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Report No. 1

GENERAL PROBLEMS OF BROADBAND AMPLIFICATION IN THE MICROWAVE FREQUENCY RANGE

CONTRACT NONR 1834(08)
CONTRACT N6-ori-07156
Project No. NR-373-162

ELECTRICAL ENGINEERING RESEARCH LABORATORY
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
URBANA, ILLINOIS

GENERAL PROBLEMS OF BROADBAND AMPLIFICATION IN THE MICROWAVE FREQUENCY RANGE

Progress Report No. 1
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30 April 1956

Period Covered:

1 January 1956

to

31 March 1956

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CONTENTS

PART I - GENERAL

1.1 Preface

This is the first quarterly progress report for Contract No. Nonr 1834(08), which became effective 1 April 1956 as a replacement for Contract No. N6-ori-07156. The ONR Project Number, NR 373-162, remains the same under the new contract.

Research under this project deals with "General Problems of Broadband Amplification in the Microwave Frequency Range." The work is, in general, a continuation of research initiated under the terms of Contract No. N6-ori-071 Task XIX.

This report covers the period 1 January 1956 to 31 March 1956.

1.2 Personnel

The following staff members have been assigned to Contract No. Nonr 1834(08):

	Percent Time
Supervisor:	
H. M. Von Foerster, Professor	17
Graduate Associates and Assistants:	
Murray L. Babcock, Research Assistant	100
Kenneth R. Brunn, Research Associate	100
Technicians and Assistants:	
Robert N. Waggener, Senior Glass Blower	33
Donald D. Pritchard, Storekeeper	25

On 1 February 1956, Mr. J. F. Lowe, joined the staff of the subject contract, quarter time, as an instrument maker.

PART II - EXPERIMENTAL WORK

1. INVESTIGATION OF BARIUM MIGRATION IN THE HOLLOW CATHODE - M. L. Babcock

1.1 Discussion

The newly designed cathode was assembled and seems to be satisfactory. However, the older lens system used in the previous beam analysis tube was found to be inadequate for the present use since the position of the cathode aperture with respect to the lens aperture could not be satisfactorily controlled for the measurements desired. Therefore, a new lens system was designed and the parts have been made. In addition, a new supporting and positioning mechanism has been built for use in the beam analysis tube. With this mechanism it is hoped that the emission from the inside of the aperture can be separated from the emission from the barium which has migrated to the outside of the aperture, and that an indication of the size of the two emissions relative to one another can be obtained.

1.2 Plans for the Next Quarter

The tube will be assembled in its final form and tested.

2. TRIODE WITH A HOLLOW CATHODE - M. L. Babcock

2.1 Discussion

The triode with the modifications mentioned in the last report was assembled and partially tested. The various faults with the first triode have been corrected in the modified triode with one major difficulty. This difficulty, electrical leakage between cathode and grid, is still present in the modified triode, but to a much lesser degree. The leakage now present seems to result from a deposit on the Alsimag ceramic spacers since it is not present at the start but becomes greater as the length of operation of the tube becomes greater. To eliminate this leakage may require only a change in the ceramic spacer material or it may require a completely new design. However, it is hoped at present that the latter will not be necessary.

Even with the leakage present, the results of the tests appear promising. For example, the grid shows some control over the electron flow, although not as much as would be expected This lack of control may be due to inaccuracies due to leakage or to the present grid structure. This grid has a mesh spacing of 0.010 inch for 0.002 inch diameter wires. Thus only one or two grid wires intercept the electron flow. New grids with a mesh spacing of 0.001 inch for 0.0003 inch diameter wires have been obtained and will be used in the triode as soon as the grid-to-cathode leakage is eliminated. This grid should exhibit much greater control since the spacing is such as to place about 20 wires in the electron flow path instead of the present one or two wires.

Another result of the tests to date is the variation of current with the variation of cathode temperature. This variation appears to be much greater than the similar variation in the diode tube. However, due to the leakage present in the triode, this may be a false indication, and so the results must still be considered only qualitatively.

2.2 Plans for the Next Quarter

A new triode has been constructed and will be tested soon. This triode has a mica spacer separating the grid from the cathode. If this fails to correct the leakage, then another tube with completely separate cathode and grid-and-plate assemblies will be constructed. Most of the parts for this latter tube are available at present.

3. THE HIGH VOLTAGE HOLLOW CATHODE INVESTIGATION -

K. R. Brunn

3.1 Introduction

The current series of hollow cathode experiments was concluded during this period and the data on Models A-8 to A-14 is reported below. Electrolytic tank measurements of the potential field inside the hollow spherical cathode were made and the results are given. As a result of the experience obtained on the series of oxide emitter cathodes it was concluded that a pure emitter would have many advantages in the high voltage regions of operation and such a cathode has been designed and is under construction.

3.2 Hollow Cathode A-8

It was intended to mask off an area about the aperture having a diameter of 0.125 inch when hollow cathode A-8 was sprayed with the Ba-Sr oxide emitting material. However, an autopsy revealed that the masking was very ineffective and a non-uniform coating was actually present on this area ranging from no coating to normal coating. Consequently the tests on this cathode appear to have little value.

3.3 Hollow Cathode A-9

The cathode consisted of a bare, grade A, nickel sphere, and was intended to verify experimentally that no direct emission from the nickel surfaces of either the cathode sphere or heater assembly is present in the current series of tests. Heater difficulties doomed this experiment.

3.4 Hollow Cathode A-10

This test was a repeat of the previous experiment with a new heater assembly and bare nickel cathode. No measurable currents were obtained. The anode-to-cathode spacing was 0.036 inch and a maximum anode voltage of 9000 volts was applied at a maximum temperature of 915°C. Thus there can be no doubt that the experimentally observed currents of the hollow cathode must originate from the oxide coating alone.

3.5 Hollow Cathode A-11

Hollow cathode A-11 was assembled according to the same specifications as Model A-4,* that is, an annular region about the aperture having a diameter of 0.25 inch was masked off when the cathode was sprayed. The cathode was converted with a maximum temperature of 943°C. The activation was normal, i.e., the initial current was essentially zero and slowly built up to a stable value in several hours. This cathode yielded higher currents than Model A-4, but the characteristics were similar.

The higher emission permitted the use of the oscillographic presentation of the characteristics, and tracings of photo-oscillograms taken with the cathode temperature as the parameter are reproduced in Fig. 1. The characteristic shape is typically that of the normal hollow

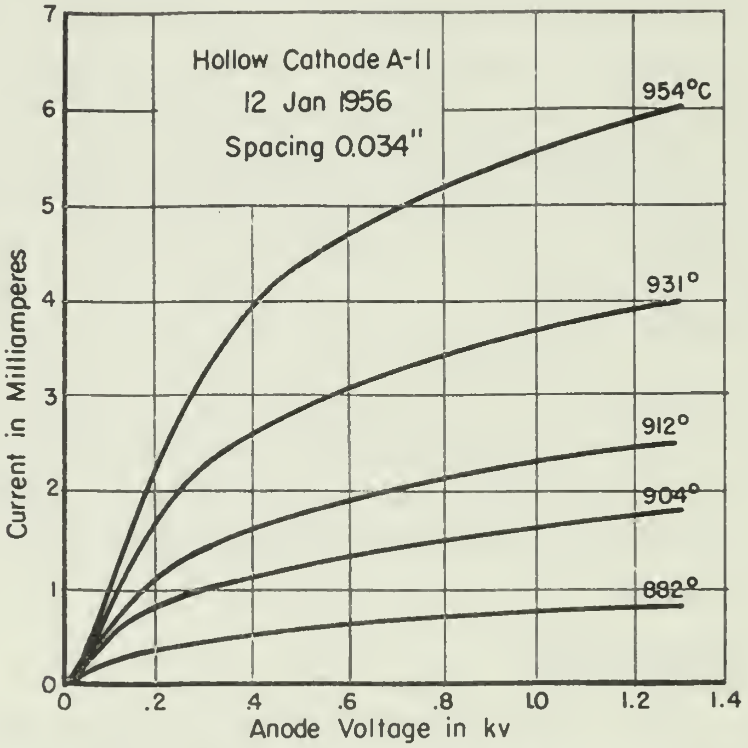

Figure 1. Hollow Cathode Characteristics with an Uncoated Area of 0.25 inch Diameter About the Aperture

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* See Page 19, Progress Report No. 2 of the previous contract, No. N6-ori-07156, October 30, 1955.

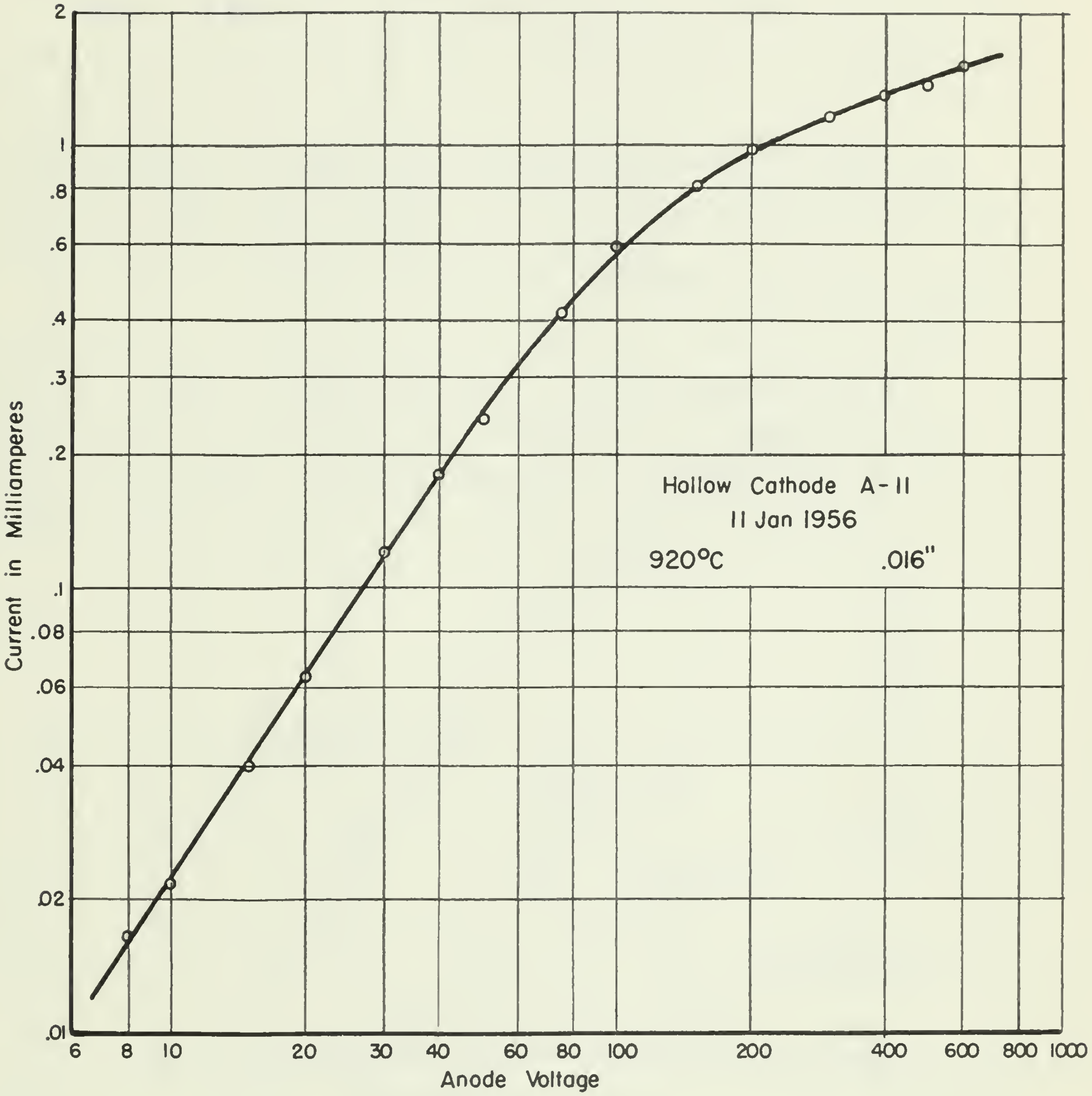

Figure 2 Logarithmic Plot of the Characteristic with an Uncoated Area of 0 25 inch Diameter About the Aperture

cathode except that of the region near the origin, i.e., below approximately 100 volts. In order to observe this region more closely, a typical set of measurements have been plotted on a logarithmic scale in Fig. 2. For anode voltages less than about 50 volts the characteristic follows a three-halves power voltage law. This is the classical space-charge-limited relationship except that one important difference must be pointed out, namely, that the current at these anode voltages is not independent of temperature, as can be observed in Fig. 1.

The temperature dependence of the emission of this cathode was found to differ from the fully coated cathode in that it did not vary as an exponential function of the reciprocal temperature. The observed temperature dependence is plotted in Fig. 3.

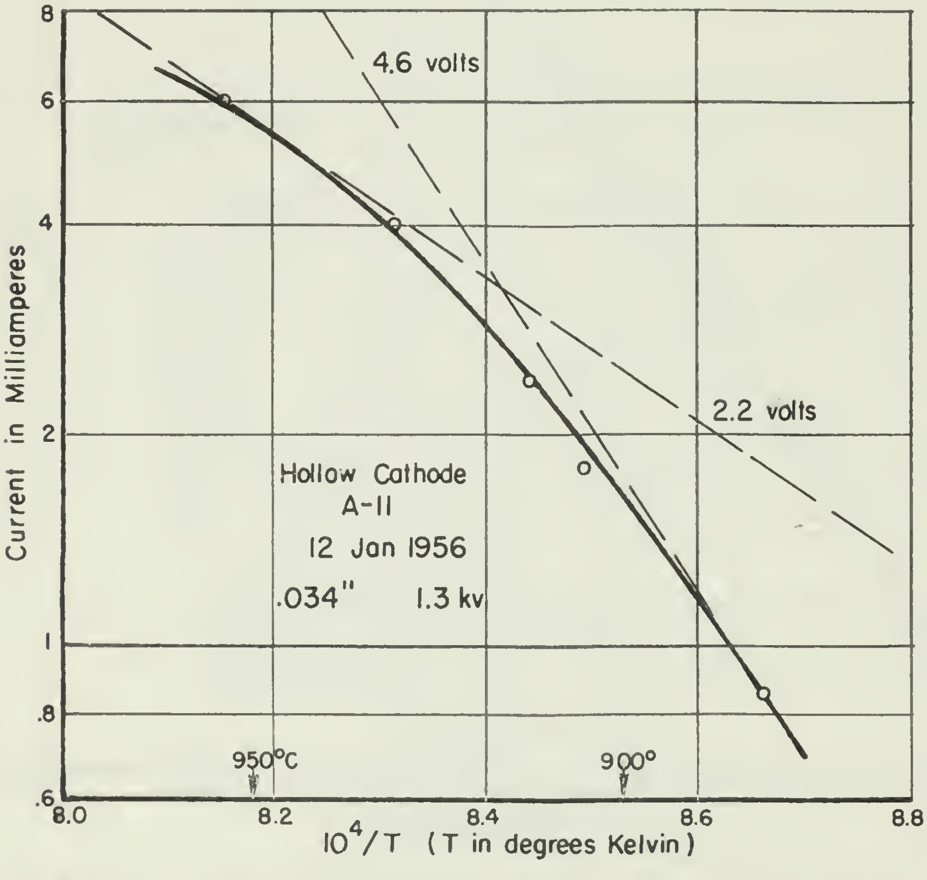

Figure 3. Hollow Cathode Current versus Reciprocal Temperature for a Cathode with an Uncoated Area of 0.25 inch Diameter About the Aperture

The cathode yielded reproducible results, and, after about 19 hours of actual operation, was removed and inspected. The cathode coating looked very good and no visible evidence of cathode material could be observed on the masked off area or on the edges of the aperture.

3.6 Cathode A-12

Cathode A-12 was not a hollow cathode, but a normal cathode approximating a parallel plane diode. It was assembled just as the previous hollow cathode models except that instead of coating the internal surface of the cathode sphere, the exterior surface was coated on an annular region about the aperture having a diameter of 0.125 inch. Thus the arrangement is an ordinary diode utilizing the same geometry as the hollow cathode experiments.

The results were as one would predict, namely, true space-charge-limited operation. By operating this cathode at relatively low temperatures so that it "saturated" at low anode voltages, a direct comparison of its characteristics and the hollow cathode characteristics was obtained. A typical comparison is shown in Fig. 4. The "internal coating" curve is that of Model A-6 at a temperature of

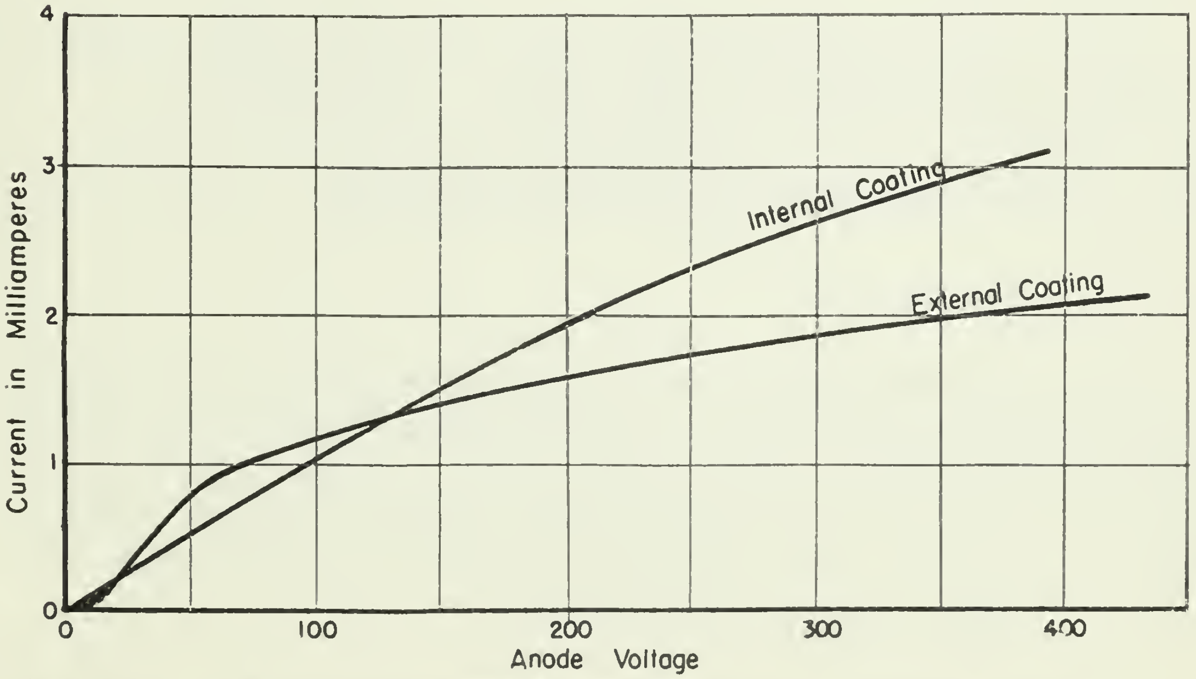

Figure 4. Comparison of the Normal and Hollow Cathode Characteristics

917°C and an anode-to-cathode spacing of 0.042 inch. The "external coating" curve of cathode A-12 was taken at a spacing of 0.050 inch and about 700°C. It should be observed that the "saturation" region does not show a true saturation, but continues to increase as the anode voltage is raised. This cannot be due solely to the Schottky effect for two reasons. First, the curvature of the characteristic is contrary to that of the Schottky effect, which requires that the slope increase as the anode voltage is increased, and second, the field strengths are too small to account for the magnitude of the increase in current. The main factors which influence this portion of the characteristic are probably the roughness of the coating surface and the variation in work function of different areas of the coating which cause different portions of the cathode surface to saturate at different anode potentials. Consequently, the transition region between complete space-charge-limited operation and completely saturated operation is extended over a rather large range of anode voltage. This situation complicates the calculation of temperature-limited currents from oxide coated cathodes encountered in practice.

A comparison of the two curves of Fig. 4 shows that even under practical conditions a rather distinct knee in the curve of the ordinary cathode is clearly observable, while this is not the case in the internal or hollow cathode case.

3.7 Cathode A-13

Cathode A-13 was a repetition of the externally coated cathode of model A-12 and yielded the same results. True space-charge-limited operation was observed, and when the temperature was reduced the same "saturation" characteristics as shown in Fig. 4 were obtained.

3.8 Hollow Cathode A-14

Hollow cathode A-14 was assembled with the oxide coating present only on an annular region having a diameter of 0.148 inch about the aperture. That is, the region in the vicinity of the aperture is capable of emission and the areas distant from the aperture are not capable of emission. The cathode was converted at a maximum temperature of 1050°C and activated normally

The current-voltage characteristic of this cathode was found to be the same as that of the typical fully coated hollow cathode over the range of voltages measured, i.e., below 1000 volts. A tracing of a typical photooscillogram of the characteristic is reproduced in Fig. 5. Such a result substantiates the hypothesis that the area in the vicinity of the aperture contributes the major portion of the current over the range of voltages investigated. Typical data has also been plotted on a logarithmic scale in Fig. 6, which essentially duplicates similar plots for the fully coated hollow cathode.*

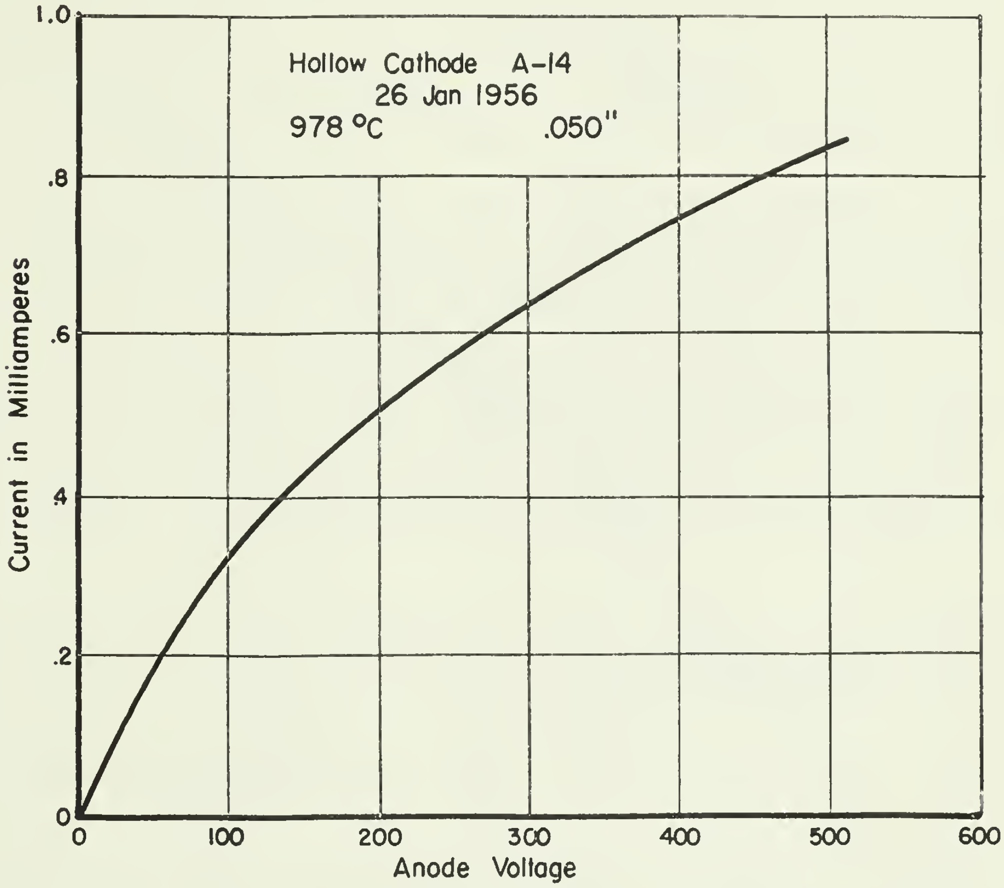

Figure 5. Characteristic of a Hollow Cathode Coated in the Neighborhood of the Aperture Only.

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* See Fig. 4, page 10, Progress Report No. 2 of this contract.

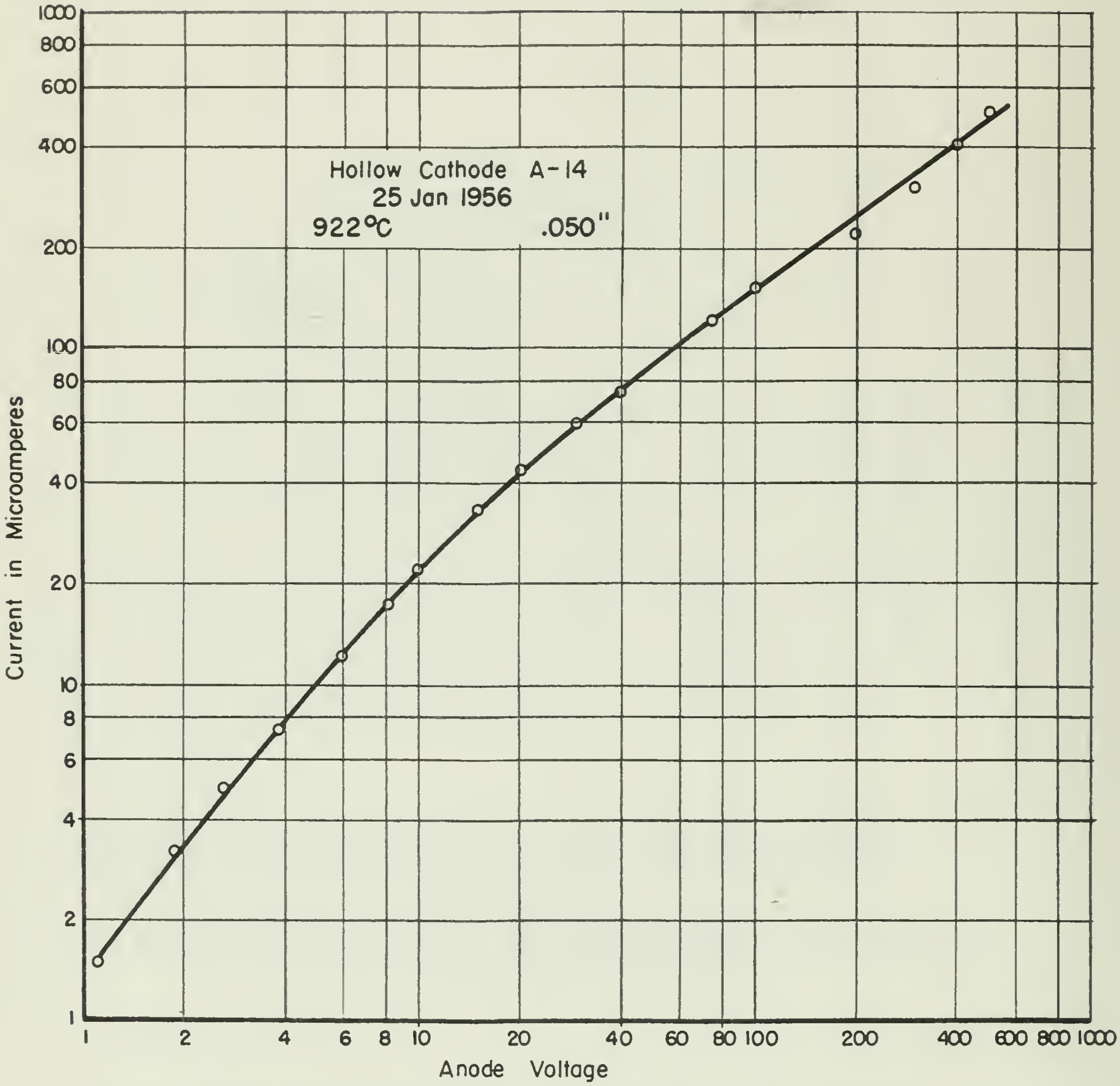


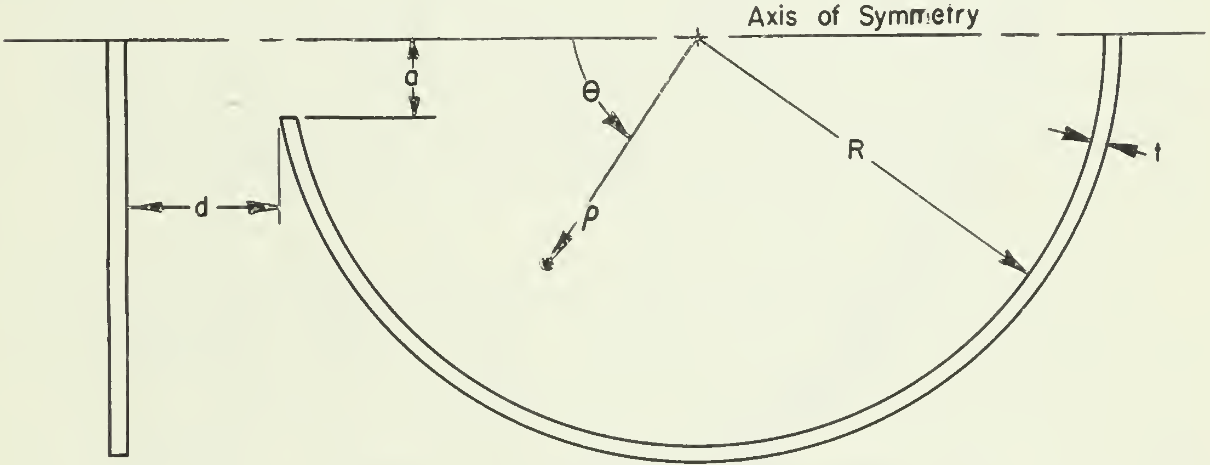
Figure 6 Characteristic of the Hollow Cathode Coated in the Neighborhood of the Aperture Only

The cathode was removed after about 98 hours of operation and inspected. The coating looked good and no visible signs of migration through the aperture could be observed.

3.9 The Potential Field in a Hollow Sphere

In any analysis of the operation of the hollow spherical cathode, a knowledge of the field distribution inside the cathode in the absence of space charge would be a valuable bit of information. An exact theoretical calculation of the potential field is quite difficult, but an approximate solution in terms of Legendre Polynomials is readily available.* However, from a practical computational viewpoint this solution has limited value as it is in a rather cumbersome form involving a double infinite series containing integral coefficients. Anticipating graphical and numerical methods of solution, the more direct approach of the plotting tank method seemed to be in order.

While the general method of the electrolytic tank potential measurement is well known, a few considerations pertinent to the particular problem are worthy of note. The geometry of the model is shown in Fig. 7. A wedge angle of five degrees and a signal



	R	d	a	t
Tank Model, inches	16.3	1.74	.87	.2175
Actual Cathode, inches	.375	.040	.020	.005
Aperture Radius Normalized to Unity	18.7	2	1	.25

Figure 7. Geometry of the Hollow Spherical Cathode Tank Model.

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* Morse, P.M., and Feshbach, H. "Methods of Theoretical Physics," Part II McGraw-Hill, New York, 1953, P. 1283

frequency of 60 cps were used with the usual bridge circuit and an oscilloscope null detector. The size was scaled as large as possible, principally to make the model aperture size large enough to insure that variations in the electrolyte meniscus in the vicinity of the aperture would have a negligible effect on the potential levels within the sphere.

Due to the fact that the potential values within the sphere are so very small, it was not practical to measure the fields everywhere within the sphere using the single anode and cathode electrodes sketched in Fig. 7. Such a procedure would be subject to large errors due to the fact that these potentials are in the region of the lowest sensitivity of the bridge, because of the very small unbalance signal magnitudes available with reasonable anode voltages, and the difficulties of sufficiently shielding the detector from stray pick-up voltages of comparable magnitude to the bridge signal voltages near the null position. Consequently, the fields were measured in the region near the aperture and a new electrode was then made to conform to the measured equipotential line corresponding to one percent of the anode potential. This new electrode was then used with the cathode electrode to measure the fields farther into the sphere. Then a third electrode was made to conform to the equipotential line corresponding to one percent of the second electrode, or 10^{-4} times the original anode potential. Using this third electrode and the cathode electrode, the remaining potential distribution could be measured. The resulting potential distribution of the entire sphere has been reproduced in Fig. 8. The values of the plotted equipotential lines have been normalized to unity anode voltage.

It is also of interest to know the value of the electric field at the internal surface of the sphere. This is readily obtained from the tank measurements and is plotted in Fig. 9. The fields can be seen to fall off quite rapidly as one moves away from the edge of the aperture. The measured field values in the immediate neighborhood of the aperture are, of course, least accurate, but for values of $\theta \geq 4^{\circ}$ the error should be small. The straight line portion of the curve yields the relatively simple relationship (for θ in degrees):

$$\frac{E_R}{V_a/R} = 48.8\ \theta^{-2.97}$$

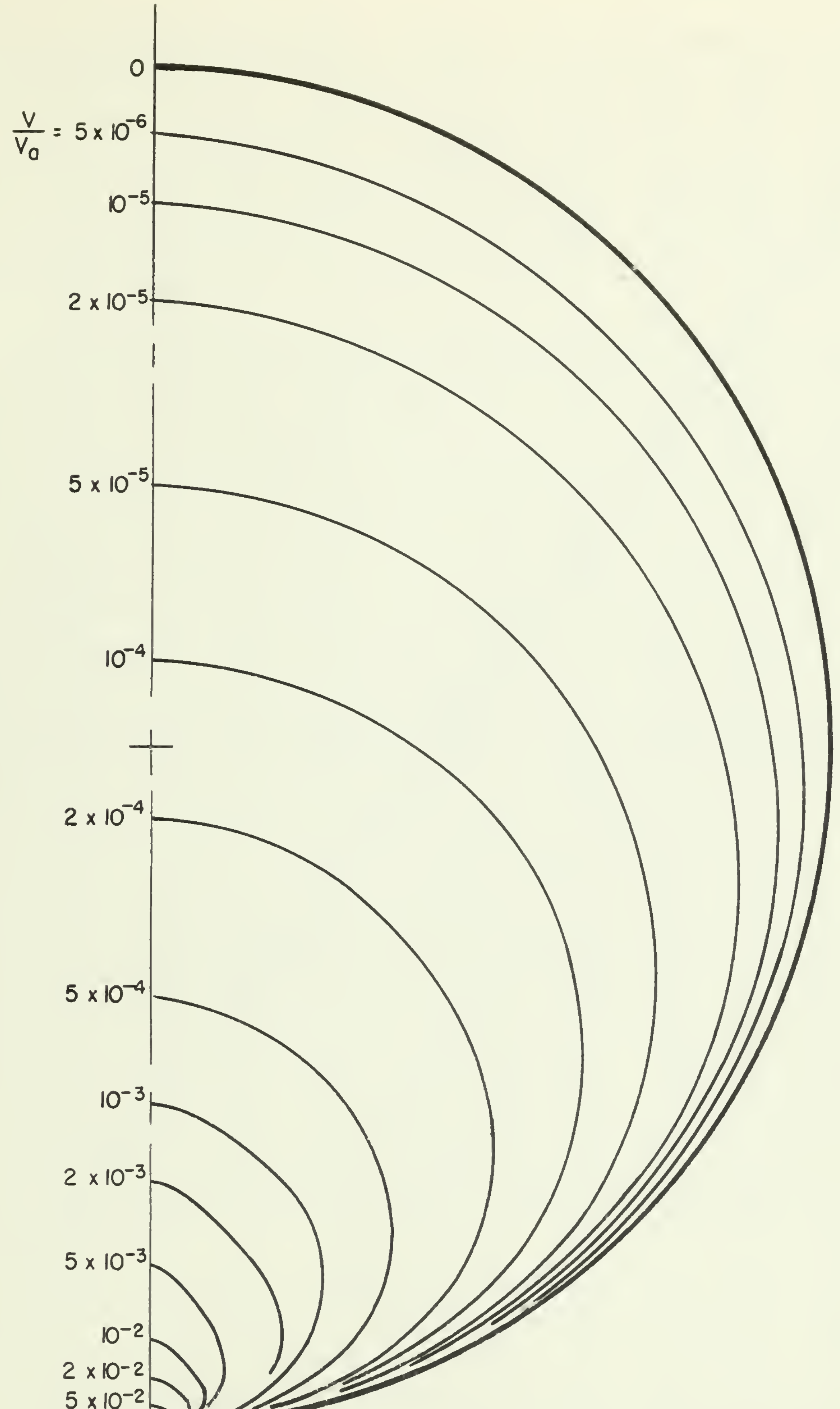

Figure 8 Equipotential Plot of the Hollow Sphere as Determined from an Electrolytic Tank Model

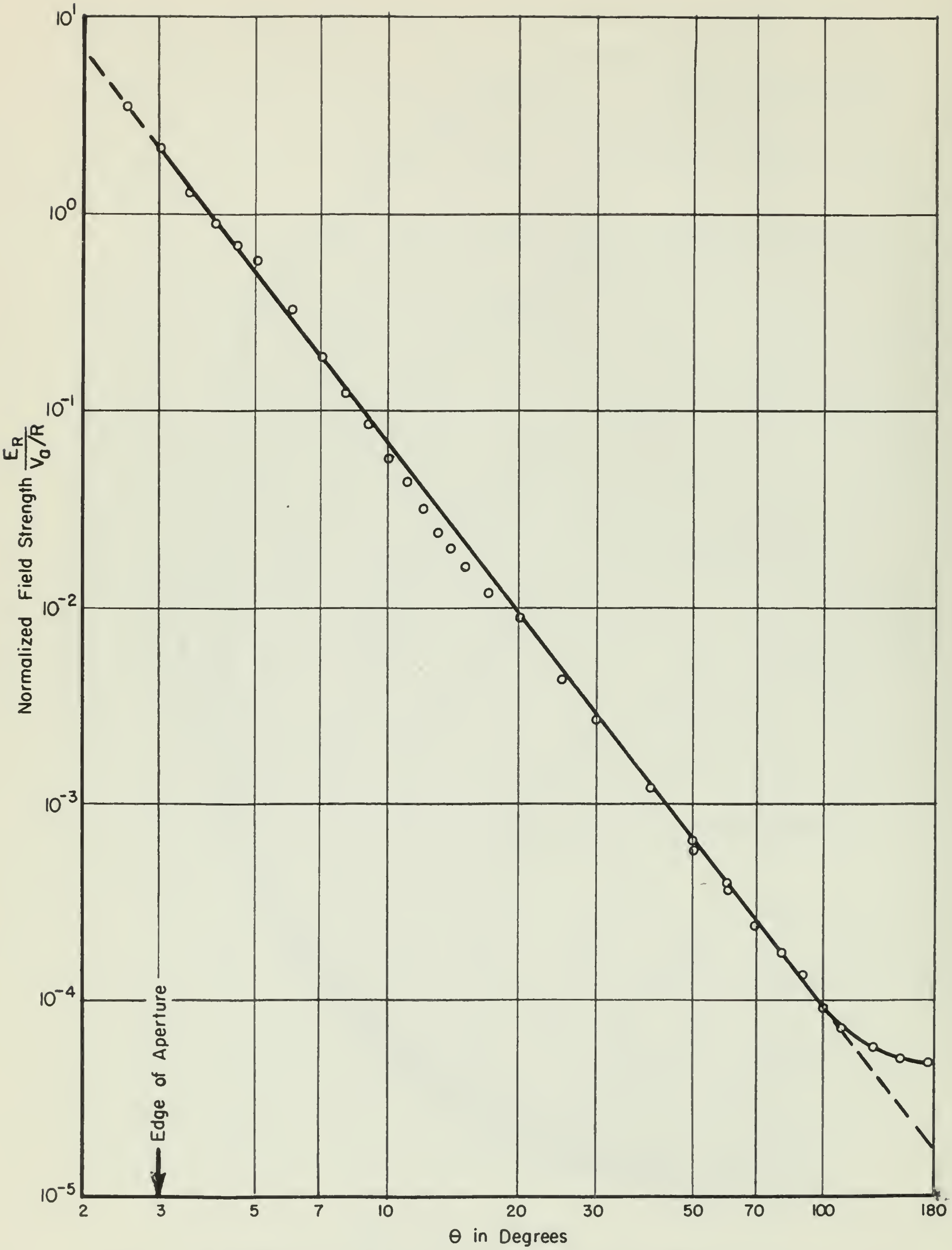

Figure 9 Normalized Field Strength at the Internal Surface of the Hollow Sphere

which is valid for $\theta \leq 100^\circ$. Of direct concern to the high voltage investigation is the result that with pulsed anode voltages of the order of 200 kv one can obtain field strengths of the order of 10 v/cm at the back of the cathode in the absence of space charge. Thus at these high voltages one can feel assured that a considerable portion of the cathode surface will actively contribute to the operation.

3.10 Miscellany

As regards the high voltage investigations of the hollow spherical cathode, the experience obtained with the series of cathodes using oxide emitters has led to one principal conclusion, namely, that the use of oxide coated cathodes is not particularly suited for the high voltage experiments. This conclusion is based on several factors including sparking, reproducibility, and temperature-limited characteristics of oxide cathodes. Sparking problems which were troublesome but not insurmountable arose at anode voltages of several kilovolts, but at voltages of several hundred kilovolts there is little doubt that the results would be disastrous. As greater portions of the cathode surface will be operating under temperature-limited conditions as the voltages are substantially increased, the problems with oxide coated cathodes become increasingly important. The fact that temperature-limited characteristics of oxide cathodes are both nonpredictable and nonreproducible within any reasonable limits makes even approximate analysis invalid and interpretation of experimental data almost impossible. In the light of these facts, the use of a pure metal emitter would be an immeasurable improvement. The pure emitter would be far more predictable and reproducible, would not be subject to variations due to sparking, and would completely eliminate the conversion and activation irregularities inherent in the oxide cathode, as well as poisoning effects. Another advantage which the pure emitter offers is the elimination of the question of migration.

There are practical experimental disadvantages of the pure emitter, of course. Since higher work functions must be accepted it means operation at rather elevated temperatures. For laboratory experiments this is not a distinct disadvantage, and it is planned to heat the pure emitter hollow cathode by means of RF induction heating. A problem of greater concern is the reduction of the direct emission from the external surface of the cathode sphere to a negligible value. The basic technique will be to use a material having a work function sufficiently greater than the internal emitting surface. Since the saturation current density varies exponentially with the work function, such a technique becomes plausible. The following relationship is easily derived from Richardson's equation for the saturation current density, where T is in degrees Kelvin and $\Delta\varphi$ is the difference in work function in volts

$$\log_{10} \frac{j_i}{j_o} = \frac{5050}{T} \Delta\varphi \ .$$

Thus, for a difference in work function of one volt at a temperature of about 2000°K, one obtains a saturation current density ratio of the order of 300. The direct emission can be further effectively reduced by geometrical means such as measuring the current to the anode directly opposite the aperture separately from the current collected by the outer areas of the anode.

A tantalum emitter offers the advantage of being easily drawn to shape and has a work function of 4.13 volts. Platinum appears to be a suitable metal for the external surface as it can be plated or evaporated on the tantalum sphere, has a high melting point, and a work function of 5.36 volts. An experimental setup utilizing RF induction heating, reduction of direct emission by geometrical means, and other details has been designed and is under construction.

3.11 Plans for the Next Quarter

Having completed the series of tests on the low voltage hollow spherical cathode, the results will be studied. The pure emitter hollow cathode will be assembled and testing should be initiated during the next quarter. Methods of utilizing the field plot of the hollow spherical cathode obtained during this quarter for analysis of high voltage operation will be investigated.