the surface area of a cathode determines the saturated emission; they contend that the centers of emission are probably caused by small protruding low-work-function areas.

It is certainly clear that, for whatever the reason, the surface of a dispenser cathode is a non-uniform emitting surface; hence, the emission density of a dispenser cathode could be improved by increasing the fractional area of low-work-function patches.

A number of recent reports,[17, 18] as well as observations in this program, indicate that work-function values of 1.65 to 1.85 ev may be obtained from "dispenser" systems impregnated with various proportions of the alkaline-earth tungstates.

A cathode composed of barium strontium tungstate ($5\,BaO \cdot SrO \cdot 2\,WO_3$) was prepared and tested. It should be noted that the work-function characteristic given in Table III is considerably lower than that of the other systems.

The emission mechanism of this system is not completely understood, but the effective work function is in the range of that associated with an oxide-coated cathode. This system is sensitive to handling, processing, environment, and cannot be exposed to the atmosphere for extended periods of time. Since this cathode was operable at high current densities, a number of unusual phenomena were observed, though probably no more unusual than would occur with any high current density cathode. If the anode is not water cooled, anode dissipation can be sufficient to cause barium to be recirculated to the cathode. This may enhance the surface coverage and the apparent emission. Frequently, the barium in the anode-cathode gap becomes ionized and, thus, can cause an increase in emission. Although the use of a water-cooled anode eliminates some of the trouble, other effects become evident. The area opposite the cathode on the anode frequently will luminesce, which is attributed to electron bombardment of the barium oxide that has been evaporated to the anode. What effect this has on emission measurements is not known.

Frequently observed, also, are small spots on the anode that glow rather brightly, similar to those reported by Worrell and Pike,[19] and can affect thermionic emission. Apparently, these spots are caused by a buildup of evaporated material, which is then subjected to joule heating due to the passage of current through these areas. They have been observed to change the perveance of a diode by growing and, thus, changing the anode-to-cathode spacing. After sufficient time, a given point will disappear as a result of evaporation; however, since new ones are continually appearing, the anode is never entirely free of these deposits.

BEAM TESTS

Ultimately, any cathode development program is faced with a demonstration of the cathode and its properties in a test vehicle that either duplicates or simulates actual operating conditions in a device. Tests at low current densities are performed routinely. Frequently, tests are conducted directly in the device under operating conditions. High current density tests, however, present many more problems.

To determine the capability of a dispenser-cathode system, and its high current density characteristics, a more complex vehicle is required -- in particular, one that can adequately dissipate the power encountered. To meet this requirement, a beam tester, which had previously been developed as part of a 40-kilowatt multiple-beam klystron program, was selected.

Initial tests were conducted using a Semicon S-80 cathode operating under pulsed conditions. Using 3.2-microsecond pulses, at 1000 pulses per second, the current-voltage characteristics obtained indicated 8.5 amperes/cm^2 at 1010° C_B. This data agrees with accepted values for this type of cathode. Under d-c operation, the I-V characteristic was measured as a function of cathode temperature. The perveance was calculated for each data point and compared to the design value of 0.8×10^{-6}. At 1060° C_B, a current density of 2.25 amperes/cm^2 was obtained at 16 kilovolts with less than a 10-percent change in the perveance. At 1015° C_B, there was an obvious departure from the space-charge curve corresponding to a current density of 1.1 amperes/cm^2. This corresponds well to the emission capability cited by the manufacturer.[20]

Attempts to test the barium-strontium-tungstate cathode in this particular design have been abortive as the result of punctures in the tube envelope.

Figures 9 and 10 depict the beam tester in the socket with the field coil in place and the associated equipment.

During these tests, the I-V characteristic was measured by both d-c and pulsed techniques. Also, a Schottky-type plot was made using the pulsed emission data, and an attempt was made to produce a retarding field plot.

The results of these tests served to point out several difficulties in evaluating cathodes in this particular structure. The beam-tester incorporates a convergent electron gun and is designed such that it must be operated with space-charge conditions existing in front of the cathode. When the accelerating field becomes too large, or the cathode is limited in emission, the beam begins to "blow up". As a result, beam interception becomes high, especially at the anode, liberating gas which usually results in arcing and temporary poisoning of the cathode. Therefore, it is necessary to operate the beam tester under d-c conditions along the space-charge line.

This severly limits the use of such a device for evaluating cathodes. Under d-c operation, it is not possible to determine the level at which the cathode becomes emission-limited or the emission for zero field conditions. Its one virtue is that it can be used to compare the emission capabilities of different cathodes under the same operating conditions. While such comparison is advantageous, it still does not contribute to the determination of a fundamental property such as the effective work function.

Originally, it was thought that the retarding-potential method could be used to evaluate the cathode. However, using the anode as the collector results in the production of gas which poisons the cathode, and requires the use of high voltages in drawing saturated emission. Several attempts to use this method were unsuccessful.

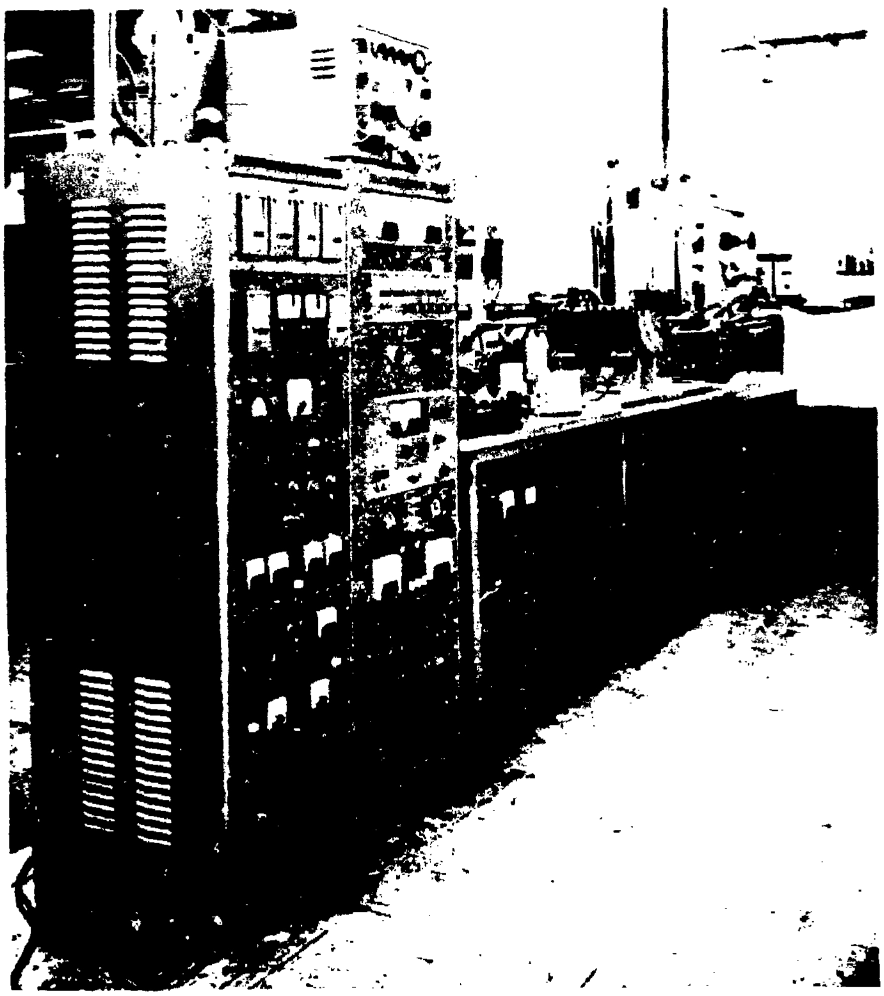

Figure 9 - Beam Tester and Associated Equipment

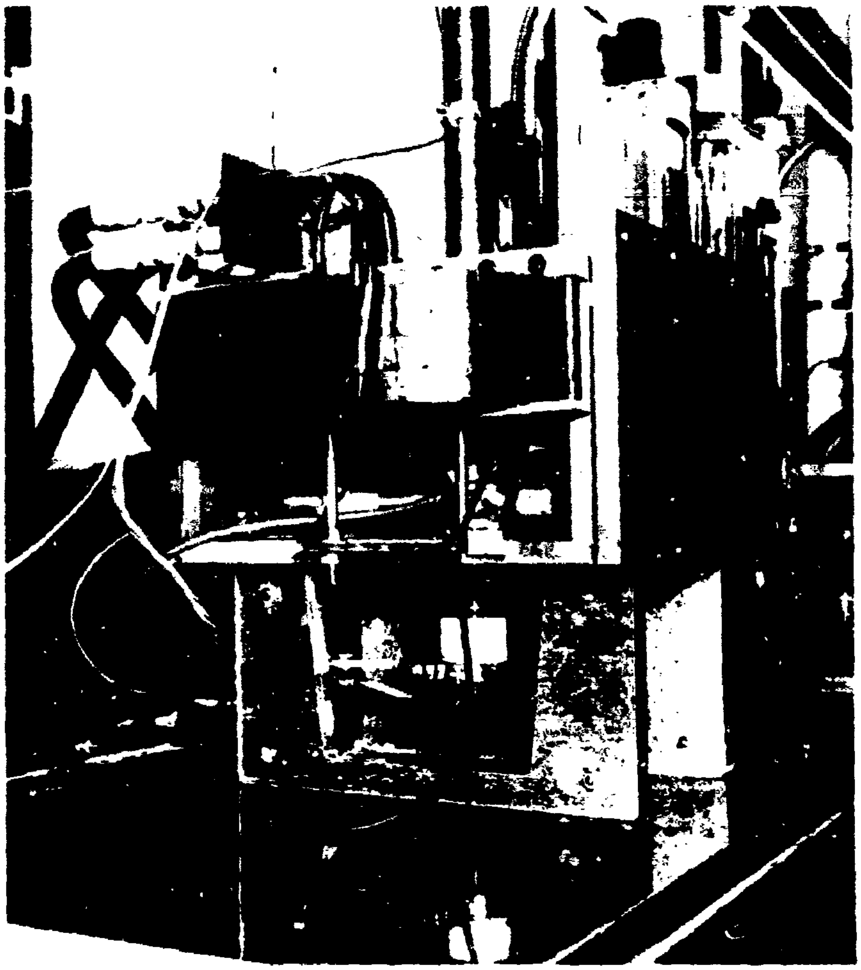

Figure 10 - Beam Tester in Magnetic Field

After exhausting the d-c methods, the only alternative was to proceed with pulsed techniques. The beam tester was set up for pulsed measurements using a 4.0-microsecond pulse and a pulse-repetition rate of 400 pps, and I-V characteristics were obtained. In the temperature range of 1050 to 1200°C, the characteristic followed the space-charge line. The cathode temperature was lowered below 1050°C, and a departure from the space-charge line was observed. The saturated-emission data was replotted in the form of a Schottky plot and the zero field emission determined. With this data, and the cathode temperature, the effective work function was found to be:

$$\phi = 1.46 + 5.4 \times 10^{-4} \text{ T ev}$$

or at 1250°K, ϕ = 2.14 ev.

This agrees rather well with data obtained in a diode test, which resulted in an effective work function of:

$$\phi = 1.55 + 4.3 \times 10^{-4} \text{ T ev}$$

or at 1250°K, ϕ = 2.08 ev. This was the only way in which any information regarding the cathode "per se" could be obtained with this type of beam tester.

Another type of beam tester was constructed, with the electron gun immersed in a magnetic field with an essentially laminar electron flow in the beam. This device, which utilizes a collector capable of dissipating 75 kilowatts, was constructed for a previous study and was designed with the aid of analog computer techniques, employing a Poisson cell field simulator. With this equipment, beam trajectories or equipotentials in a given gun design can be plotted under various magnetic-field and space-charge conditions. An example of the computed electron trajectories existing in this beam tester is given in Figure 11. The gun structure is shown

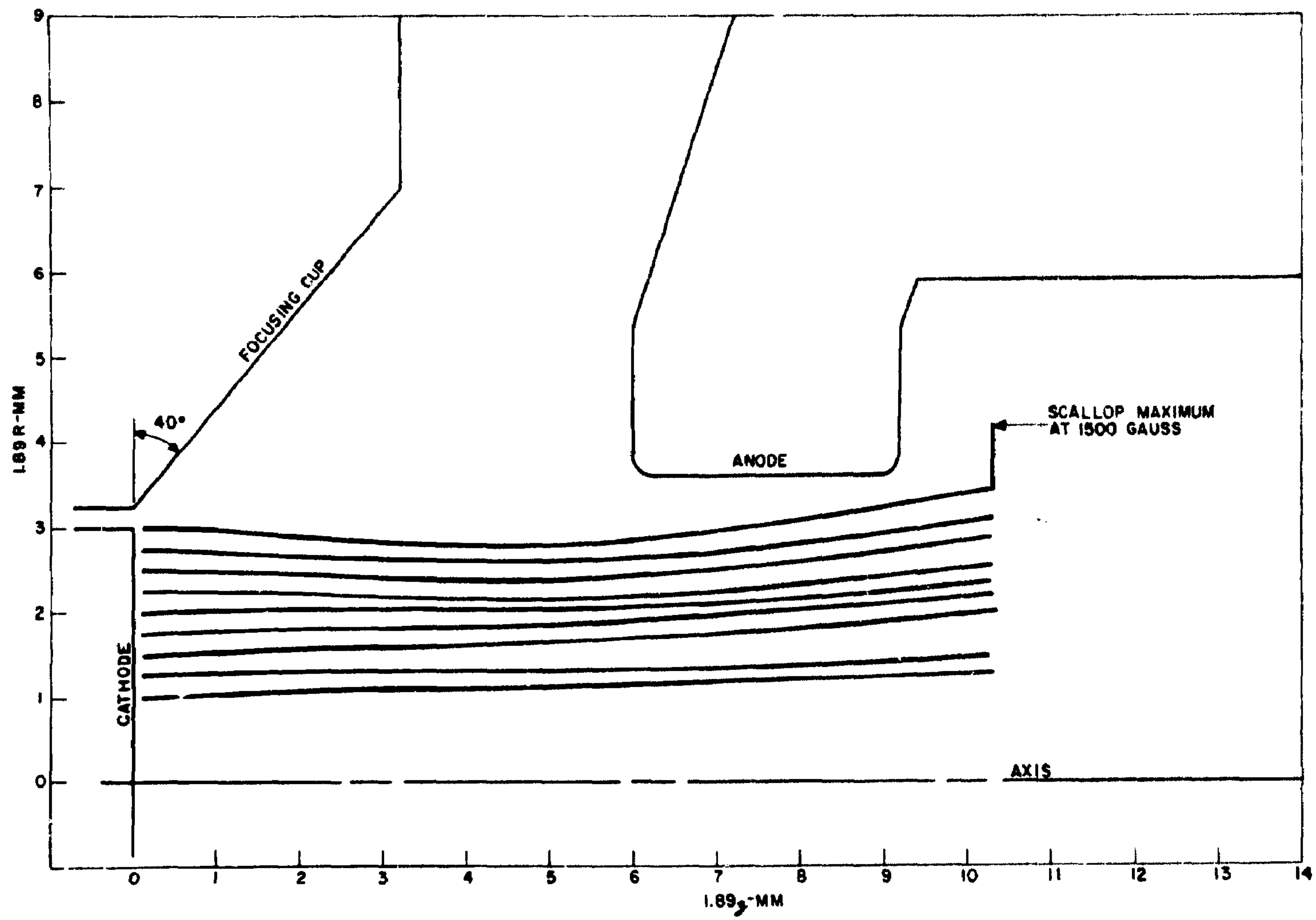

Figure 11 - Computed Electron Trajectories in 75-KW Beam Tester, With Space Charge in Uniform 1500-Gauss Magnetic Field

dimensionally in Figure 12, with the required accuracies indicated. A photograph of the beam tester is included as Figure 13.

While the new design eliminated the beam "blow-up" problem existing in the earlier device, gun structure alignment with respect to itself and the magnetic field was very critical in keeping beam transmission high. Slight cocking of the gun structure in the magnetic field resulted in a beam interception capable of puncturing the tube. For example, tests were conducted using a barium-orthosilicate cathode in a tungsten matrix, with the results shown in Figure 14. Pulsed data was taken using a 4-microsecond pulse at 1000 pps, and a maximum current density of 30 amperes/cm^2 was obtained. D-c data was then taken up to 7.2 amperes/cm^2. As the anode voltage was increased, gas bursts occurred as a result of the beam landing on different portions of the collector. As the gas increased, the emission slumped and then slowly recovered as the pressure improved. At a current density of 7.2 amperes/cm^2, the beam intercepted a portion of the entrance tunnel of the collector, resulting in a puncture of the envelope and loss of vacuum in the tube.

X-rays taken of this device showed that the cathode and cathode focusing cup were not accurately aligned with respect to the anode. This was corrected and a barium-strontium-tungstate cathode tested, giving a 2/3 power plot of current versus voltage, as shown in Figure 15. As indicated, this cathode was operated at saturated-emission levels in excess of 30 amperes/cm^2 d-c. A total of nine hours of operation was accumulated under these conditions before the heater opened. Longer life might have been obtained with another heater, such as a bonded-assembly type, or in a gun structure redesigned to reduce heat loss.

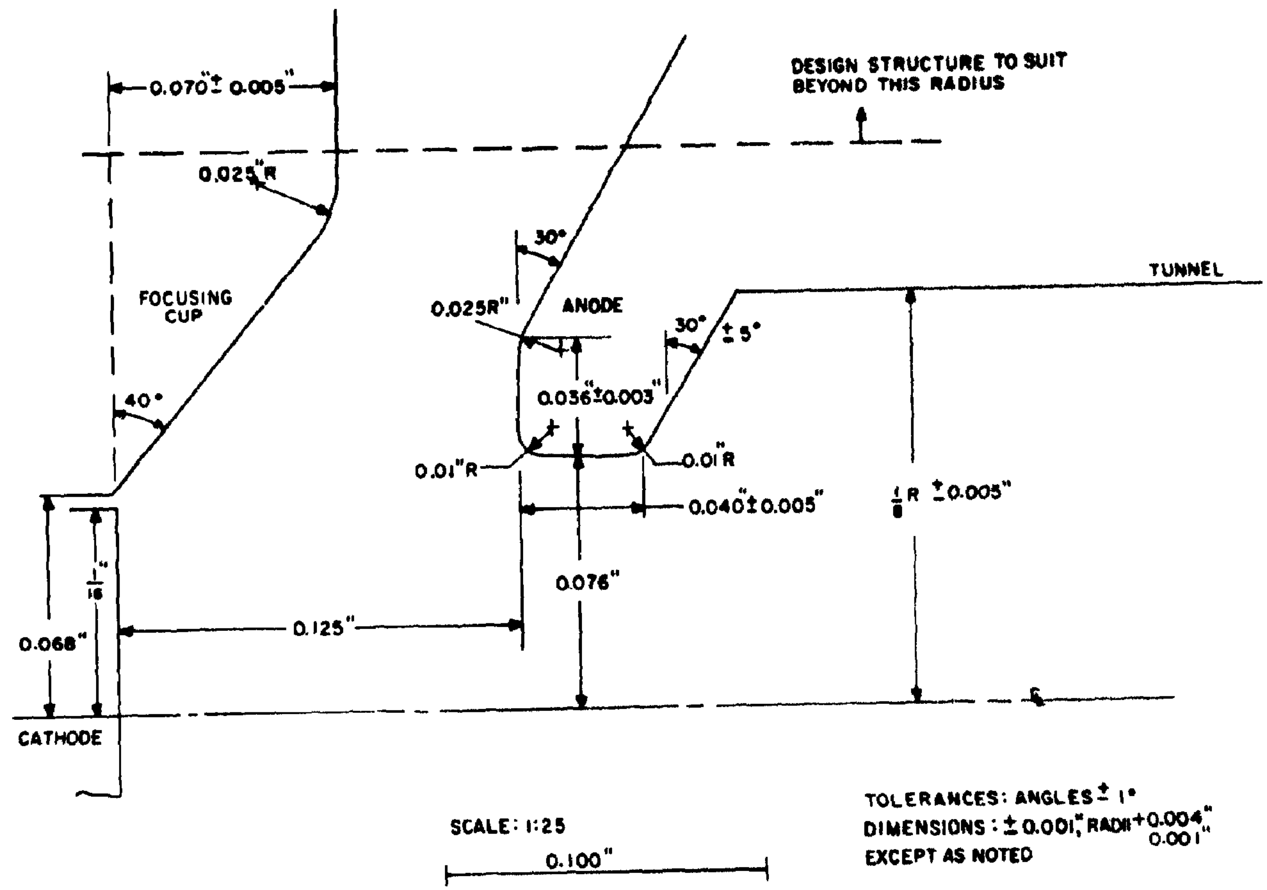

Figure 12 - Dimensional Layout of Beam Tester Gun Design

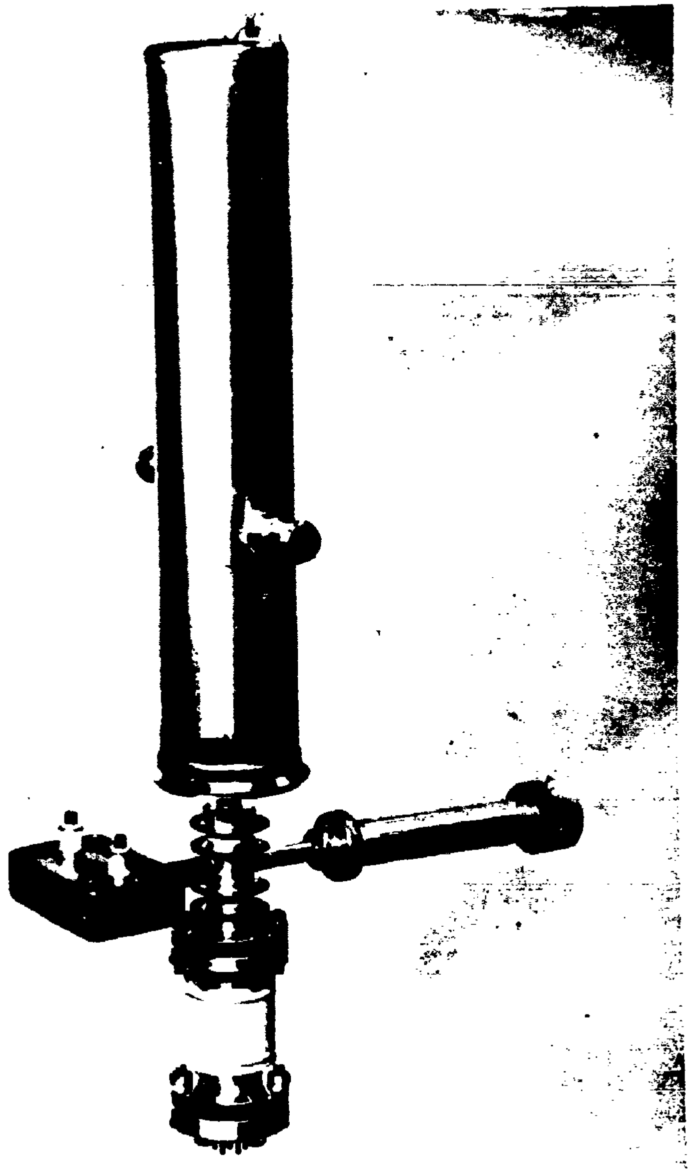

Figure 13 - 75-KW Beam Tester

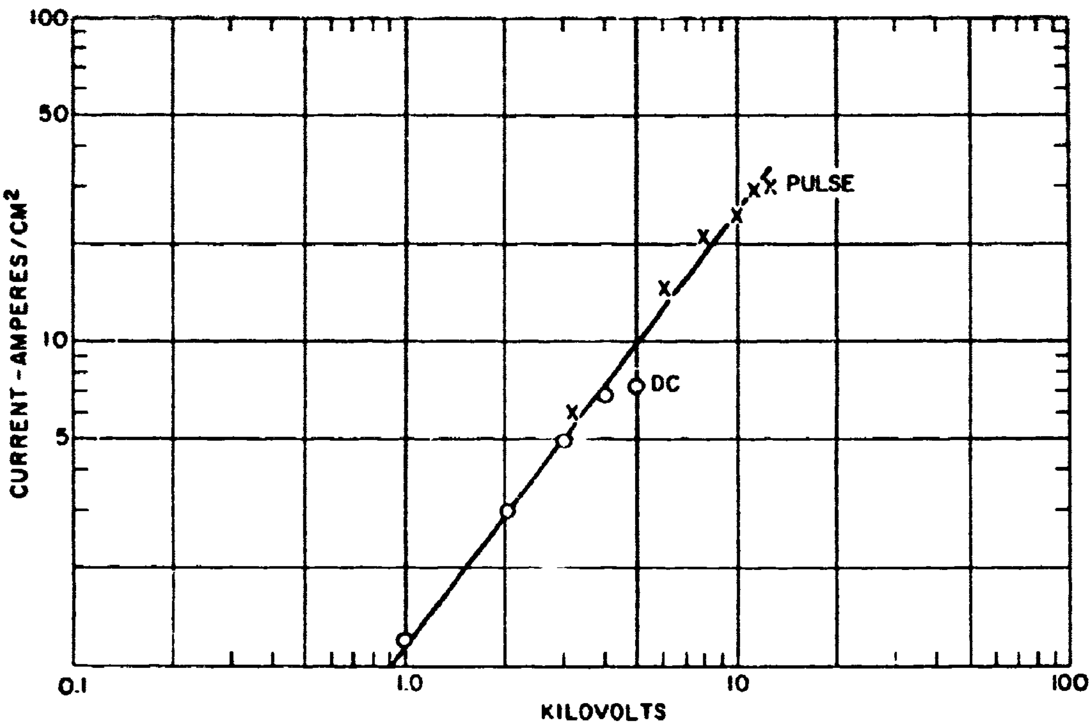

Figure 14 - Barium-Orthosilicate Emission Data from Beam Tests

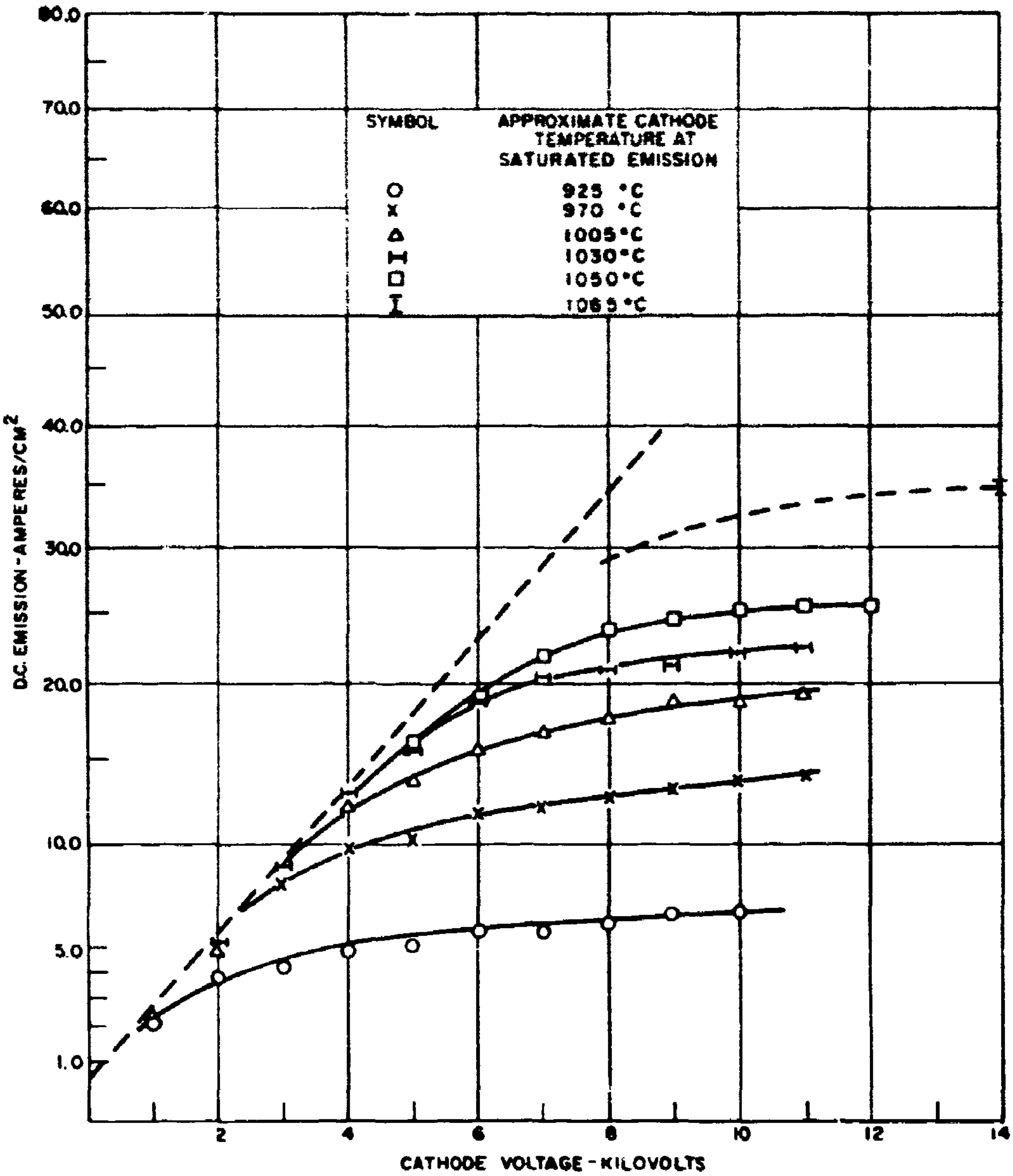

Figure 15 - Beam Test Results With Tungstate Cathode

The cathode temperatures indicated in Figure 15 were obtained from bell jar tests of heater power versus cathode temperature. Approximate corrections were made for electron cooling.

EMISSION MICROSCOPE TESTS

Another method of comparing various cathodes involves the use of an emission microscope. In this device, the focusing of electrons emitted from a cathode surface produces an image which corresponds to the emitting areas of the cathode. Such an emission pattern will indicate the uniformity of the emitting surface and whether the emission originates from pores in the cathode matrix or from thin-film coverage of the surface.

Emission microscopes vary in complexity from a very simple construction involving a single electrostatic lens to those involving a combination of many electrostatic and electromagnetic lenses with large display screens. In designing an emission microscope, a compromise must be reached between cost and desired magnification and resolution. With the objective of this study being to evaluate various refractory substrate emitters, a simple emission microscope was built to provide a means of comparing the emitting surfaces of different cathodes.

This microscope, in its final form, consisted of the components shown schematically in Figure 16. The gun was composed of the cathode, a 0.228-inch diameter aperture, and a 100-gauss magnet coil appropriately positioned. Lines were scribed on the surfaces of the 1/8-inch diameter demountable cathodes (the barium orthosilicate or barium-strontium-tungstate structures) to provide reference points in the emission pattern. The screen was a 1-inch square glass slide coated with a thin layer of manganese-activated zinc sulphide.

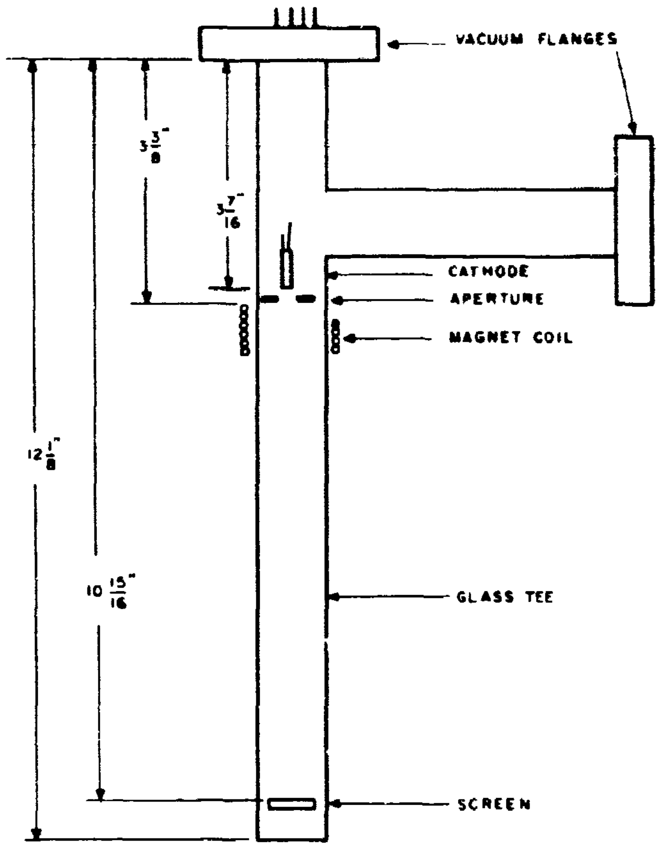

Figure 16 - Emission Microscope Outline

The emission microscope produced patterns which were magnified approximately 25 times and resolved scribed lines 1-1/2 mils apart on the emitting surface. Resolution was limited by the size restrictions present in the gun structure and the graininess of the screen. The screen problem prevented the taking of reproducible photographs suitable for this report, but did not interfere with visual inspection of the patterns from the bombarded side of the screen. This view displayed a patchy emission pattern, typical of many dispenser cathodes.

After weighing the added expense of further microscope magnification against the value of the information obtained, it was decided to terminate the microscope tests. This decision was supported by recent literature describing techniques for precisely measuring the work function of patches 10-microns in size on emitting surfaces.[21] With techniques as elaborate as these showing micro-patches on emitting surfaces, the simple emission microscope tests seemed too crude to pursue further.

Section 6
CONCLUSIONS AND RECOMMENDATIONS

Since the early 1950's, considerable attention has been devoted to the barium-aluminate dispenser cathode system, which has now progressed to the point where various versions are available from several commercial sources.

One of the major theses of this entire study has been that there are a number of systems, in addition to the barium-aluminate system, which are suitable for use as dispenser cathodes. This point has been demonstrated as shown in Table III where systems such as the barium orthosilicate and barium yttriate are shown to have work-function characteristics comparable to the aluminate system. These systems also exhibit similar evaporation rates. Further, recent work has produced a dispenser-type system that has a work-function characteristic which is even lower, approaching that of an oxide-coated cathode. Another significant feature that has been demonstrated indicates that the work function can be lowered by reacting excess amounts of barium oxide with a refractory oxide.

There is considerable evidence[5, 6] to show that emission originates from active "patches" of barium/barium oxide or from other barium compounds, and that the work-function characteristic may be as dependent upon the uniformity of the emitting surface as upon the emitting material itself.

There appears to be a greater sensitivity of the dispenser system to environment as the work function is lowered. The presence of excess barium oxide makes the system sensitive to water vapor in particular, and frequently produces "blooming" or swelling of the cathode structure. In the case of the barium-tungstate system, the processing steps are such that the cathode is pre-activated, requiring a subsequent machining operation. It then becomes necessary to seal the cathode in an evacuated vial for storage or mount it in a tube as rapidly as possible.

The merit of the dispenser is, of course, its ability to produce high current densities under d-c operation. The metallic nature of the matrix, and the thin emitting layer, aid in eliminating joule heating of the coating. However, as previously discussed, a number of difficulties arise in measuring the work-function characteristic at high current densities and dissipating a large amount of energy in the anode.

The best method of evaluating a cathode per se, as independent of tube geometry and spacing as possible, is to first determine the zero field emission at a convenient current level and the temperature, and then the resultant effective work function. The work function characteristic:

$$\phi = \phi_o + \alpha T$$

may then be determined and represents what is considered to be a basic or fundamental property of the cathode.

When one is concerned with a tube design or particular configuration, an I-V curve may serve as a means to make relative comparisons between emitters.

This brings us to the actual demonstration of the high current capabilities of a dispenser system. A test performed in a device-like structure such as a tetrode assembly or beam tester would produce meaningful results. Tetrode tests have been attempted in earlier phases of this study, as described in the Final Reports.[22,23] For example, an effort was made to pulse test a barium-orthosilicate dispenser cathode mounted in a General Electric Company GL-6942 tetrode structure. Excessive grid emission prevented operation of the tube under rf conditions. With the grids and anode connected, pulsed diode tests gave a work-function value agreeing with earlier determinations and resulted in a pulsed emission identical to the d-c saturated emission. Comparing heater-power requirements with the indirectly heated thoriated-tungsten cathode normally used in this tube, showed that for peak emission, 50 percent less heater power and a cathode temperature 400°C lower were required with the dispenser cathode. Recent tests, again under pulsed diode conditions, produced emission levels of 9 amperes/cm^2 with the orthosilicate cathodes. Grid emission, however, again prevented rf testing.

In a study sponsored by General Electric Company, a barium-strontium-tungstate cathode was tested in a G-E GL-7399 tetrode structure. Under rf and pulsed operation, this cathode performed no better than the oxide-coated cathode normally used in the tube, and produced essentially the same grid emission characteristics. Considerable handling of the tungstate cathode prior to test probably contributed to the failure to improve that performance.

The utilization of dispenser cathodes in gridded tubes presents problems involving the design of grid assemblies. Since this was primarily a cathode program, and not a grid study, emphasis was placed on the beam tests with no additonal work on the tetrode assembly. We believe, however, that to successfully utilize a dispenser system in a gridded tube, a special or new design will be required. It is not just a simple matter of replacing a dispenser cathode for either a thoriated-tungsten or oxide-coated cathode. Special attention must be given the grid interface, especially the temperature of operation and composition of the grid material. For these reasons, it would be worthwhile to further examine the tungstate cathode in GL-6942 structures. With a high emission-density capability already shown for this cathode, it should be possible, through reduction in operating temperature, to reduce the evaporation rate and extend the long-life capability of the tube.

For beam devices, it is standard procedure to check cathode performance and gun design in a beam tester consisting essentially of an electron gun and a large water-cooled collector. The design of such a device can be a major task in itself. As a part of this program, two designs from previous studies were used.

It was apparent from test results that cathode evaluation in such a device is difficult. This difficulty arises from the critical nature of gun alignment and other effects such as gas bursts which poison emission. With care, however, Schottky plots can be obtained from this device and the cathode work function measured. No attempt was made to determine the work function from the data in Figure 15 because of the uncertainty in cathode temperature.

In summary, there are several general observations that should be made concerning high current density cathodes.

1. Dispenser cathodes find the greatest application where current densities in excess of 1 to 2 amperes/cm^2 are required under d-c conditions or long-duty-cycle operation.

2. One should not expect dispenser cathodes in their present state of development to unconditionally replace the oxide cathode in performance -- for example, especially under pulsed conditions with short duty cycles.

3. In-tube tests point out problem areas such as grid emission, gun design, anode dissipation, and gas evolution that will require special attention before full capability can be realized.

4. Cathode current densities are limited when heated indirectly by radiation alone. Electron cooling is sufficient to limit the temperature and, consequently, the current. Attention should be given to the bonded-type heater which is an integral part of the cathode structure.

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Unclassified

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
General Electric
Schenectady, NY

2a. REPORT SECURITY CLASSIFICATION
Unclassified

2b. GROUP

3. REPORT TITLE

Investigation of Various Activator Refractory Substrate Combinations

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Final Technical Report

5. AUTHOR(S) (Last name, first name, initial)
Affleck, J.H.
Boyd, W.T.

6. REPORT DATE
January 1967

7a. TOTAL NO. OF PAGES
60

7b. NO. OF REFS
23

8a. CONTRACT OR GRANT NO.
AF30(602)-3395

b. PROJECT NO.
5573

9a. ORIGINATOR'S REPORT NUMBER(S)

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
RADC-TR-66-656

10. AVAILABILITY/LIMITATION NOTICES

Distribution of this report is unlimited.

11. SUPPLEMENTARY NOTES
Anthony S. Cardello
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12. SPONSORING MILITARY ACTIVITY
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13. ABSTRACT

This investigation was a study of various thin film refractory substrate combinations capable of producing high current density in dispenser type cathodes. Work function was used as the fundamental property common to all systems in evaluating the emission properties of the various dispenser cathode systems fabricated and evaluated during this program. The cathode systems were evaluated in a beam tester at both dc and pulsed operation and a barium-strontium-tungstate cathode produced dc emission in excess of 30 amperes per cm^2 for a period of nine hours in a saturated emission condition. It is generally concluded that the dispenser cathode is capable of high current densities for use in devices where 1 to 2 amperes per cm^2 is a requirement and dc or long duty cycle operation is desirable.

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