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MEASUREMENTS IN LOW-PRESSURE MERCURY ARCS, 1957

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ABSTRACT

The basic concepts upon which the theory of probe measurements depend were established by Langmuir and Mott-Smith combined with the more detailed studies of Langmuir and Tonks and Killian in their pioneering work. Klarfeld introduced new techniques and pointed more specifically toward the development of methods capable of giving more reliable results than had hitherto been available.

For the past ten years a coordinated study program has been in continuous operation sponsored by the Research Laboratory of Electronics. This investigation introduced advanced methods of vacuum technique to minimize the disturbing influence of unwanted residual gases. The condensation of such gases as well as that of mercury atoms alter the true work-function of the charge collecting electrode or probe and thus introduce systematic inaccuracies unless necessary corrective precautions are used. Probe geometry and probe location within the plasma serve to differentiate quantitatively certain random and nearly isotropic plasma properties from those determined more specifically by tube geometry and tube operating characteristics such as total drift current and the related axial and radial fields. The combined studies of Howe and Aisenberg serve as a basis for the results presented in this paper. The mercury pressure range was determined by the wall temperature of the discharge tube maintained in a thermostatically controlled bath at temperatures ranging from 20°C to 60°C. With the mercury density maintained constant at selected temperatures within this range, arc properties were investigated as a function of the arc current. These properties include: (1) the longitudinal gradient, (2) the radial field, (3) the electron energy distribution, (not Maxwellian), (4) the electron density in various parts of the discharge, including its radial variation, (5) the ion density, (6) the average ion generation rate, (7) the saturation electron current to ion current ratio, (8) the mobility of ions and electrons.

In addition to the above factual data certain deductions may be made. Of these the most important (although not unexpected) conclusion is that over this pressure range the ionization results predominantly from the two-stage process which involves the excitation of a sufficient number of mercury atoms to the metastable levels so that low-energy electrons can complete the ionization process. The most remarkable fact is that half of all of the excited atoms become ions. It is the intention of this paper to integrate into a single presentation the contributions which these studies have made towards a better understanding of the mechanisms and the properties of the plasma in the low pressure mercury arc.

molecular formation either collisions between metastable or atoms with followed by collisions with

Glossary of Symbols

a_x empirical constant related to excitation rate in Eq. 31

A area of discharge tube m^2 (πR^2)

A_1
A_2 anodes of tube in Fig. 1

A_p probe area in m^2

b_x empirical constant expressed in electron volts and related to excitation rate in Eq. 31

e base of natural logarithms 2.718

E_x drift field in volts per m

$f(V)$ fraction of electrons in a Maxwellian distribution per unit range in electron energy V. Eq. 26

f_x fraction of mercury atoms taking part in the excitation—de-excitation process. (Eq. 35

f_{x+} fractional rate of ion production compared with excitation rate. Eq. 40

i electron current (amp) to probe

i_o electron current (amp) at space potential for range I of Fig. 4

i_I observed electron current (amp) range I, Fig. 4

i_{II} observed electron current (amp) range II, Fig. 4

i_+ ion current to a wall probe of area A_p at floating potential Eq. 36

I drift current, amp

I_x integration of Kenty's function combined with Maxwellian distribution of electron energy. Eq. 30

j_o electron current density at space potential

k Boltzmann's constant 1.38×10^{-23} joule/deg

$K_x(V)$ Kenty's function as in Fig. 8 and Eq. 28

m electron mass 9.19×10^{-31} kg.

M_d drift mobility in m per sec, per volt per meter. (m^2/volt-sec)

n electron concentration number per m^3

Glossary of Symbols, contd.

$\bar{n}$ average electron concentration, number per m^3

n_a concentration of neutral atoms, number per m^3. Eq. 29 for relation to p_o

n_{ao} concentration of atoms in number per m^3 at one micron pressure and 0^oC. Value is 3.536×10^{19}

n_c electron concentration number per m^3 at center of plasma. Eq. 6

$\bar{n}_c$ average density of "energy-losing" electrons. Eq. 15

n_e electron concentration in number per m^3. Eq. 5

n_i concentration of ionized mercury atoms in number per m^3

n_w electron concentration, number per m^3, at wall probe. Eq. 6

n_x concentration of excited atoms, number per m^3

n_{xo} concentration of excited atoms making transitions to the "ground-state" of the mercury atom

p_o mercury pressure in microns Hg *that the atoms present would have at 0^oC. Eq 29.*

P_c number of collisions per meter total distance of travel in the gas at at one micron pressure at 0^oC

$P_x(V)$ number of excitations per meter travel of an electron with energy V in electron volts at a pressure of one micron at 0^oC

$6^3P_{0,1,2}$ identification of energy levels of mercury atom

q electron charge of 1.602×10^{-19} coulomb

r radial distance from axis of cylinder in m

R radius of discharge tube in m

t time in sec.

T_e equivalent electron temperature. Eq. 4

V probe potential relative to space potential (volts)

V_a applied potential relative to anode A_2 (volts)

V_c electron energy at a collision, volts

V_{cw} effective potential difference between the center and the wall of the discharge Eq. 24

V_p measured space potential relative to anode

Glossary of Symbols, contd.

V_T electron-volt equivalent of temperature,   Eq. 4

a ratio of electron current at zero field for range II compared to i_o

β (V_T of range I)/(V_T of range II)

ν_c collision frequency number per sec   defined by Eq. 14

τ_1 average travel time for one meter as obtained from a Maxwell-Boltzmann distribution.   Eq. 9

τ_c average travel time between collisions at pressure p_o in microns for a given average value of P_c

Figure Captions

Fig. 1   Scale diagram of discharge tube used by Aisenberg.

Fig. 2   Observed work-function changes of probes related to time after heating to incandescence (Aisenberg).

Fig. 3   Probe current measurements as a function of applied voltage as observed by Howe. Note expanded scale for the low current range. Linear extrapolation used for ion current correction to obtain net electron current is dashed line.

Fig. 4   Typical semilog plot of electron current to a probe as a function of applied voltage. Observations by Aisenberg; water temperature $54.6°C$; wire probe at center of discharge nearest cathode; $p_o = 16.6 \mu$. Main group of electrons in range I, high energy group in range II, very low energy group in range III, ion current to probe at floating potential 1.15×10^{-4} amp.

Fig. 5   Average electron density as a function of the parameter $p_o V_T^{1/2}/E_x$. This line determines the collision cross-section parameter P_c of Eq. 12.

Fig. 6   Application of function in Eq. 20 to available experimental data.

Fig. 7   Electron concentration. Values at center, wall, and average shown. Data from Aisenberg and Howe

Fig. 8   Kenty function given in Eq. 28. Basic data from Kenty[13], Fig. 2.

Fig. 9   Evaluation of the integral of Kenty's function combined with the Maxwellian distribution for various temperatures. Results summarized by Eq. 30.

Fig. 10   Estimated cross-section for collisions of the second kind based on Kenty's[13], Fig. 5.

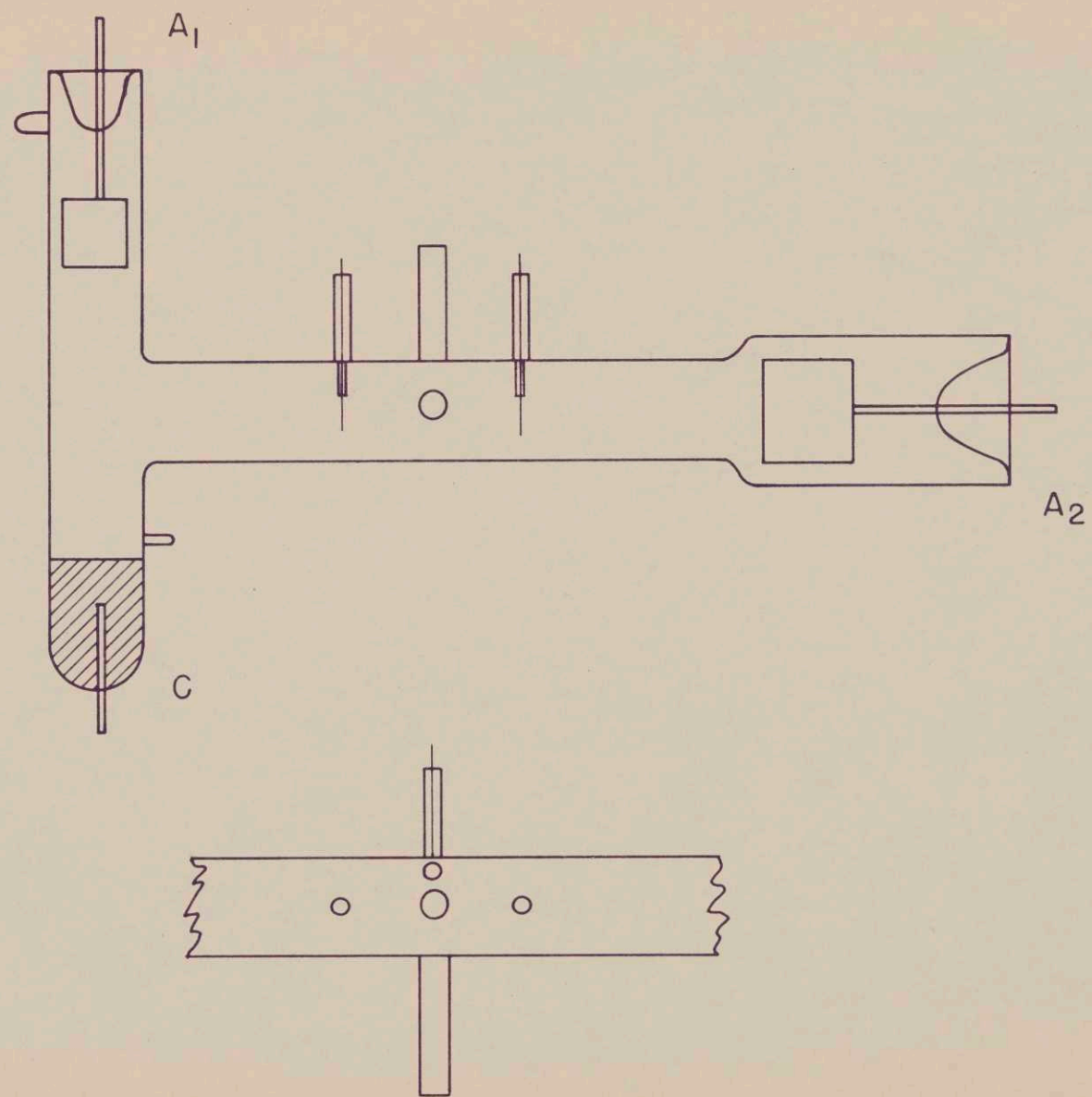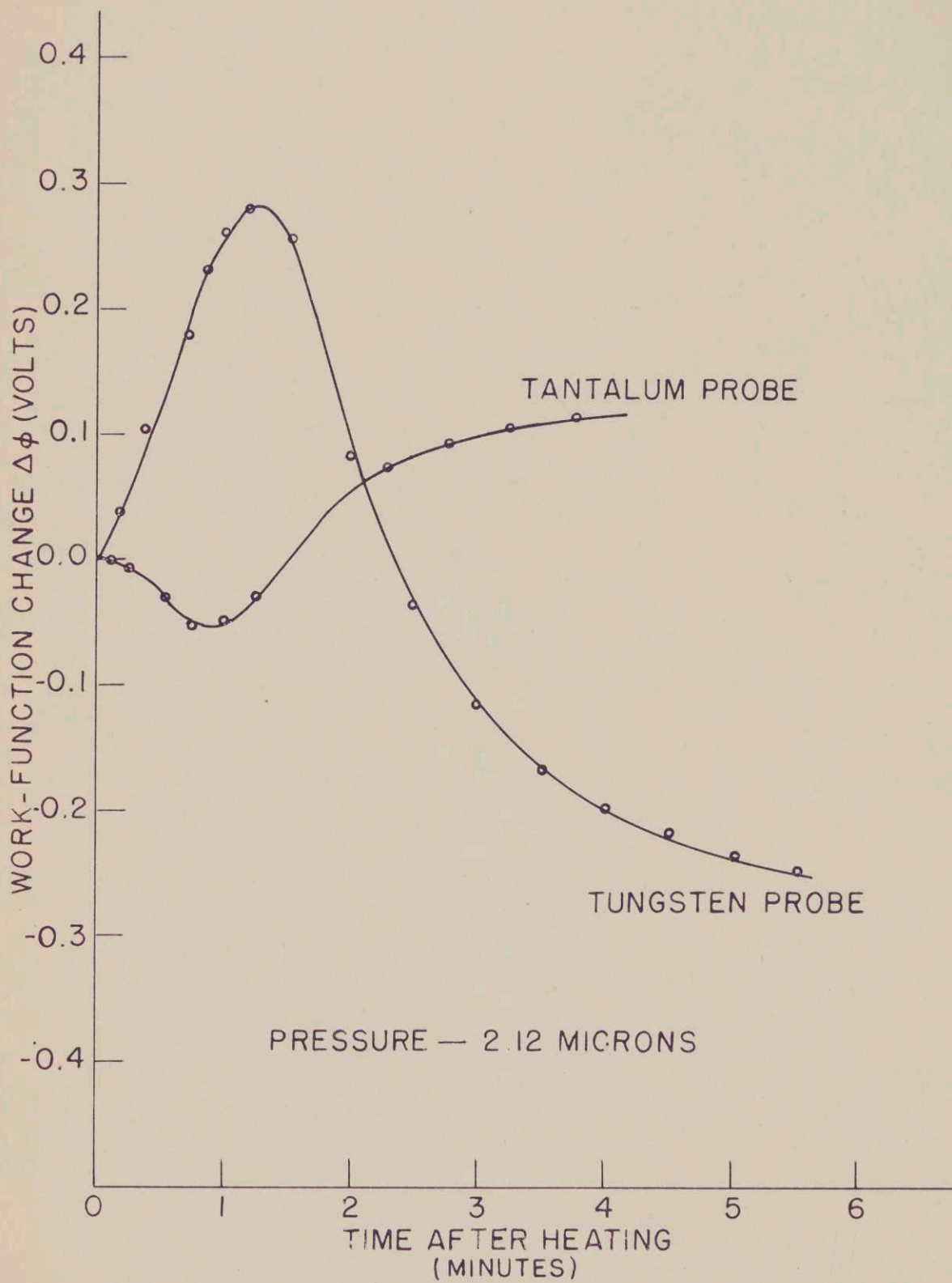Fig. 11   Computed excitation rate as given in Eq. 39 represented by dashed line. Observed ionization rate as a function of the corresponding V_T^{-1} (Aisenberg data).
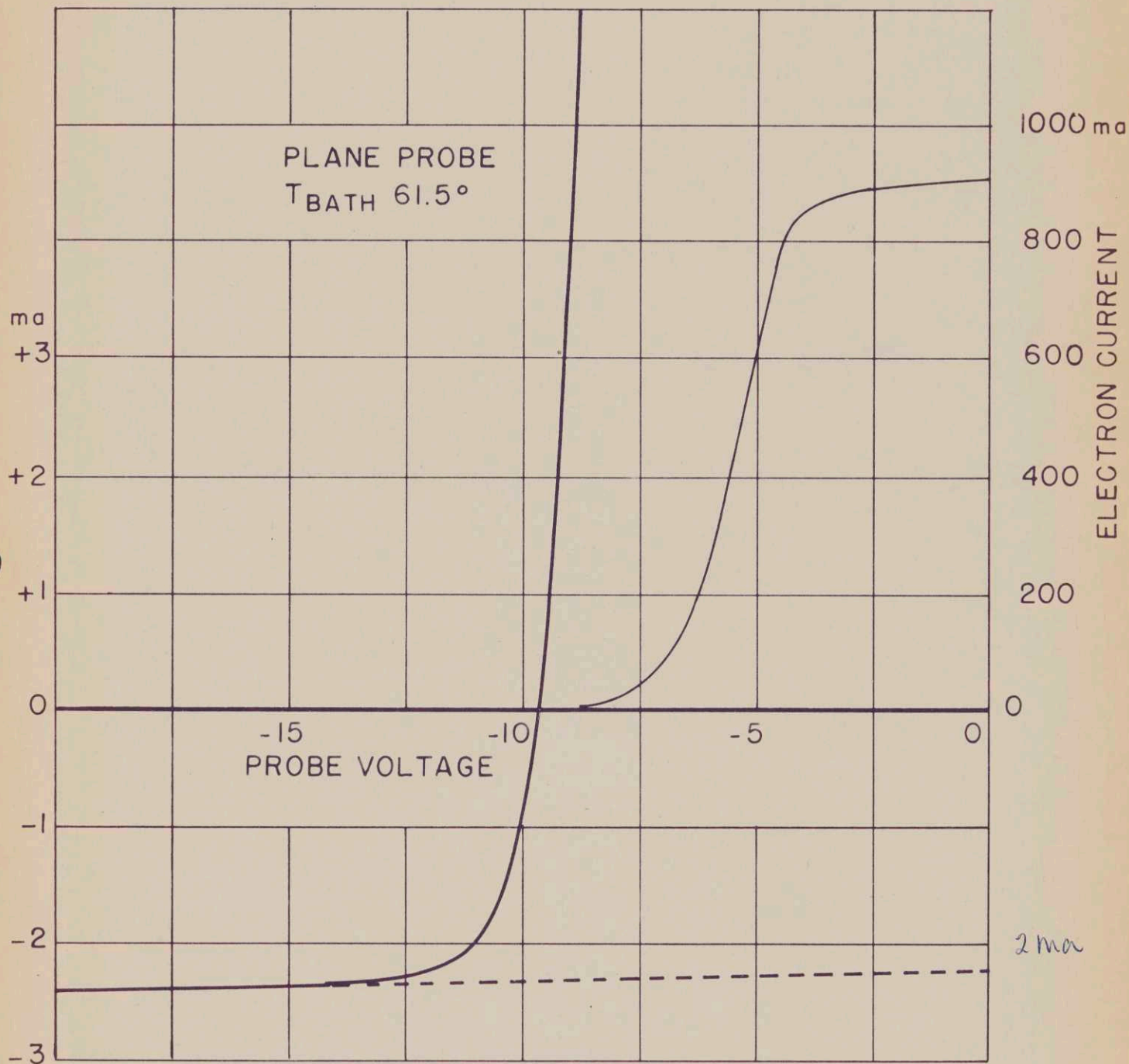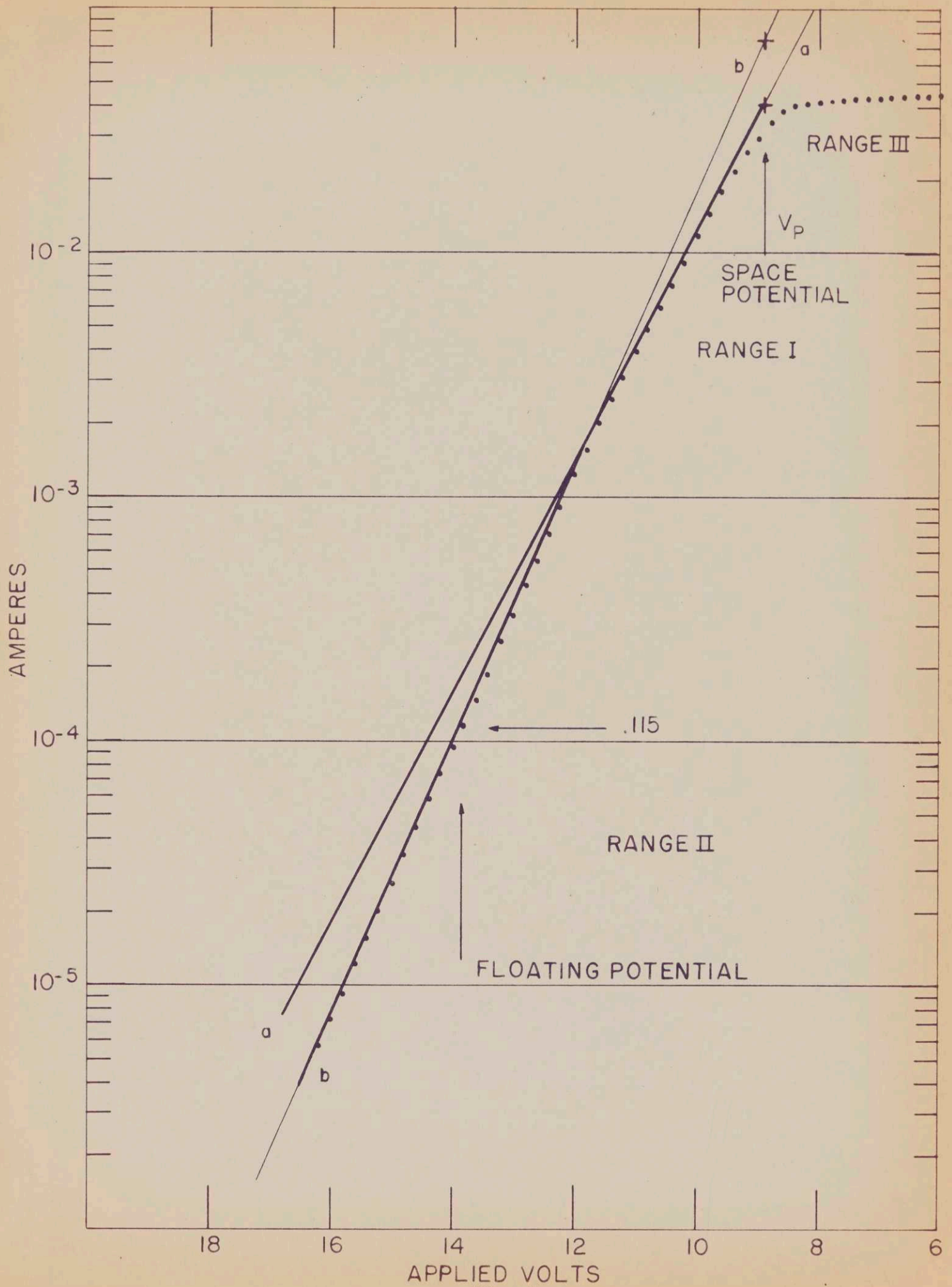
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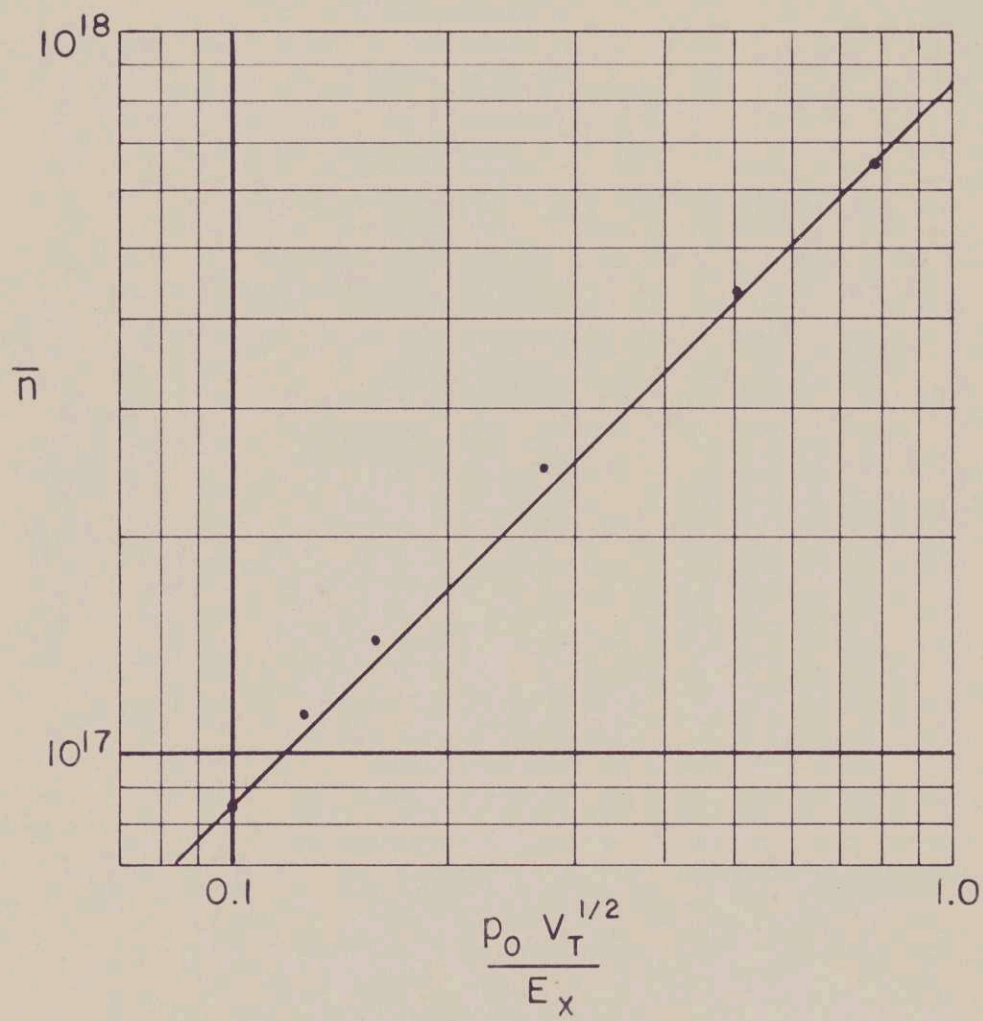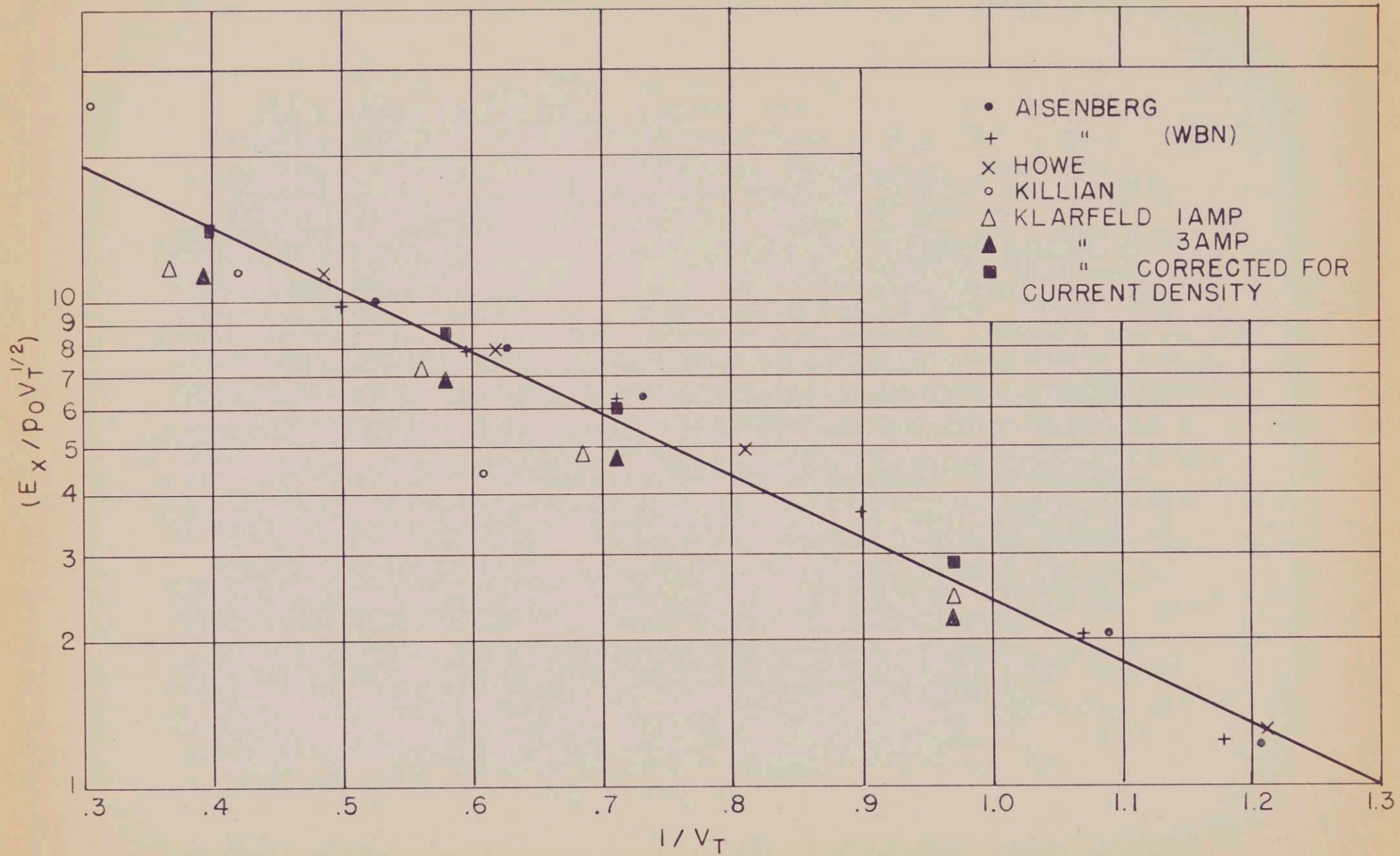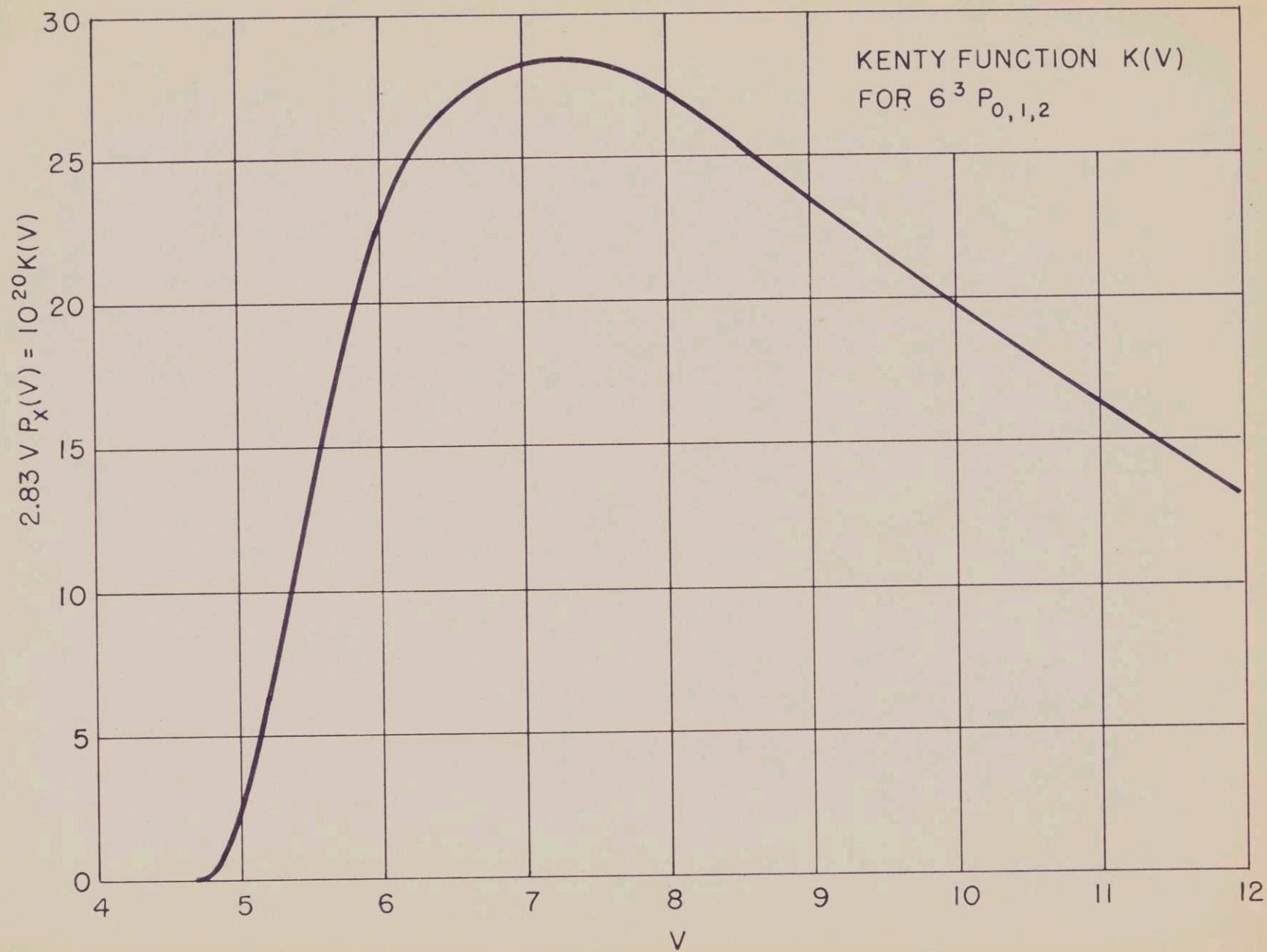
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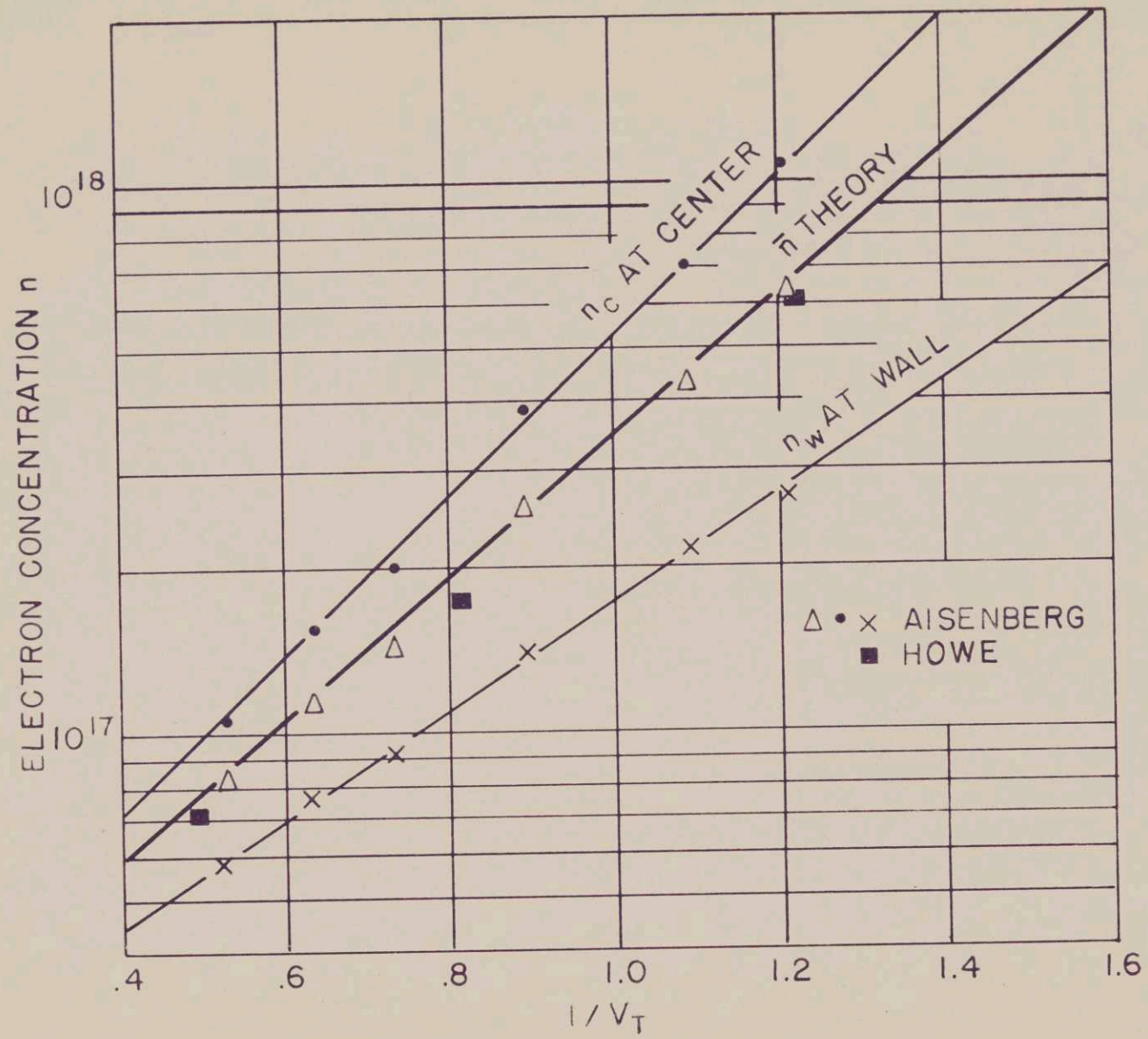
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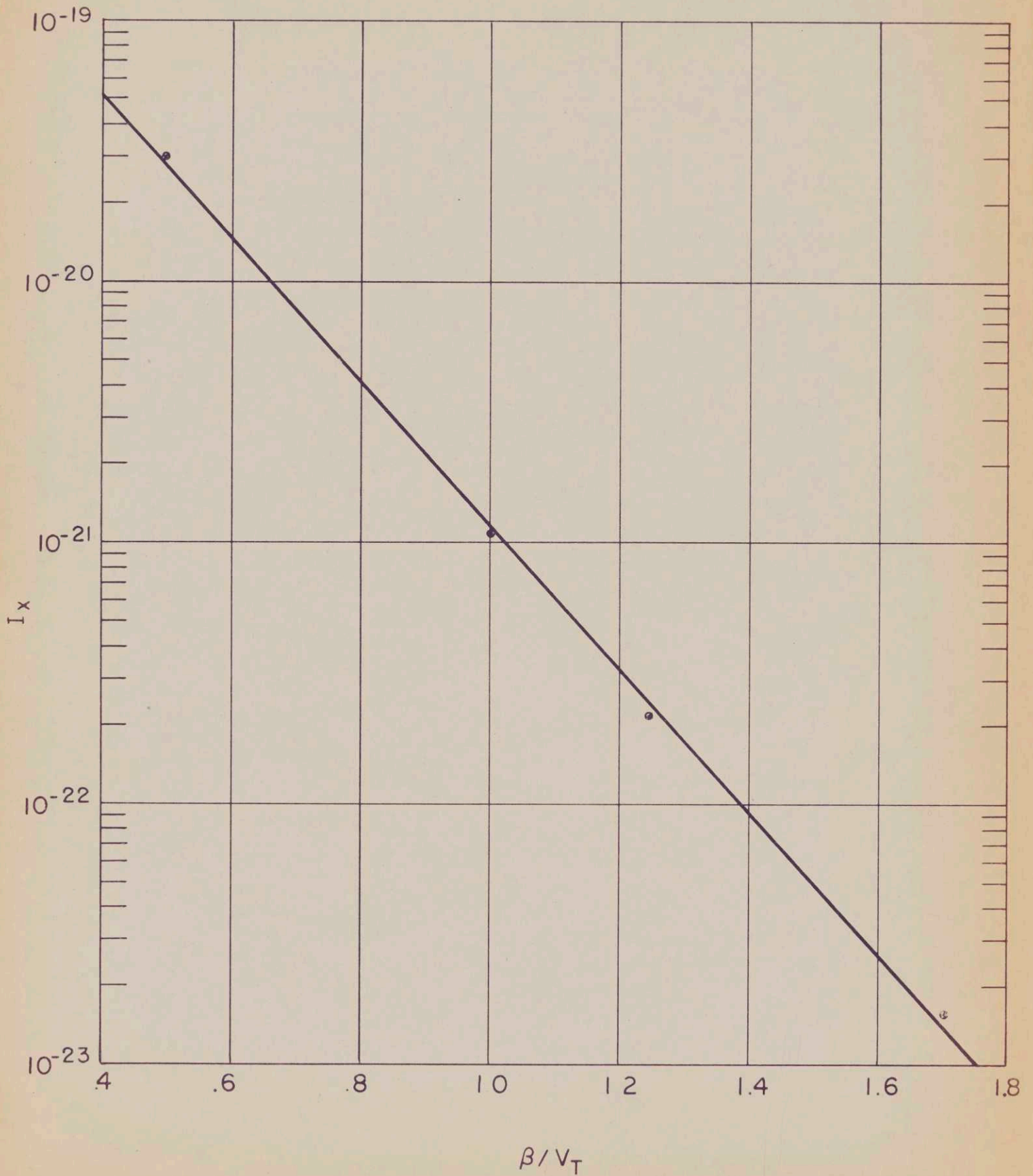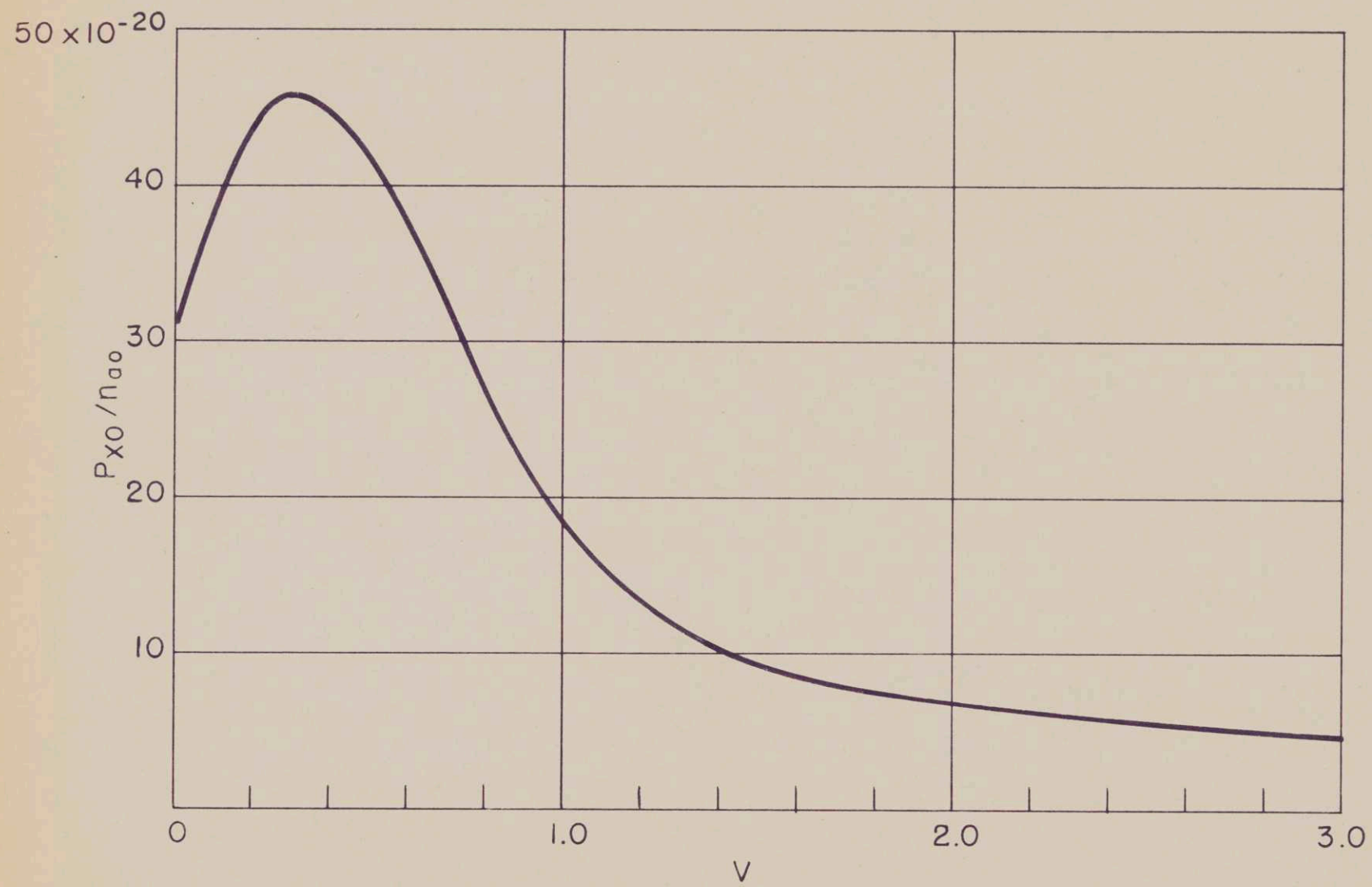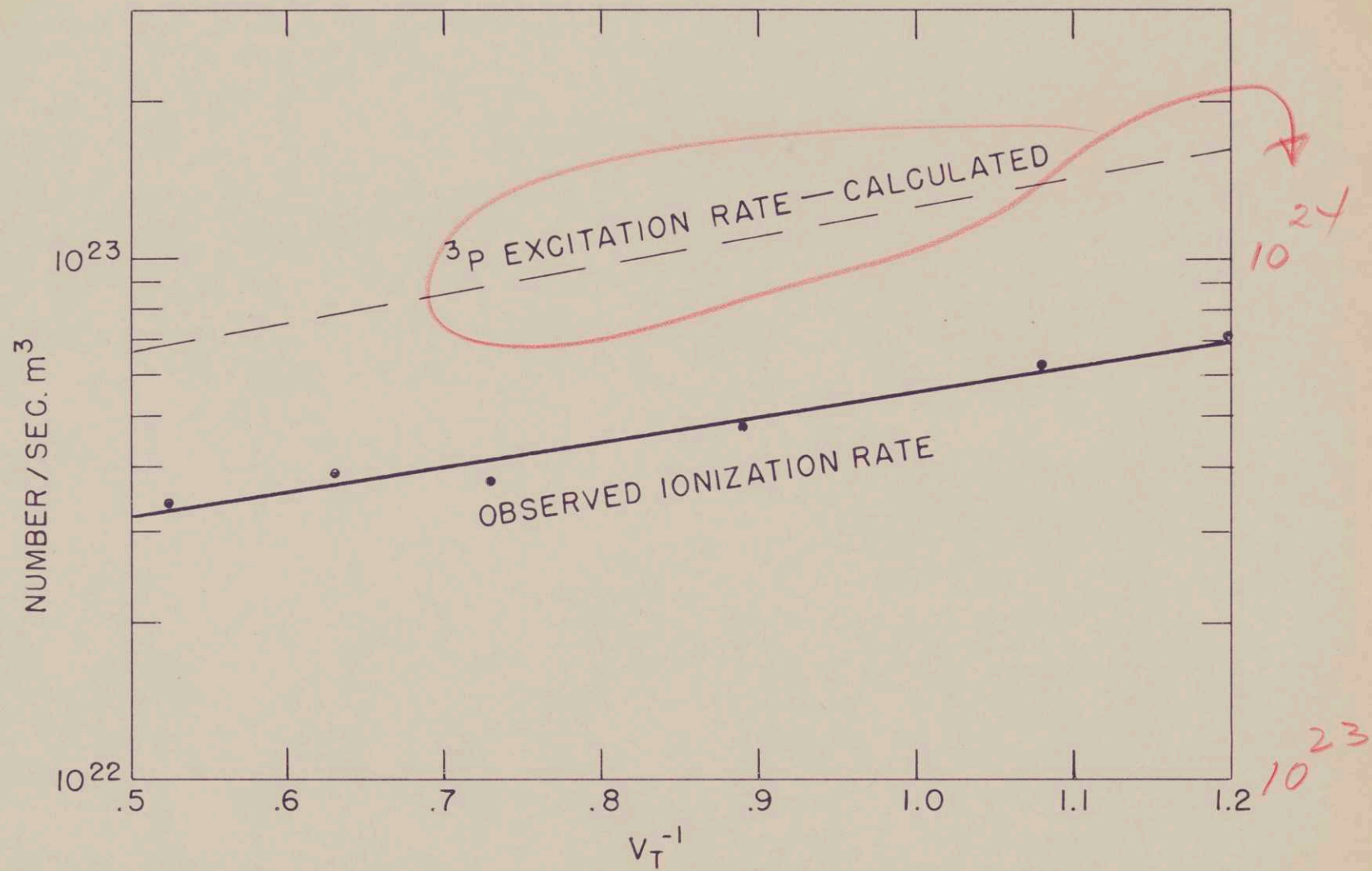
Fig. 8

Fig. 9.

Fig. 10.

Fig. 11.

Introduction

The electric arc in its many forms has long been the subject of scientific investigation, and yet, many of its basic features are poorly understood. The electron emission from the negative terminal of the arc is likely to remain a mystery for many years to come because of the complexity of the phenomena. Ever since the introduction by Langmuir of the concepts associated with probe measurements in the plasma of the low pressure arc, there has been the hope that the properties of the plasma would finally be understood in terms of basic concepts. Franck and Hertz[1] showed that electrons can be accelerated through an atmosphere of mercury vapor with practically no loss in energy until a critical value of approximately 5 electron volts has been exceeded after which losses occur. Even though the facts of atomic excitation by electrons have been known for well over fifty years, details concerning the efficiency of the process are lacking. The quantitative data on the efficiency of the ionization process by the direct impact of electrons on unexcited mercury obtained by Nottingham[2] may be used to establish the fact that little or no ionization by direct impact occurs within the plasma of a low pressure mercury arc. Since the only other likely mechanism for the generation of ions involves a cumulative process of some form, it becomes one of the objectives of any investigation of the electrical properties of the mercury arc plasma to understand quantitatively the main features of this more complex process.

Typical of the experiments which yield information are those of Killian[3], Klarfeld[4], Howe[5], and Aisenberg[6]. Not a single one of these studies has been designed to yield even the major electrical information required for a fairly complete analysis of plasma properties. Since the combination of the four studies referred to does supply much of the needed information, it will be the purpose of this paper to put together as concisely as possibly the necessary pieces of information required for a quantitative application of basic electronic properties of mercury to explain many of the electrical properties of the plasma in the low pressure discharge.

1. J. Franck and G. Hertz, Ver. D. Deut. Phys. Ges. 16, 10 (1914)
2. W. B. Nottingham, Phys. Rev. 55, 203 (1939)
3. T. J. Killian, Phys. Rev. 35, 1238 (1930)
4. B. Klarfeld, Tech. Phys. U.S.S.R. 5, 913 (1938)
5. R. M. Howe, J. Appl. Phys. 24, 881 (1953)
6. S. Aisenberg, PhD Thesis, Department of Physics, Massachusetts Institute of Technology, May 1957

Experimental Procedure

A typical tube structure for these studies is illustrated by Aisenberg's design shown in Fig. 1. Current is carried by the discharge from the mercury pool cathode to the anodes A_1 and A_2. The plasma in the side arm is maintained in a steady state by the power fed in through the electrical connection at A_2. The details of tube design and operation differ among the four experimenters listed but the general idea is that during a sequence of investigations of the plasma, the drift current in the A_2 branch and the wall temperature of the tube are maintained constant in order that steady state conditions of drift current density and gas pressure (more specifically atom concentration) become the directly controlled parameters. An auxiliary circuit arrangement permits the observer to measure the current flowing in any one of the probe circuits as a function of the applied potential adjusted to accurately determined values and referred to the anode. Since the potential difference thus established measures the displacement of the Fermi level in the probe relative to that of the anode circuit, a necessary condition for the current measurements to be quantitatively useful is that the work-functions of both the anode and the probe remain constant. Great care was exercised both by Howe and Aisenberg to heat the probe electrode by electron bombardment and make the measurements within a very few seconds of the termination of that heating period. Typical of the changes in contact potential with time are those shown in Fig. 2. A probe-current voltage characteristic is that shown by the curves of Fig. 3. If the curve is examined by starting at zero applied voltage, it shows that the current decreases rather slowly to about 4 volts, after which it falls very rapidly to zero at about 9 volts. In the low current range, the data are plotted on an expanded scale to demonstrate that in the range of negative potential of 15 volts and more, the ion current is nearly independent of the applied voltage. The dotted line of the figure represents the linear extrapolation of the ion current curve so that the difference between the rising observed curve and the extrapolation is the best measure of the electron current able to penetrate through the electron retarding field of approximately 5 or 6 electron volts. Langmuir not only taught this method of electrical measurement, but he showed that very simple empirical equations could be used to represent with very satisfactory accuracy the rise in the electron current. He neglected to give emphasis to many details of the observed characteristics

that form an important part of the present discussion. Data from Aisenberg's study are shown in Fig. 4 and serve to show the method by which an empirical equation clearly reminiscent of Maxwell-Boltzmann statistics serves to represent the data.

Range I from an applied voltage of 8.9 to 12 is represented by the following equation:

$$i_I = 0.042 \; e^{-\frac{V_a - 8.9}{0.957}} \quad \text{amp} \tag{1}$$

Range II is represented by the equation

$$i_{II} = 0.075 \; e^{-\frac{V_a - 8.9}{0.778}} \tag{2}$$

for V_a values 12 to 16.

In general terms, these equations may be written as follows:

$$i = \alpha i_o \; e^{-\frac{V\beta}{V_T}} \tag{3}$$

For Range I, α and β are each equal to one, but for Range II, in the example illustrated by Eqs. 1 and 2, α is 1.8 and β is 1.23. The reason for this choice of constants to represent the experimental data will become evident in the analysis to follow.

It has been conventional to recognize the close similarity between an energy distribution of electrons characterized by a straight line on a semi-log plot as a distribution identified by an "electron temperature." Such a temperature is computed by the following equation:

$$T_e = \frac{q}{k} \; V_T = 11,600 \; V_T \tag{4}$$

$$q = 1.6 \times 10^{-19} \quad \text{coulombs}$$

$$k = 1.38 \times 10^{-23} \quad \text{joule/degree}$$

The experiments of Howe[5] and others show that the electron energy

distribution as represented by these equations is practically independent of the orientation of the electron collecting surface which indicates that the velocity distribution is isotropic except for a very slight disturbance which is the superimposed drift velocity that accounts for the conduction current. Since Brode's[7] measurements of the collision cross-section for mercury atoms shows a strong tendency to follow the "inverse velocity" rule, the momentum gained by each electron on its average time of free flight is independent of the electron energy. This fact contributes to some extent to the maintenance of the random distribution observed. Under these conditions, the current density to a probe held at space potential may be converted into a good measure of the electron density in its immediate neighborhood. The equation used is the following:

$$n_e = \frac{1}{q}\left(\frac{i_o}{A_p}\right)\left(\frac{2\pi m}{q V_T}\right)^{1/2} = j_o \frac{3.61 \times 10^{13}}{V_T^{1/2}} \tag{5}$$

These experimental considerations may be summarized by the following statements:

(1) The main features of the electron energy distribution may be characterized by the two empirical constants which are given by Eq. 5 to represent the electron density n_e and the quantity V_T which is the voltage difference associated with a change in electron density by a factor of e. These constants apply specifically to the low energy range and are supplemented by two additional constants α and β to apply to the high energy range.

(2) A measured voltage V_p is identified as indicated in Fig. 4 and related to the space potential. Note that a second probe located somewhere else in the tube can under the same plasma conditions yield a second voltage, again related to the space potential in its neighborhood. The difference between these voltages will be the difference in the space potentials only in case the work-functions of each of the probes are exactly the same. Thus two probes, located a specified distance apart and similarly located with respect to the axis of the tube, serve to measure the potential gradient correctly only if the work-functions are identical. This experimental condition is difficult to attain even though the materials are nominally the same since work-functions of clean surfaces depend on crystallographic

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7. R. B. Brode, Proc. Roy. Soc. (London) A125, 134 (1929)

direction as shown by Hutson[8] and others[9]. This same point is very important in relation to any attempt to measure radial differences in potential.

(3) The electron current flowing to a probe as indicated in Fig. 4 at the floating potential is the most accurate measure of the ion current which flows to the probe at that potential. Since insulating walls that surround the plasma discharge receive no net current the ion generation within the plasma is best determined by this observation.

Deductions That Come From Probe Studies

The Average Electron Density

Schottky's[10] theory of ambipolar diffusion leads to the conclusion that the density variation with radius should follow a Bessel function. Since the experimental conditions often do not satisfy the detailed requirements associated with this theory, it is appropriate to gain the advantages in simplicity associated with the empirical equation put forward by Klarfeld[11] which also agrees with very satisfactory accuracy with the meager data available. This equation is the following:

$$n = n_c - (n_c - n_w)\left(\frac{r}{R}\right)^2 \tag{6}$$

In this equation n_c is the electron density on the axis of the cylindrical tube and n_w is the electron density in immediate neighborhood of the wall. Integration of this equation shows that the average electron density which is very useful for further analysis is equal to the average of the wall density and the on-axis density. This relation is

$$\bar{n} = \frac{n_c + n_w}{2} \tag{7}$$

Drift Current and Electron Mobility

The drift current density can be related to the average electron density and the measurable longitudinal field by the following equation:

$$\left(\frac{I}{A}\right) = \bar{M}_d \, \bar{n} \, q \, E_x \tag{8}$$

$\bar{n}$

8. A. R. Hutson, Phys. Rev. **98**, 889 (1955)

9. W. B. Nottingham, "Thermionic Emission", Handbuch der Physik, Vol. 21, 1956

10. W. Schottky, Physik. Z. **25**, 342, 635 (1924)

11. B. Klarfeld, Tech. Phys. U.S.S.R. **4**, 44 (1937)

This equation has relatively little meaning unless the drift mobility M_d can be expressed in terms of fundamental properties of electrons and mercury atoms. If P_c is the number of "energy-losing" collisions that an electron makes in travelling through a gas under specified standard conditions such as a temperature of 0^oC and a pressure of 1 micron, then the reciprocal of this number is the distance it should travel between such collisions. The average time between collisions is then the average time required to travel a unit distance multiplied by this distance between collisions. Let the average time to travel a unit distance be defined by the following equation which comes directly from a calculation based on the Maxwell-Boltzmann distribution function:

$$\tau_1 = \frac{1}{\pi} \left(\frac{2\pi m}{kT}\right)^{1/2} \cong \frac{1.9 \times 10^{-6}}{V_T^{1/2}} \tag{9}$$

If an average electron is accelerated in a field then the free time for acceleration is given by the product expressed by Eq. 10, and the mobility is given by Eq. 11 as follows:

$$\tau_c \cong \frac{\tau_1}{P_o P_c} \tag{10}$$

$$M_d \cong \frac{q}{2m} \times \frac{1.9 \times 10^{-6}}{P_o P_c V_T^{1/2}} \cong \frac{1.67 \times 10^5}{P_o P_c V_T^{1/2}} \tag{11}$$

This equation may be combined with Eq. 8 to yield the following relation:

$$\bar{n} \cong 3.75 \times 10^{13} P_c \left(\frac{I}{A}\right) \left(\frac{P_o}{E_x}\right) V_T^{1/2} \tag{12}$$

In this equation all quantities are known except P_c. It follows therefore that if the relation is valid, a plot of $\bar{n}$ as a function of $(p_o/E_x) V_T^{1/2}$ should yield a straight line of unit slope. If this occurs then the value of P_c can be determined.

This plot is presented in Fig. 5. It is evident from the figure that the points fall close to a straight line of the predicted slope and that the intercept is close to 8.5×10^{17}. With a current density of 2.08×10^3 a/m^2 the

value of P_c is 10.9. The physical interpretation to be placed on this number may be expressed in either of two ways, of which the first is that as the electron moves a total distance of 1 meter in an atmosphere of mercury at 1 micron, it will on the average make 10.9 energy-losing collisions. The second way of interpreting this number is that on the average an electron will travel 9.2 centimeters through a gas at 1 micron without experiencing an energy-losing collision.

Brode[7] has published results which relate a quantity similar to P_c to the electron energy. His results may be expressed in the same units as used here by the following empirical equation:

$$P_c = \frac{41.3}{V_c^{1/2}} - 6 \tag{13}$$

In this expression V_c is the electron energy expressed in volts and the range of application is for V_c greater than one volt. Between zero and one volt, the value of P_c seems to be constant at 35. If the value of P_c of 10.9 is used, the equation yields a value of V_c of 5.9 volts. If consideration is given to the character of the integrated energy losses associated with the excitation of the $6^3P_{0,1,2}$ levels in mercury, then this choice of the average energy loss could very well have been predicted.

Energy Gained Per Collision and Electron Temperature

It is to be expected that a close relation must exist between the effective electron temperature as expressed by V_T and energy parameter (E_x/p_o). Such a relation can be derived from very elementary considerations, which upon completion can be tested by a comparison between prediction and experiment. The first step is to write an equation for the average number of energy-losing collisions which take place per second. This equation comes directly from the combination of Eqs. 9 and 10 and is written as follows:

$$v_c = \frac{1}{\tau_c} = \frac{p_o P_c V_T^{1/2}}{1.9 \times 10^{-6}} \tag{14}$$

Assume that the average energy lost on each of these collisions is V_c and use the approximate value of 5.9 volts obtained by the use of Eq. 13. Assume that practically all the power put into a unit length of the gas discharge is lost by the electrons because $\bar{n}_c$ of the electrons make these energy-losing

collisions in each unit volume of the plasma. The power balance equation then may be written as follows:

$$\left(\frac{I}{A}\right) E_x = \frac{p_o P_c V_T^{1/2}}{1.9 \times 10^{-6}} \times 1.6 \times 10^{-19} \bar{n}_c V_c \tag{15}$$

This equation may be solved for $\bar{n}_c$ to give:

$$\bar{n}_c = \frac{1.19 \times 10^{13}}{P_c V_c} \left(\frac{I}{A}\right) \frac{E_x}{p_o V_T^{1/2}} \tag{16}$$

Divide this equation by Eq. 12 to obtain the following result:

$$\frac{\bar{n}_c}{\bar{n}} = \frac{0.325}{P_c^2 V_c V_T} \left(\frac{E_x}{p_o}\right)^2 \tag{17}$$

If we make use of the Boltzman equation by letting the ratio of densities be exp $- (V_c/V_T)$ then Eq. 17 may be solved for (E_x/p_o) as follows:

$$\left(\frac{E_x}{p_o}\right) = 1.75 \, P_c \, V_c^{1/2} \, V_T^{1/2} \, e^{-\frac{V_c}{2V_T}} \tag{18}$$

The introduction of the previously determined values for P_c and V_c gives the equation in its final form:

$$\left(\frac{E_x}{p_o}\right) = 46.3 \, V_T^{1/2} \, e^{-\frac{2.95}{V_T}} \tag{19}$$

Many measurements have been made from which we may assemble data to test the validity of this equation. The easiest method of doing it involves a plot of the observable quantities as defined by the following equation:

$$\ln \left(\frac{E_x}{p_o}\right) V_T^{-1/2} = \ln 46.3 - \frac{2.95}{V_T} \tag{20}$$

The experimental data are assembled on Fig. 6 and the straight line corresponding to the above equation is drawn on this graph. Considering the simplifications that were introduced in the derivation of this equation, the agreement with the experimental data is remarkably good.

9.

Average Electron Density Related to Electron Temperature

Inspection of Eqs. 12 and 19 shows that a relation should exist between the average electron density and the electron temperature. The following equation gives this relation:

$$\bar{n} = 1.84 \times 10^{16} \, e^{\frac{2.95}{V_T}} \tag{21}$$

In Fig. 7 experimentally determined average densities as found by Howe and Aisenberg are plotted as a function of V_T^{-1} and the straight line drawn is that corresponding to Eq. 21. Recorded on this same diagram are Aisenberg's measurements of electron density at the center of the discharge and also at the wall. Empirical equations to represent these data are the following:

$$n_c = 1.93 \times 10^{16} \, e^{\frac{3.3}{V_T}} \tag{22}$$

$$n_w = 1.75 \times 10^{16} \, e^{\frac{2.3}{V_T}} \tag{23}$$

If the ratio of these two equations is taken and then related to the Boltzmann factor, the effective potential difference from the axis to the wall is given by Eq. 24

$$V_{cw} = 1 + 0.095 \, V_T \tag{24}$$

The important point to note is that in terms of the electron density ratio, this potential difference is nearly independent of the pressure and of the actual radial concentration of electrons, since for the range of V_T from 0.8 to 2.0 the change in potential difference is only 11 per cent. Although the potential difference observed by Howe and also by Killian was slightly greater than the 1.1 volt value given on the basis of Aisenberg's data, there was no guarantee that the work-functions of the probes at these two locations were sufficiently identical to justify the evaluation of the potential difference as being accurately given by the apparent one measured as described above.

Generation Rate for Metastables and Their Equilibrium Density

The method used for the calculation of the generation rate of metastables depends on the application of the basic formula written out in detail as follows:

$$\left[\frac{dn_x}{dt}\right]_V dV = \left[n_a n_e\right] \ \left[af(V) \, dV\right] \ \left[\frac{2V\beta}{m}\right]^{1/2} \left[\frac{P_x(V)}{n_{ao}}\right] \tag{25}$$

On the left is the rate of production per unit volume for a unit range in electron energy (V) multiplied by a small element in range dV. The expression on the right is made up of four factors as shown which are: (1) the product of the concentrations of atoms and electrons; (2) the fraction of electrons with energy between V and (V + dV); (3) the speed with which an electron of a given energy passes through the gas; and finally, (4) the excitation cross-section given in terms of the number of excitation collisions which occur for electrons of the specified energy in a total distance of travel of 1 meter in a gas of arbitrarily chosen standard density (n_{ao}) associated with a pressure of 1 micron at 0^oC. The total rate of excitation is computed by integrating this expression over the entire range of electron energy from zero to infinity. On the basis of the empirical equation, Eq. 3, it is assumed that over a limited range in energy the fractional distribution can be expressed in terms that are strictly appropriate only for a true Maxwellian distribution. By the use of this concept the following equation applies:

$$af(V) \, dV = \frac{2a\beta^{3/2}}{\sqrt{\pi} \, V_T^{3/2}} \ V^{1/2} \, e^{-\frac{\beta V}{V_T}} \, dV \tag{26}$$

The introduction of the quantity a into this grouping of factors in Eq. 25 is arbitrary since it represents the empirically determined increase in the coefficient associated with the high energy group of electrons represented graphically in Fig. 4 by the line bb. With these limitations in mind, both a and β will be selected to have appropriate values associated with the important range in V which in any particular case contributes most to the value of the integral to be determined.

The quantity $P_x(V)$ is most difficult to express analytically. Klarfeld[12] has suggested the use of empirical equations and carried through the integrations based on his proposals. His method has not been used in this study because graphical integration at three or four values of (V_T/β) has been found to yield empirical equations for the integral that follow closely the exponential form:

$$I_x = \int_{V=0}^{V=\infty} \frac{P_x(V) \cdot V \; e^{-\frac{\beta V}{V_T}} \; dV}{3.54 \times 10^{19}} = a_x \; e^{\frac{b_x}{V_T}} \qquad (27)$$

Although this method of computation and the preparation of the data for further use is clearly an approximate one, the very great uncertainty in the detailed validity of the fractional energy distribution function used, and the still greater uncertainty in the correct values of the $P_x(V)$ function make this method of analysis at least as good as the functions that one, of necessity, must use to make the calculation. The final result, of each such calculation, is to determine an appropriate value for a_x and b_x applicable to each case.

This method will be applied first to the excitation of the $6^3P_{0,1,2}$ levels in mercury. Kenty[13] has analyzed this problem in all the detail that the limited experimental observations available warrant. This set of levels in the mercury atom are the most important because of their metastable character including the trapping of the resonance radiation associated with the $^3P_1$ level. Kenty's function symbolized by the following equation is shown graphically in Fig. 8.

$$K_x(V) = \frac{V \, P_x(V)}{3.54 \times 10^{19}} \qquad (28)$$

The numerical factor introduced into Eqs. 27 and 28 represents the number of atoms per cubic meter in an ideal gas at $0^\circ C$ and 1 micron pressure. This factor is introduced here in anticipation of its use in calculating the atom concentration in terms of the pressure by the following relation:

$$n_a = 3.54 \times 10^{19} \, p_o \qquad (29)$$

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12. B. Klarfeld, Jour. Phys. U.S.S.R. 5, 173 (1941)
13. C. Kenty, J. Appl. Phys. 21, 1309 (1950)

The integration has been carried out graphically at four values of V_T and the results are plotted as points on Fig. 9. The straight line on this figure is represented by the following equation:

$$I_x = 6.6 \times 10^{-19} \, e^{-\frac{6.35\beta}{V_T}} \tag{30}$$

The integrated form of Eq. 25 may be rewritten with the help of Eqs. 27 and 29 to be ready for the direct calculation of the excitation rate by the following equation:

$$\frac{dn_x}{dt} = 2.37 \times 10^{25} \frac{\alpha\beta^{3/2} P_o n_e}{V_T^{3/2}} a_x \, e^{\frac{b_x\beta}{V_T}} \tag{31}$$

After use is made of the graphical evaluation of the integral I_x the equation takes the form of:

$$\frac{dn_x}{dt} = 1.56 \times 10^7 \frac{\alpha\beta^{3/2} P_o n_e}{V_T^{3/2}} \, e^{-\frac{6.35\beta}{V_T}} \tag{32}$$

A restriction must be mentioned which could limit the applicability of this equation without further modification which is that the equilibrium density of excited atoms must be a small fraction of the total number of atoms excited. It is therefore necessary to carry through the next step in the calculation and attempt to evaluate the rate of removal of excited atoms which must be equal to the rate of generation for a steady state population to exist.

One important removal process is the de-excitation of the metastable states by collisions between excited atoms and low velocity electrons. The cross-section for this process of removal by collisions of the second kind should be large for very slow electrons and fall off at least as rapidly as the inverse velocity line as a very rough approximation. Practically no quantitative data are available to estimate the cross-section and therefore the guess made by Kenty[13] will be used as the basis for the function shown in Fig. 10. If this function is treated by the method associated with Eq. 27, the numerical integration yields the following approximate results:

$$I_{xo} = 4.3 \times 10^{-19} \, e^{-\frac{1.04}{V_T}} \tag{33}$$

If the assumption is made that the loss of excited atoms by either the radiation process or the diffusion of these atoms to the surrounding wall is quite small in comparison with the de-excitation that results from collisions of the second kind, then this de-excitation rate can be expressed by the following equation:

$$\frac{dn_{xo}}{dt} = 1.02 \times 10^{7} \, \frac{f_x p_o n_e}{V_T^{3/2}} \, e^{-\frac{1.04}{V_T}} \tag{34}$$

The second important removal process is the one that ultimately yields practically all of the ionization necessary to satisfy the space-charge conditions that the plasma is a region of zero space-charge through which the electrons drift with a constant average velocity to provide the principal mechanism for the conduction of the arc. An ~~The~~ ionization process pictured here is that approximately one-half of all of the atoms excited into the ^3P levels become attached very quickly to neutral mercury atoms to form semi-metastable mercury molecules in a highly excited electronic state. It is further presumed that these molecules hold their excitation in that they are not easily de-excited by collisions of the second kind but serve as an effective step toward the production of ionization in that there are a sufficient number of electrons in the energy group above approximately 4 electron volts to ionize practically every one of these excited mercury molecules. The rate of metastable de-excitation provided by this process will be shown to account for almost exactly 50 per cent of the metastable production. Therefore, in calculating the population of metastables, the de-excitation rate associated with the collisions of the second kind will be set equal to one-half of the excitation rate and the fraction of atoms f_x taking part in this process can be determined to be the following:

$$f_x = 0.75 \, \alpha\beta^{3/2} \, e^{-\frac{6.35\beta - 1.04}{V_T}} \tag{35}$$

At the highest pressure used in the experiments being reported here, α is approximately 2.5, β approximately 1.2, and V_T is approximately 0.8.

The insertion of these numbers into Eq. 35 yields the result that f_x is 7×10^{-4} and therefore the assumptions upon which the calculation was based are satisfied. This is not so true for the very lowest pressure for which the value of f_x is probably close to 0.1. This means that in calculating the actual density of excited atoms, the density will be too great in the low pressure region and some means should be introduced to correct for this fact. Attention may be directed to a result which was to be anticipated from Kenty's analysis of a very similar problem and that is that the equilibrium density of excited atoms is independent of the local electron density and therefore the distribution of metastables should be nearly uniform except in the immediate neighborhood of the walls of the tube. At the walls, it is never justified to assume that the only mechanism for metastable removal is electronic. Annihilation at the wall by diffusion to it will create a depletion region that destroys the uniformity. The lower the pressure, the larger the depletion region will be. This action serves to decrease the fraction of atoms in the excited state under the lowest pressure conditions.

The Ionization Process and Its Generation Rate

The probe method of exploring the processes of ion generation in the plasma is ideally suited to the purpose. The "floating potential" of a probe may be determined with high accuracy and recognized to be that applied potential for which the net current to the probe is exactly zero. In principle, secondary effects can occur at the probe. These include the photoelectric emission of electrons, the emission of electrons generated by the de-excitation of metastables, and the emission of electrons under the influence of ion bombardment. All of these processes should be expected to be sensitive to surface contamination, and since the current measured with the probe one or two volts negative with respect to the floating potential shows no measurable ~~sign of~~ variation while at the same time contact potential measurements do indicate that the surface condition is changing, it is taken as an experimental indication that the above mentioned secondary effects are negligible. On this basis, the zero net current at the floating potential is taken to be a perfect balance between the arrival of ions and electrons. Since the electron arrival at this potential can be determined with accuracy, the ion current density at an insulated wall is thus measured.

The next assumption applicable to the low pressure arc is that ion neutralization occurs only at the wall and that recombination within the volume of the discharge can be neglected. It follows then that the rate of ion generation can be directly related to measurable quantities by the following equation

$$\frac{dn_i}{dt} = \frac{2}{qR}\left(\frac{i_+}{A_p}\right) \tag{36}$$

The observed ion current density at the floating potential is (i_+/A_p) and the discharge tube radius is R. The best method for making comparisons over the entire range of observation included in these studies is to relate the quantities to a single variable. The one chosen is V_T^{-1} and empirical equations are used to express the relations. Aisenberg's observations of ion generation rate as computed by Eq. 36 are plotted as points in Fig. 11 and the empirical equation taken as a suitable representation of the data is given as follows:

$$\frac{dn_i}{dt} = 1.88 \times 10^{22} \ e^{\frac{1.08}{V_T}} \tag{37}$$

The computed excitation rate was first expressed above as Eq. 32 which involved the variables p_0, n_e, and $V_T^{3/2}$ in the coefficient. Since for the present purposes we wish to determine the average rate of metastable production, we use the electron concentration $\bar{n}$ and its dependence on V_T^{-1} as given in Eq. 21. Use is made of Aisenberg's observed data for V_T^{-1} and its relation to the pressure p_0 to deduce the following relation:

$$\frac{p_0}{V_T^{3/2}} = 3.8 \times 10^{-2} \ e^{\frac{5.8}{V_T}} \tag{38}$$

For the present purposes, the previously selected values of α and β namely, 2.5 and 1.2, will be used as representative of the data over the entire range of V_T although a more detailed analysis will show that these quantities are not strictly constant. The combination, therefore, of these constnats, with Eqs. 21, 32, and 38, provide the required final result expressed as follows:

$$\frac{dn_x}{dt} = 3.6 \times 10^{22} \; e^{\frac{1.25}{V_T}} \qquad (39)$$

The dashed line on Fig. 11 represents this equation.

An instructive way of making the comparison between Eqs. 37 and 39 is to define a quantity f_{x+} which is the fractional comparison between the rate of production of metastables and the rate of production of ions expressed explicitly as follows :

$$f_{x+} = \frac{(\frac{dn_+}{dt})}{(\frac{dn_x}{dt})} = 0.53 \; e^{-\frac{0.17}{V_T}} \qquad (40)$$

This equation yields the result that over the range of values of V_T from 0.8 to 2.0 the value of this fraction changes from 0.46 to 0.49 and serves as the justification of the statement previously made that approximately half of the metastable production in the plasma of the low pressure arc is converted to ions. It is assumed that the other half of the metastable production is lost to the discharge mainly by the process of collisions of the second kind with very slow electrons.

Evidence for a Deficiency of Very Slow Electrons in the Electron Energy Distribution

Identified on Fig. 4 are the three ranges of interest in probe measurements. Needless to say, all three of these ranges are always found in the low pressure mercury arc. Range I includes the dominating group which serves to establish the most suitable value of the parameter V_T used in this analysis. Range II is the high energy group which in comparison with an extrapolation from Range I indicates the region of depletion in the population of high energy electrons compared with the number that would have existed in a true Maxwellian distribution. Range III is the rather anomalous distribution always observed very close to space potential.

Variability of work-function locally over the surface of a particular probe could account for this apparent deficiency of low energy electrons because of the ambiguity which would follow with regard to the true nature of zero field in the immediate neighborhood of the probe. A second cause for this apparent deficiency could be electron reflection. This cause may also be discounted because it is not likely that reflection could account for much of the observed deficiency. A third alternative would be that collisions

of the second kind with the excited mercury atoms are most prevalent
for the electrons of low energy. It is therefore suggested that at least
part of this deficiency in Range III should be attributed to the removal of
electrons from the low energy group as they absorb the energy from the
metastables and return to the high energy range. Details have not been
worked out.

Summary

It has been the purpose of this article to show some new methods for
the analysis of Langmuir probe data. Not only have the methods been
explained but the results illustrated by relating the equations to the best
experimental data available at present. These analyses do not exhaust
by any means the wealth of information found particularly in the experi-
mental studies of Howe and Aisenberg. It is hoped that further reports
can be made in the near future. The theories outlined here have had to be
tested by information pieced together from a combination of sources. A
more critical investigation with improved experimental techniques may
warrant the application of more advanced methods of analysis than the
simple ones presented. Probably the most radical feature brought out by
these studies is the extraordinary efficiency of the process by which
excited atoms of mercury are converted into positive ions. It is proposed
here that this high efficiency results from the formation of an excited
mercury molecule which is then ionized and dissociated. An alternate
explanation might involve a "metastable -
metastable" reaction to yield a
neutral and an ion.

SERVICE SPONSORED TRIP TO EUROPE

Period Covered: 30 May 1957 to 16 September 1957

Professor Wayne B. Nottingham

Research Laboratory of Electronics and the Department of Physics

Massachusetts Institute of Technology

Cambridge 39, Massachusetts,   U.S.A.

$$\omega = \int d\omega = 2 \int_{\theta=0}^{\theta=\pi} 2r dx \frac{\sin\frac{\theta}{2} \, d\theta}{2r\left[\left(\frac{\Delta L}{2r}\right)^2 + \sin^2\frac{\theta}{2}\right\}^{3/2}}$$

value at $\theta = 0$ is 0

  " " $\theta = \pi$ $\dfrac{1}{\left\{\left(\frac{\Delta L}{2r}\right)^2 + 1\right\}^{3/2}}$

ONR SPONSORED TRIP TO EUROPE

Professor Wayne B. Nottingham

Period Covered: 30 May 1957 to 16 September 1957

Purpose of Visit

The two purposes of the visit were: (a) to attend the Third International Conference on Ionization Phenomena in Gases in Venice, Italy, June 11-15 and present a paper there on "The Properties of the Plasma Determined by Langmuir Probe Measurements in Low Pressure Mercury Arcs" and (b) the visiting of research institutes and commercial establishments interested in the general field of physical electronics both with respect to theory and practical applications.

Principal Activities Visited

1. Department of the Navy Headquarters in Frankfurt, Germany Commander Doyle and Dr. Schuetty.

2. Third International Conference on Ionization Phenomena in Gases, Venice, Italy. A complete report on this Conference is being prepared by Dr. Ugo Facchini, Laboratori C.I.S E., Via Procaccini 1, Milano, Italy.

3. Siemen Halske in Munich. Principal sponsor there was Dr. W. Kleen.

4. Rohrenlaboratorium der Telefunken B.m.b.H. Ulm (Donau) Germany Principal contact, Dr. Brück.

5. Siemens Schuckertwerke Ag. Erlangen, Germany. Principal contacts: Dr. Trendelenburg, Dr. Finkelnburg, and Dr. Spenke

6. N. V. Philips Gloeilampenfabrieken, Eindhoven, Holland. Principal contact Dr. H. B. G. Casimir

7. Technical High School of Royal Institute of Technology, Stockholm, Sweden. Principal contact, Dr. Dattner.

8. Ambassador R. Sohlman (Swedish Ambassador to Moscow) Stockholm.

9. Upsala University, Principal contacts: Professor T. Ohlin, Professor Noringer and Professor Müller-Hildebrand.

10. Visit to Allmanna Svenska Elektriska Aktiebolaget (ASEA) at Ludvika, Sweden. Principal contact: Dr. Lars Olof Tiderman

11. Philips Laboratory again with Dr. Casimir
12. Fritz-Haber Institute of the Max Planck Gesellschaft, Berlin-Dahlem
    Principal contact, Dr. E. Ruska and also Dr. M. Drechsler
13. Telefunken Tube Laboratory, Berlin. Principal contact Dr. Wiegand
14. Allgemeine Elektrizitats Gesellschaft (AEG) Principal contacts:
    Dr. Meyer and Dr. Rohde

GENERAL REMARKS CONCERNING THIS REPORT

Previous experience in this field of study taught me the impossibility
of realizing the maximum benefit of such a trip without the preparation of a
complete report of activities for my own use. An interest in this complete
report was expressed to me both at the Frankfurt and the Berlin Headquarters
of the U. S. Navy. I realize the fact that such a detailed report is not
required under the instructions by the Department of the Navy through the
Office of Naval Research.

The above listing of activities visited will serve as a Table of Contents
to the attached complete report. It is to be expected that many of the readers
of this abridged report, which serves as an introduction to the complete one,
will not be interested in the technical detail. Some readers however, I know
desire this information, and it is therefore being made available in this
form. Opinions expressed there should be clearly understood to be my own
and the material made available in this form should not in any way be used
to the disadvantage of any company or any individual mentioned in the report.

I wish to acknowledge as strongly as I can my indebtedness to the
various governmental agencies and in particular to the representatives of
the Department of the Navy who cooperated so splendidly to make this trip
a worthwhile activity. Every contact including especially the MATS operation
between Washington and Frankfurt and return was completely satisfactory.

If any additional information is desired by readers of this report, I
shall be only too glad to furnish it if I have it available.

Signed: *Wayne B. Nottingham*

Wayne B. Nottingham
Professor of Physics
M. I. T.
Cambridge
Massachusetts

COMPLETE TECHNICAL TRIP RECORD - June 24 to Sept. 13, 1957

VISIT TO SIEMENS- HALSKE, MUNICH

Coating Resistance

I arrived here Monday morning. The first two days of discussion related specifically to thermionic emission studies from oxide cathodes. The work is done largely under the direction of Dr. W. A. VEITH. He has a special structure for measuring both bulk resistance and interface resistance for various cathode materials. The symmetry is cylindrical. The first anode has slots cut in it which are very narrow. Behind these slots is a collecting box which also has slots but in this case the slots are slightly larger than the first set. The cathode diameter is 1.14 mm; the first anode is 7 mm; the first set of slots are 0.2 mm in width and approximately 4 or 5 mm in length. The second set of slots are 0.7 mm. The electron collector is nickel; the anode is moly; the final collector is worked in the retarding potential region to the first anode and is pulsed with arbitrary lengths of pulse from 2 microseconds to 200. The time space between pulses can be varied. The entire range of voltage-current characteristics of the collector is taken and is reproduced in one fiftieth of a second, approximately. The presentation is on a scope. As the current from the cathode is varied, the current observed at the collector as a function of voltage shifts and the shift is taken to be a direct measure of the coating resistance. Some details of this method were given at the Electronics Conference this year by Dr. KLEEN.

Special Coating With Calcium Carbonate

Dr. W. A. VEITH has been experimenting with an unusual cathode structure which involves the spraying of a barium-strontium carbonate followed by a layer of calcium carbonate. The general idea is that the barium supplies the impurity centers to the calcium and in this way he obtains a cathode which has excellent emission and presumably less evaporation. This cathode structure is new and many of the details have not been worked out.

Space-Charge Equations

It is the opinion of most of the staff that the space-charge equations are not valid as they apply to practice. I have two memoranda recently prepared by Drs. HEYMANN and WOLFRAM. It was the purpose of these memoranda to show

that the space-charge equations predict a better performance on the tubes than are actually measured. I have not read these memoranda yet but it seemed as though there must be some error in the analysis. We made observations on a special very close spaced diode. These data were then analyzed according to my methods and showed very satisfactory results in that the predicted curve was in good agreement with the experiment except in the immediate neighborhood of that space-charge condition which produces zero field at the collector. It seems as though here there is a considerable reflection of electrons which may be of a fundamental character, or it may be the result of collector inhomogeneity. Further studies may reveal the answer.

Harmonic Output Measured

Another study is being made in practical tubes in which a direct measure is being made of the fundamental, the second harmonic and the third harmonic in the triodes or their equivalent. My idealized theory which yields the square law tube equation indicates that the amplitude of the first harmonic is largely a direct measure of the transconductance, while the amplitude of the second harmonic in my equation should be a constant, independent of the current that is flowing. In some of the more symmetrical tubes, it turns out that this is a very good representation of the facts as long as the space-charge minimum lies between the emitter and the modulating grid. If the current is reduced, the space-charge minimum moves over and the second harmonic output falls. Since there is a particular voltage in general for which the second harmonic reaches its maximum, the third harmonic of course is zero under this condition. They were very much interested in my tube equation because it represents their results better than anything they had used in the past.

Dispenser Cathodes

Spent some time talking about dispenser cathodes. As a result of my remarks that the best way to study dispenser cathodes was to use them as receivers, my attention was called to a paper from this laboratory by Dr. H. BENDA This paper was published in a magazine called Frequenz, Vol. 7, issue 8, 1953. His analysis is very much like mine but he does not complete the usefulness of the method by studying the receiver under the conditions of space-charge limitation from the emitter.

The techniques for making the dispenser cathodes (called here metal capillary cathodes) have improved so much that they are considering many new

applications for them. Their method of construction involves the introduction
of a considerable amount of barium oxide, not the carbonate, pressed in behind
the first porous disc of tungsten which is held in position mechanically and then
on top of this is the second one which is actually the emitter and this disc in its
final assembly is welded into position. Various types of surfaces have been
produced including plain surfaces, hollow surfaces designed to give the require-
ments needed for the Pierce gun and other irregular surfaces included a structure
of parallel lines which are raised above the rest of the structure to give the
application of a stronger field in that neighborhood to produce a triple beam
emitter. The processing associated with these dispenser cathodes is established
on a sufficiently well-controlled basis so that they can be used as production items.
This is work done under the direction of Dr. KATZ.

Silicon Semiconductors

I saw some of the work in the semiconductor plant which dealt mainly
with the production of silicon to be used in photo transistors, high-frequency
transistors and many other devices. The silicon is prepared by drawing out a
long rod of silicon which after it is first heated by radiant heat becomes a good
enough conductor so that it can be heated by direct current conduction to a
sufficiently high temperature so that silicon chloride will decompose and deposit
the silicon on this rod. After the rod has been built up to 1 to 1-1/2 cm in diameter
it is then purified by the zone melting in which the lower end of the rod is held
stationary and as soon as the melting takes place, which is caused by induction
heating, the upper end of the rod is rotated at a constant speed and the melting
zone is moved down the rod very gradually so that it requires approximately
1/2 hour for each zone melting. Then the induction heat is returned up the rod without
actually melting it. In a time of approximately 10 minutes afterwards the power is
increased again until the silicon is melted and then the slow dropping of the
melting zone takes place again. This method seems to give extremely pure
silicon crystals with a minimum of dislocations. The orientation of this crystal is
given by the seed crystal used at the upper end. This crystal is welded of
course to the silicon crystalline material by the melting process. After the
crystals have been prepared, then they are further treated to introduce the
required impurities in well-determined proportions to create rectifying boundaries
and the end junctions of one sort or another. In general, the technique is

relatively simple, but the results show high precision in the control. In the high frequency transistor (good up to about 10 megacycles) it is important that the thickness of each wafer of silicon be controlled to high accuracy. This is done by a special pneumatic caliper. In this device the wafer is measured by bringing it into contact with a plunger which in turn tends to seal an airgap. The wafer thickness controls the air passed through this gap under a known pressure condition the pressure difference across the gap is an accurate measure of the thickness of the wafer.

High Transconductance Long-life Tubes

Returning now to the problems of oxide cathodes and the production of high transconductance tubes, the group here recognizes the importance of having extremely smooth cathodes and extremely well constructed control grids. The philosophy on the operation of these cathodes is to use rather low temperatures compared with the standard temperatures used in most receiving tubes in the USA. They feel that their tubes should have a life of at least 10,000 hours or more to be considered satisfactory. The reason for this is that in general they do not sell their tubes to the public but use their tubes in their own equipment which they then sell, as an entire equipment. This is an interesting policy and can remain effective as long as the components which they produce are superior to those produced by their competitors. That way, if the equipment which they produce outperforms all other people's equipment, then it is necessary for them to buy the equipment from Siemens. The main customer for Siemens is the Post Office Department which of course operates the telephone and other communications systems including much of the radar and radar links and radar carrier telephone systems.

The technique for making the grids depends on a grid winding engine which does very high precision work with wires as small as 5 microns in diameter. These wires are produced by a drawing technique usually by Osram or some other producer including a supplier from Sweden. Then the wires are further processed by etching to give them the very smallest wire diameters. These wires are run onto a framework and finally welded with gold to join the wires together at their crossing points and fasten the wires to the grid frame. The whole technique is very well carried through with high precision and yields results which give transconductances higher than are produced anywhere in the world. The transconductances run as high as 30 milliamps per volt grid swing. Have met many people here and some time before leaving will try to

obtain a list of those who I have met and a brief description of the type of work they are now in.

VISIT TO TELEFUNKEN

Arrived there morning of July 4. Was received by BRÜCK and DAHLKE and talked over program with DAHLKE. The afternoon was split with the first part on semiconductors. The basic research features that interest me have not been studied. The principal effort here is on production and development of new circuit elements. My impression is that the Siemens semiconductor laboratory with their concentration on silicon may be working in a more advanced field than Telefunken.

Noise Measurements for Cathode Evaluation

Conventional developments of the oxide cathode is being carried on here with interesting methods and unusual results. Previous to the last one or two years, the variation of transconductance with heater voltage was assumed to be the best indication of cathode quality. Now they find the noise measurements as a more sensitive method and easier to carry on. They have now developed a noise measuring equipment which they produce for their own use that seems to be well engineered. One or two American companies have asked the price of this instrument and whether or not it could be bought and then the approximate price of about $1500 has been set for a single unit with a much lower price if many units are ordered at the same time. The principle of operation is very simple. For either diodes, triodes or more complex tube structures the noise current is measured as a function of the emission current. When the emission is limited by a space-charge potential minimum of approximately 1 kT or more, the noise is directly proportional to the current. But if the potential minimum is in the critical range of about 1 kT, the noise rises rapidly and this increase in noise is very easy to detect. It serves as an excellent means of determining that important condition.

Development of an Activation Schedule for Long-Life Tubes

A particularly interesting use of the method relates to their development of an activation procedure specifically useful for the activation of passive nickel material. This material is now used in many of their most important tubes and especially the ones that require very long life. They find that there

is a definite difference between the various tube types as to what constitutes the optimum activation procedure. The method used to arrive at the best procedure follows: the tubes are made on a standard production machine according to a particular schedule of baking, oxide breakdown and so forth. During the break-down procedure, the metal elements, the grids and the plates are kept hot by induction heat. The tube is finally sealed off with no current having been drawn from the cathode. After the seal-off, the activation takes place and the study proceeds as follows: assume that the normal heater voltage is 6 volts. One set of tubes is run for 1 minute at 10 volts and then at a standard operating voltage of 5 volts. The current drain associated with a standard amount of noise is observed. This value of current drain is plotted. The activation at 10 volts is continued for another minute or more and the current drain is again measured for the standard noise. In general, with such a high activation temperature, the current drain reaches a maximum after a few minutes of this activation and then falls. The same procedure is done at 9 volts and 8 volts and 7 volts. These figures are chosen to illustrate the operation. As the lower heater voltages are taken, it turns out that the maximum is the same but longer and longer times are required to reach that maximum. In this way it is possible to find the highest activation voltage which will reach the maximum since if the activation heater power is too high then the maximum is not reached at any time. An activation schedule is finally made up from a compilation of the entire study which might indicate, for example, that 2 minutes at 9.5 should be followed by 6 minutes at 8.5 and 15 minutes at 8 or some such schedule.

The results obtained by this schedule are then studied not only in terms of the emission properties and the tube properties immediately after activation, but at various stages of tube life. These results are then compared with the ones obtained by the activation schedule devised by "cut and try" in the factory. In many cases almost complete failure is obtained by using the cut and try method whereas the quality of the product that results from this study seems to be excellent and they have examples of tubes containing passive nickel cathodes that not only have superior operational properties early in life but continue with almost complete absence of any interface or the usual troubles for 10, 20, 30 thousand hours of life.

The fact that a different schedule is needed in each tube makes me feel that the activation material that is used to reduce the oxide comes from the

associated parts, the grids, the plates, and other parts of the tube. It had not occurred to the Telefunken people that this might be true and yet they had no method to account for the fact that similar cathodes put in dissimilar tubes required different activation procedures. I suggested that they build some tubes, diodes, triodes, pentodes, anything, in which they were extremely careful to use completely purified parts throughout the entire structure. I anticipated that under those circumstances they would not achieve either good activation or good life on any schedule that they could devise and that if such were the case it would prove that they were obtaining their activation and long life by having the supply of activating material come from the neighboring parts. They expect to undertake these experiments very shortly.

Transconductance Theory

Dr. Walter DAHLKE has given me a reprint of his paper on the life of oxide cathodes. This shows a great deal of quantitative data on this subject. It should be studied with care.

Equations for transconductance up for discussion. DAHLKE has the theory that the statistical distribution of the grid dimensions is an important factor in the determination of transconductance. He has based most of his calculations in the past on the 3/2 power law but now is going to apply the more exact equations combined with his theory of mechanical irregularity of the grid. In the general discussion Dr. ROTHE was present and he holds the opinion that the 3/2 power law is basically correct. His conservatism is based on the curves that he has in his book, but I asked that we plot real tube data by the method indicated in his book and compare it with my method. There seemed to be none available.

Theory of Oxide Cathodes

The discussion on oxide cathodes included a discussion of the depletion layer ideas, interface problems, flow of positive ions and the identification of the activation center. Opinion here seems to favor the idea that has been proposed by Nergaard and Plumley and others of the RCA that it is not barium. It remains for further experiments to establish this point. I indicated that I felt that it was the barium excess or oxygen vacancy. Extensive use is made of noise in all problems of cathode evaluation that have been mentioned before.

The life conditions for long-life tubes was discussed and it is generally agreed that <u>vacuum</u> is extremely important, especially as it applies to the cleanliness of the materials. Discussed at some length our methods of measuring temperature, anticipating that they will do the same. Observations on long-life tubes lead them to conclude that basically it is not a loss of coating that terminates life. They are not certain what it is and I expressed the opinion that it is likely to be any one of a number of factors.

Pentode for Ionization Gauge

Measurements were made of the use of an ordinary tube, principally of the pentode type as a vacuum gauge. As I remember, the connection involved the use of the screen grid as the electron collector. The plate was connected negative with respect to the cathode and the suppresser grid still more negative. This permitted ions that were generated to go to the plate but inhibited the emission of electrons from the plate. Electrons emitted from the secondary emission grid could go to the plate as well as the ions. Comparison was made with the conventional Bayard-Alpert gauge. They found the response in comparison with the Bayard-Alpert gauge was not exactly linear and I pointed out that this could be due to the fact that the Bayard-Alpert gauge without end plates seems to indicate a higher vacuum than the true vacuum and that their vacuum as observed in the conventional tube was probably more correct.

Temperature Coefficient of Work-Function

Discussed very briefly the problems of work-function and temperature coefficient. They also are beginning to recognize that the important factor is the <u>temperature coefficient</u> of the work-function, and not the work-function itself. There is uncertainty in their minds concerning the use of Fowler equations, etc. but since it is all written up in my book they intend to study the same.

Residual Pressure in Vacuum Tubes

Discussed the use of omegatrons, "massitrons" and the linear accelerator used by their man, P. F. VARADI, who was formerly with the research institute for telecommunication at Budapest, Hungary. I have a reprint of his paper. His scheme permits the identification of ions by the frequency by which they are accelerated through a multiplicity of electrodes. The tube required for this is

very simple and the sensitivity is fair. Anticipate that they will not be able
to detect partial pressures less than about 10^{-9} with this system. **This scheme**
may be perfectly satisfactory for determining some of the residual gases but
will not be satisfactory in my opinion for the most important ones which are
electro-negative gases that can react with the cathode. Have suggested that
they use the scheme of studying these gases by the removal of thorium from
an activated thoriated filament. The idea is that once the filament has been
activated then if it is allowed to stand at low temperature, the emission can be
measured after a certain period of time. In general, at a very small adsorption
of objectionable gas, the emission may go up but the objectionable gas reacts
with the thorium and when the temperature is raised to about $1900^{\circ} - 2000^{\circ}$K, the
compound
leaves the filament and then a second measurement of the emission is a
direct indication as to how much has been taken away from the filament. This
method can be made quantitative, although we have never used it that way.
Think it would be a good idea if we tried it as well.

Semiconductor Work

Visited very briefly with the semiconductor man who gave me two
transistors which we should test as rectifiers to see whether or not we can
find useful information about the nature of the barriers. My general impression
of the work going on at Telefunken is that it is of a very high calibre and that
BRÜCK is a very active and able administrator of his group. Some men however
seem to be somewhat dissatisfied with management policy and all seem to be
looking for better jobs, especially in the U.S.A.

Dr. ROTHE's Tube Equation Analysis

Dr. ROTHE has developed a method of analysis dependent on the 3/2
power "law" which he has applied (as in his book) to tube characteristics. He
is so satisfied with the results that he does not think that his data could fit
the "square law." This question cannot be answered without subjecting new and
reliable tube data to both methods of analysis so as to let the electrons tell the
story. We should undertake such a study before I publish my theory in IRE.

electrode and have the melting zone move up instead of down. I am under the impression that the Munich people have analyzed the problem better from the mechanical point of view, even though they started using this floating zone technique later. The purification at Munich is done in hydrogen I think, whereas the purification at Pretzfeld is on a vacuum basis. The main feature is that at Pretzfeld, they are making very good alloyed junction rectifiers which depend on there being an intermediate insulation layer so-called which is only very slightly P type and it is this insulation layer which accounts for the very high back voltage permitted on their rectifiers. Good rectifiers have a back voltage of 1000 volts with practically no leakage. One contact is made with aluminum, and aluminum foil whereas the other contact is made with gold containing 1 per cent antimony. The final system is sealed together in glass; i.e., with glass insulated sealing against covar. The entire assembly is much like those made by Raytheon and others, but I am not sure that they have developed the very high back voltage found in the ones produced at Siemens-Schuckert.

Rectifier Theory

They are convinced that the conventional diode theory does not represent the behavior of their rectifiers and they made a strong distinction between diode theory and diffusion theory. That is something that I must study up so that I can see under which circumstances a correct diode theory actually is distinguishable from diffusion theory. In most cases that I know of, the diffusion theory really is basically diode theory because of the introduction of the EINSTEIN diffusion relation, which is really the equivalent of the BOLTZMANN relation, although not usually recognized as being so.

Met MADELUNG while in Erlangen, had considerable discussion with him on problems of semiconductors. He gave me two copies of his handbuch article, one for myself and one for SLATER. Must be sure to send him a copy of SLATER's report.

Discussion with Dr. SCHOTTKY

Had very interesting discussions with SCHOTTKY. Since these discussions were quite general, there were no particular points of disagreement. He was very much interested in some of my ideas, and I was interested in talking to him about the problems of potential and motive. His point of view

is often strongly dominated by theories applicable to ionic solutions and in this case the concept of potential is determined more by chemical analysis than by studying the behavior of the electrons. He was interested in my point of view that the basic thoughts of potential as it relates to electronics should be expressed entirely in terms of electrons with an elimination of some of the more conventional methods. He was also interested in problems of cathode activation and was feeling inclined toward the activation theories of NERGAARD, not realizing the inadequacies of the experiments which the RCA had carried out. This whole problem concerning the important activating element is still open for research.

VISIT TO PHILIPS, EINDHOVEN

Arrived Thursday afternoon, July 18, and met Dr. CASIMIR, since Dr. H. G. BRUINING was out of town. After short discussion went to Dr. A. VENEMA's office and laboratory to discuss emission problems. Talked for some time about the evaluation of emission and the fact that SCHOTTKY plots as a means of obtaining zero field emission are not satisfactory. Discussed with them some problems of a dispenser cathode. They are using barium aluminate mixed with tungsten powder as the filler. They find that this is much more satisfactory than using the barium strontium carbonate which in the breakdown process oxidyzes the tungsten of the porous plug and then requires more barium to remove the oxygen to the suitable thickness. They have the opinion here that a single layer of oxygen associated with a single layer of barium is the ideal cathode and that the emission properties of this cathode are unaltered in the presence of oxygen at a pressure of between 10^{-8} and 10^{-7}. The theory is that at this oxygen pressure, the rate of production of barium exactly equals the rate of arrival of oxygen at the surface and thus holds the cathode in a fully activated state. Without the oxygen this barium presumably evaporates and condenses on neighboring parts. They apparently have not heard of the Siemens developments using barium oxide directly as the filler. It is not evident that there is as much enthusiasm here for the use of these cathodes in practical tubes as there is at Siemens. It may be that even though this type of cathode was first discovered here, and the theory more or less worked out by RITTNER in America, the technical developments of Siemens seem on the surface to be moving more rapidly.

Discussed problems of energy distribution measurement with a colleague of VENEMA's who is considering measuring the emission as a function of angle. The scheme that they had in mind   I think would not be satisfactory because of the very great difficulties of interpreting the results of electron flow through a set of slits.   I indicated that the equivalent amount of manpower used to study the presence of active gases such as oxygen and water vapor by thorium emission technique would probably be of more value. Was unable to finish the discussion with VENEMA in the time available.

Morning of July 20 was taken discussing problems of phosphors and fluorescent lamps with Dr. K. H. KLAASSENS and with Dr. Th. P. J. BOTDEN. Discussed the question as to whether or not there is much room for an improvement in the efficiency of fluorescent lamps and it seems that the development has been carried just about as far as possible. The question as to whether neutralization of metastables at the fluorescent surface can produce an excitation and the conclusion seems to be that they do not think that it is possible. The main process involved is that of exciting an electron in one of the impurity states to a higher energy level and yet not into the conduction band. The second type of impurity is incorporated in the phosphor at a sufficiently high concentration, possibly not too far from one per cent so that the excited level of the first center delivers its energy to the other center which in turn holds it for a considerable time, probably the order of 1/50th of a second. It then gives out light since the transition is of the so-called "forbidden" type and accounts for the length of time that the energy is held. Did not inquire concerning the actual nature of the compounds used since it is probably well known by the makers of these powders.

Spent the latter part of the morning with Dr. H. J. VINK and Dr. F. H. STIELTJES. We talked for some time about thermionic problems and my analysis to show the location of the donor state with respect to the bottom of the conduction band. After that, we started a discussion on the transfer of electrons across a boundary and came to the conclusion that the product of the electron current which impinges on a boundary multiplied by its transmission probability is a constant. It was my opinion that the transmission probability in the two directions must be the same and therefore the currents must be the same, but it is their opinion that only the product is equal and that the individual components are not equal.

Dr. E. J. W. VERWEY is in charge of the analysis and research related to gas discharges in fluorescent lamps and has a very good program for the use of probe measurements for the analysis of the plasma in the fluorescent lamp. He was interested in the results of my paper in Venice and was not convinced that the collision cross-section exhibited by our work could be applied generally. There is no question but what his argument has merit and further experiment is necessary since our data are too incomplete to prove or disprove the point. He is studying electron energy distributions, mobilities, potential distributions and other such matters in mercury vapor to which various additions of neon at approximately 2 mm. pressure and argon at approximately 0.7 mm pressure have been added. The objective that they are seeking is to put in more power per unit length of a fluorescent tube at a level of efficiency in the plasma that now exists. If they can do this, then they figure that the overall efficiency of the lamp will increase. The measuring techniques are well developed and they have adopted our method of preheating the probe before each measurement. Their probes are only 20 microns in diameter and one of the most recent tubes which they have developed for these studies involves an array of four different probes. I think two of them are tungsten, one moly and one tantalum. The probes are all alike except for these differences in material. The method of construction involves the surrounding of the probe by a spiral wire to give it strength out toward the middle of the discharge and then enclose the entire system in a fine quartz tube. The quartz tube is used of course to suppress the entrance of the discharge along the wire toward the larger cross-section. The design seems to be a good one. I think that if I were using this type of probe, I would chose to put a cylinder of metal on the outside of one of the probes in order to study the influence of nearby potentials. There is still another probe in the tube; it was movable. It was still a cylindrical probe and was approximately 2 or 3mm in length outside of the quartz surrounding protector and could be moved all the way across the arc stream along one of the diameters. There was not sufficient time to discuss very much of the actual results which have been taken to date.

Both Dr. E. J W. VERWEY and Dr. A. A. KRUITHOF are interested in color measurements and in photometric standards and therefore they would like to borrow a copy of my 803 report on colorimetry and photometry. They would also like a copy of Larrabee's report on spectral emissivity. Two

copies should be sent them, one to VERWEY and one to KRUITHOF.
Dr. KRUITHOF suggested we send a copy to Dr. WENT. His address is
Kema-Lab, Utrechtscheweg 210, Arnhem, Holland. A letter should be sent
with this report indicating that it was Dr. KRUITHOF who suggested that a
copy of the report be sent. This laboratory is the equivalent of the National
Bureau of Standards.

Visits to Technical High School, Stockholm; Upsala University;

Allmanna Svenska Elektriska Aktiebolaget

Dr. A. Dattner, Stockholm 70, Royal Institute of Technology

Dr. DATTNER showed me around the laboratory. It was a very well equipped
laboratory where a good deal of research is being done on atmospheric electricity
problems. The head of the Laboratory is Dr. H. ALVEN. The only work
directly related to physical electronics was the development of a switching tube.
Studies of electron trajectories in electric and magnetic fields have resulted
in a tube that scales to ten counts as it transfers the discharge from one set
of elements to the next. The original tubes were rather large but the final
tubes now being produced by a local manufacturer are small enough to be
practical.

Visit with Ambassador SOHLMAN

Perhaps the most important part of the Stockholm visit was the conversation
with Ambassador SOHLMAN concerning the scientific developments in Russia.
He indicated that the educational program is very competitive there and that
in the early years of schooling, the amount of instruction included is nearly
30 per cent more in each school year than is given in either Sweden or America.
A large fraction of the better students are then sent on for advanced work
which not only is given free of charge for those that qualify but many of the
students are paid more or less in proportional to their ability. Students that
fail to meet the competition are not permitted to continue their studies. After
the completion of their study work, the engineers are assigned to specific
enterprises related to their specialty. There seems to be relatively little
free choice.

An important project which he mentioned relates to the transmission of power over long distances by high voltage direct current. The same problem is of importance in Sweden and ASEA has been given the contract to develop suitable equipment for transmitting power across to the island of Gottland. The Russians came to Sweden to study this development and many Swedes went to Russia to study their work along this line. The Russians tried to negotiate an arrangement with Sweden for the use of their developments, but ASEA would not agree to this and offered to build their stations for them. This the Russians refused and obtained the services of some German scientists and built a laboratory in which there are over 400 scientifically trained people attempting to solve the development and engineering problems associated with this system. According to the Swedish reports, they are not succeeding as well as the Swedes are with their special tubes. The Swedish design is being kept secret. More concerning these tubes will be given later in this report.

In general the scientists in Russia are given very favorable laboratory and living conditions and considerable freedom to do research. Under the conditions there, it is inevitable that a large part of that research is directed toward specific developments. If scientists have independent thoughts about politics, they must say nothing or else all of their privileges are taken away.

Ambassador Sohlman has set up a number of "exchange" visits between Sweden and Russia for scientific people. The Swedish scientists have found that the Russians either agree to tell all and seem to do it with remarkable freedom or else they tell nothing. There seems to be little or no middle ground.

Upsala University

The physics laboratory at Upsala has practically doubled in size since my time in 1920. It is a fairly modern laboratory although on the whole rather small. The shop facilities are excellent. One of the most important new operations has to do with extremely high intensity gas discharge. This system involves the charging up of a bank of very carefully made condensers arranged in such a manner that the current path is entirely coaxial. Thousands of amperes are shot through the discharge and the properties of the discharge studied with the oscilloscopes. It was this work that was reported at the Third International Conference by Professor T. OHLIN and Professor K. SIEGBAHN.

When the discharge takes place, the magnetic field in the discharge is so great that it concentrates the discharge to the core so greatly that its diameter oscillates back and forth. First it is large, then it pinches down and then it expands and pinches again and on the third pinch a thermo-nuclear reaction takes place and neutrons are created. Apparently experiments with this system have also been announced by the Russians but at the moment I do not know exactly about the hydrogen that is used as to whether it is ordinary hydrogen or heavy hydrogen. It is admitted to the discharge tube continuously through a paladium tube. A few other research problems are going on there at the Institute including cosmic ray research and x-ray studies.

There is a separate institute connected with the university formerly under the administration of Professor NORINGER and now administered by Professor Dr. MÜLLER-HILLEBRAND. In this laboratory, many high voltage studies are being made, especially those related to lightning and lightning protection. They have automatic equipment for direction finding in which the location of a lightning storm is made evident on a cathode ray tube with a P7 screen. Since it is necessary for the observer to see and record the facts concerning the storm locations, it could very well be an advantage in the operation of the equipment to design it to use the Skiatron (a dark-trace tube) which would record semi-permanently and also give a qualitative integration of the storm activity by the nature of the dark traces that would be recorded on the face of the tube. The observer can then erase the record by the use of light and start again. I have promised to send particulars to HILLEBRAND.

Allmanna Svenska Elektriska Aktiebolaget at Ludvika, Sweden

At ASEA, Ludvika, I was entertained by Lars Olof TIDERMAN and saw some of the work that they are doing with high power high voltage rectifiers. Also saw the new laboratory in which germanium rectifiers are being constructed. The gas rectifiers are all with mercury pools and very large. The particular type that TIDERMAN wanted to talk about is the air-colled type JB. ASEA has prepared a very good booklet on this rectifier in English and listed as 7161E. These rectifiers are all essentially grid controlled rectifiers and should perhaps be classified as thyratrons instead of rectifiers. A selenium rectifier is used to generate dc for the "keep alive electrode". A cathode spot carrying approximately 10 amperes is operated by the selenium rectifier system. In the JB rectifier there are altogether six anodes and six separate

control grids.

One of the most difficult problems has to do with evaluation of the graphite used in the anode material. A back-fire in a rectifier of this kind can cause a great deal of damage or at least a temporary shutdown. Therefore it is important to have good anode material that is not likely to discharge in the reverse direction. TIDERMAN tried to evaluate the anode material by studying the thermionic emission from a sample of the material. He has found no correlation at all between thermionic emission from these samples and the likelihood of backfiring. After a discussion of the problem it did not seem to me as though he should have expected any such correlation because the two phenomena are so different. I suggested, however, that he study the field emission properties of the anode samples. If some correlation developed there it could very well pay to study the field emission properties of all of the anodes that are actually used. The idea was to enclose the anode within a cylindrical tube on the wall of which is a phosphor covered with aluminum so that a very high voltage can be applied and the observer can note the voltage at which florescent spots begin to show. If this scheme worked out, it would be entirely practical to examine every anode before it is put into a tube and after it has been processed to the point of final assembly. As a preliminary he should study the field emission properties of the sample material that comes out of each anode since a core of it is drilled in anticipation of the creation of a threaded section used to support the anode.

The ASEA bulletin 7313E has been issued to describe the high voltage dc transmission to Gottland. I have a copy of this bulletin also. On page 27 of the bulletin is a schematic drawing indicating the arrangement of the electrodes within the controlled rectifier so that it will withstand the very high back voltage required for operation with 100-200 kilovolts. The implication there is that the structure involves the placing of a number of disks each two or three centimeters in thickness and separated from each other by the order of one centimeter. Early models of this rectifier had disks made with graphite but the latest models have disks made of the purest iron. They are no longer made with a center hole. As I understand it, there is a patent which describes the fact that they can be made with angular rings through which the discharge makes its way. The details are a "company" secret. The development for this special type of rectifier has gone on with

relatively little pure research to solve the problem but with a very extensive empirical study. Presumably about 140 different rectifier designs were experimented with before the one which is now being constructed was obtained. It is this particular type of rectifier which the Russians would like to have but the details of its construction are being kept secret.

Some attempts were made by TIDERMAN and are still underway to determine something more about the properties of the discharge. His method of study however involves the use of probes in a manner which I do not think is likely to yield valid results. It is not perfectly obvious how studies of this kind should be made but since they are not equipped very satisfactorily for doing research, there is hardly any point in going into a lot of detail to figure out what would be the best way to make the investigation. Also there is relatively little urge to do so because of the fact that they feel quite satisfied with the rectifiers as they are now being constructed.

The building for the germanium rectifier work has just been constructed and it does offer a very fine plant facility. Practically nothing has been done so far except to develop in a very conventional manner small power rectifiers capable of carrying a few amperes and a back voltage of approximately 100 volts. The sealing methods they are using for their rectifiers are claimed to be fairly unique. We did not go into the details because much of the same work is being done in the U.S.A. with probably similar results. They expect to undertake some work with silicon, but have not done so yet. In general I find very little physical electronics work going on anywhere in Sweden.

VISIT TO AEG and TELEFUNKEN LABORATORY

Berlin NW7, Sichingenstr. 71 Germany

Dr. WIEGAND is in charge, and Dr. Ernst WILLNER is responsible for most of the activity.

The tube factory at Telefunken is in the old building of AEG. Dr. MEYER is head of what remains of the AEG which is a rectifier and thyratron division. Under Dr. MEYER is Dr. ROHDE who is in actual charge of production and development. Some of the cathodes used in the thyratrons are oxides sprayed onto what seems to be a nickel gauze. It is claimed that these oxides give 10 amperes per square centimeter in actual use. The tubes, although not very big are rated at 80 amperes. ROHDE discussed the theory that he has concerning sparking which he considers to be due to the differential cooling

and heating as the electrons condense after being emitted into and accelerated across the pores of the coating. Such a process he thinks makes individual crystals break under the heat differential. I have my doubts about this theory of sparking since I think donor migration followed by very high resistance heating would be important.

He was surprised that the overall voltage of a thyratron increases with current and seems to think that that increase in voltage has something to do with the quality of the cathode. The reasoning behind this was not at all clear. He did not think that it had to do with the resistance of the cathode as such because when the resistance is high, he thinks that the pattern of current-voltage is distorted, due to the heating of the coating. Many of the tubes made in this laboratory are made with zenon gas instead of mercury. He also makes ignitrons with mercury and has quite a range of thyratrons and rectifiers. We did not have time to go into the details of their performance.

A two hour trip was taken through the Tube Production plant at Telefunken guided by Dr. WILLNER. I promised him a copy of Report No. 321 which was delivered to the driver of the Navy Office and Commander NOWACK will see that it is delivered. The plant is in the old AEG Factory which was not seriously damaged during the war. The Russians removed all of the equipment and the entire production is being made on very new equipment, all of which was designed and built there. They have a very large tool room for making all such equipment. They apparently do an excellent job both from the point of view of design and speed of production of the tools needed to make new tube parts. Most of the machines are designed so that the reinsertion of some special parts of the mechanism can be done in a matter of minutes and change the machine from one tube type to another.

Three methods are used for cathode coating which are spray, painting, and cataphoresis. The latter is used on the battery operated tubes with filaments of tungsten nickel which require 25 milliamperes heating current. The spray technique is used on round cathodes which are mounted on a frame-work which along with six other frames moves around on a track. Each time the frame passes by the two spray guns, the guns automatically turn on and spray coating materials. At the end of each spray operation, the track carries the frame through the air approximately 5 feet before it returns again to the spray compartment. During this time, the previously sprayed material is dry enough so that the second coat will stick. In general, the coating thickness is only about 60 microns. They give a great deal of attention to the production of the material which in general is the triple carbonate. The crystallization

in the processing is such that long crystals are made. Each crystal being approximately 10 to 20 microns in length, and 2 microns in diameter. The details of the crystal's shape and size after milling were not discussed.

Certain restricted areas of the factory are very carefully air-conditioned and maintained dust free. The painting process is used on flat type cathodes. In this case, the cathode is held on a frame and a sponge or a brush-- it is not clear exactly what the carrier was-- goes down into the solution and comes up and automatically paints the cathode in one single stroke. These cathodes are then carried directly into a drying oven where they are dryed. In general, much more care is exercised with regard to the production of the carbonates than is given to the nickel. Each batch of carbonate is tested by making quite a few test tubes which are a standard triode of some sort that they use. If the batch is acceptable, then it is used for production. The cathode in general is the "normal" nickel type. The actual cathodes are processed by their own machinery from tubing supplied outside. The tubing comes in approximately 10 foot lengths about 1 centimeter in diameter and is drawn in their own machinery to any given size and shape which they desire. Before the tubing is actually made from a new melt of nickel by the producer, sample tubes of the melt are furnished for inspection. These are analyzed spectrochemically only, and not an appreciable proportion of the melt is put into test production. If the analysis indicates that tubing is O.K., then the melt is prepared as described.

One of the big problems here is the question of activation. Apparently in order to get the activation they desire, it requires at least thirty minutes, and in some cases, more. They would like to reduce this activation time to five minutes if possible and discussed with me ways and means of doing this. My reply was that the only way to find improved activation methods was to do good measurements on cathode properties. They were not prepared to do this at this laboratory, but there is no reason at all why they could not. One of their ideas was that the use of some pulse method of applying the anode voltage might be helpful and I agree that it would be well worth the experiment. I think that the method used by DAHLKE of determining cathode properties with the help of noise combined with an accurate determination of the cathode temperature under test conditions would allow them to determine the best activation schedule in relatively short order. At present they are activating at above normal operating temperature by the application of a sufficiently high voltage to the grids and plates of the tube connected together so that there is a considerable amount of heat dissipation at these elements. It is possible

that the long activation time is due to the presence of gases and other dirt coming from the receiving elements under severe bombardment. These objectionable gases may be cleaned up by the getter and finally leave the tube a much better tube than it would otherwise have been.

Detailed studies are necessary, yet the factory does not seem to have the available trained manpower to carry out such studies so they carry on much as other places do by the cut-and-try method.

In general grids are made from moly with nickel support rods. The rods are notched and the moly wire wound in to give approximately the right shape. The final shaping of the grid is done in a press which puts enough tension on to give nearly a ten per cent increase in long axis dimensions in order to give the grid its final shape. The cathode heaters are made by coiling tungsten onto a moly rod. The insulation is sprayed on and then the moly is dissolved out. They prefer the V with coiled tungsten over the folded cathode heater. The main trouble with the folded heater is that at the sharp folds at the end, the insulation breaks off. The coil cathode is slightly more expensive but the cost difference is negligible in comparison with the entire tube. They think that the heater in a coil cathode runs at a lower temperature than is the case for the folded cathode. Micas are coated with a very thin film of magnesium oxide. In general the plates are made of iron with a nickel inside surface and an aluminum outside surface. During the tube processing, the aluminum reacts with the iron in such a way as to produce a black outside surface. This apparently has good radiating properties.

In the tube evacuation process the usual sort of machine is used. After a very short baking and pre-exhaust, the induction heat is used to heat up the plate structure and shields. After a short heating there, the plates are kept hot and the cathode is heated for the first time. This gradually brings the cathode temperature up to a relatively high value for breakdown and conversion. The evacuation process continues until the getter is fired prior to seal-off. The seal-off takes place and the tubes are ready for activation. Every tube is tested for shorts and emission under a standard condition. A certain fraction of the tubes depending on the tube variety is given thorough tests. In general this fraction is likely to be about 5 per cent of the production. If these tests are sufficiently perfect in quality, the entire production is passed and ready for   sale.

Visit to Fritz-Haber Institut der Max Planck-Gesellschaft, Berlin-Dahlem

On Monday afternoon when we arrived here, we made arrangements
for the visit to Telefunken on Tuesday and talked to Dr. Michael DRECHSLER
at the Fritz Haber Institute. Dr. E. RUSKA asked me to talk at their
colloquium. They set up a special one on Thursday, September 12. Dr.
E. RUSKA is well known for his work on electron microscopes and is in
charge of the Institute when Dr. M. VON LAUE the director is absent.

I discussed some problems of field emission with DRECHSLER and saw
the progress made on the model which he is preparing. Saw a demonstration
of a piece of equipment in which he applies pulse voltage to his field emission
point which may be adjusted to give pulses making the point negative with
respect to the collector as much as 15,000 volts at a frequency of 50 cycles.
This equipment also gives pulses in the opposite direction when that is
desired and is controllable up to nearly 30,000 volts. During these reverse
pulses, the electric field combined with the heating of the cathode to give
mobility permits the building up of the surface structure on the tungsten
point. In principle either positive or negative fields will do this except
that by making the point positive, the emission is absent. It is therefore
possible to use higher fields in that way. During the other half cycle
the point may be observed to see the changes in structure. The results are
then compared with the model to try to determine what the atomic changes
have been. The main objection that I would have is that the vacuum
technique seems to be very inadequate. It may, however, be perfectly
satisfactory for the purposes at hand.

I also saw some work being done by Dr. I. BROSER and his wife whose
name is Dr. R. BROSER-WARMINSKY. They have been working on cadmium
sulfide crystals for some years and published a paper in "Strahlentherapie"
90, 1953, on the use of a cadmium sulfide crystal as a dose meter for
gamma rays. They demonstrated the action which indicated a relatively
high sensitivity and great ease of operation.

They are doing all kinds of electrical conductivity and luminescence
experiments on single crystals of cadmium sulfide and zinc sulfide doped
in various ways. They do their own chemical work to produce the particular
crystals they are interested in having and are able to make them relatively
large. Their largest crystals are not perfect single crystals at all but

they do make some long, needle-like crystals. This work should be
discussed with Hutson who is doing similar work at the Bell Telephone
Laboratories. If Hutson is not fully familiar with their activities, he
should contact them.

CONCLUDING REMARKS

The above account of the visits made during this European trip
has been transcribed from the dictation made while in Europe very
shortly after each visit described. It therefore suffers from some lack
of unity in that it stands more or less in chronological order. It is hoped
that readers who may have access to this complete report will not use it
in any way detrimental to the individuals or organizations mentioned in it.
It is also of importance to realize that opinions and conclusions expressed
above are entirely personal.

October 18, 1957

Amphenol Type N connector

shield not connected to case

Two positions on switch non shorting
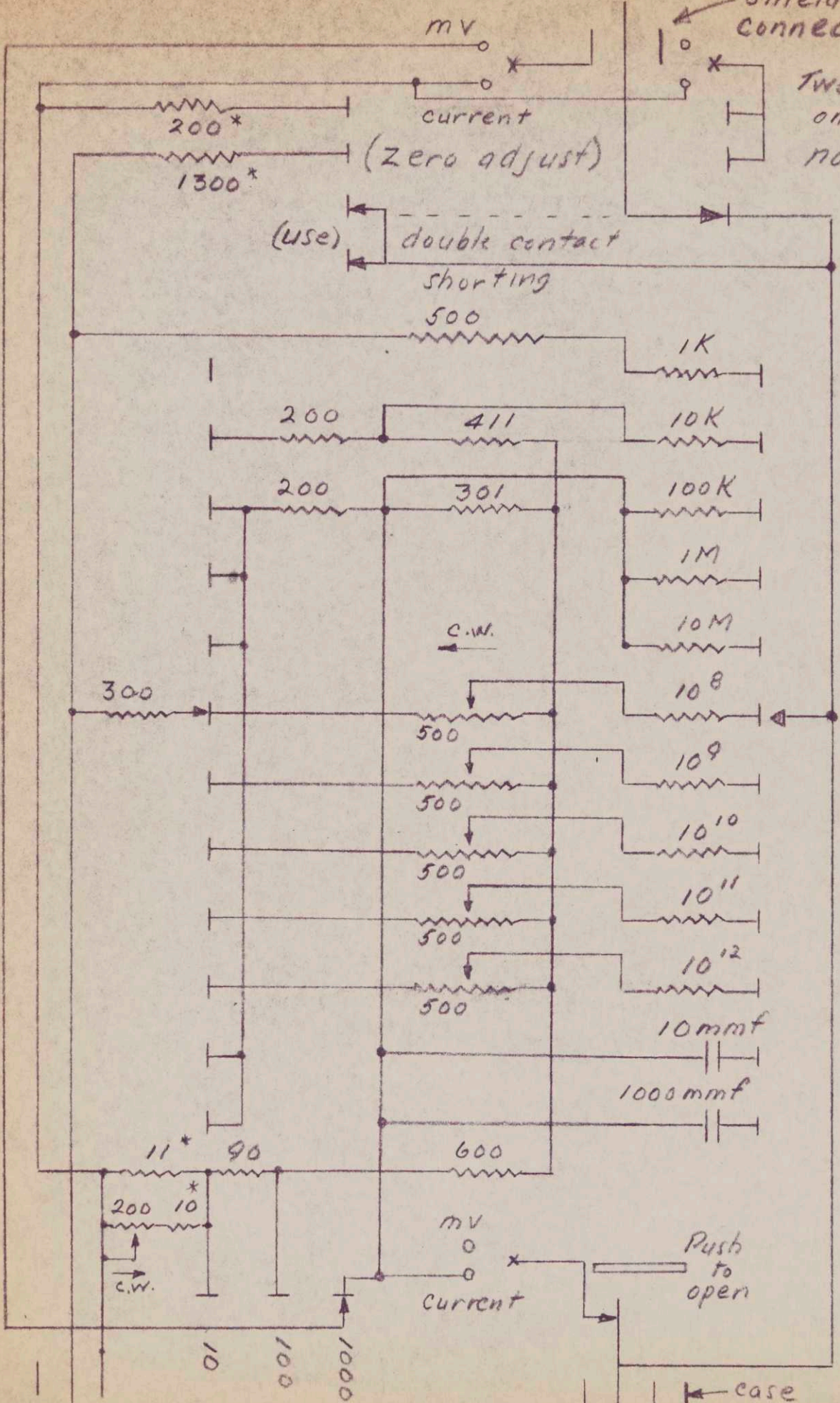
June 25 '58
W.B. Nottingham

Pots ± 5%
Res ± 5% marked *
" 10⁸ thru 10¹² ± 10%
" All others ± 0.2%
Cap ± 1%

mv
current
(zero adjust)

200 *
1300 *

(use)   double contact
          shorting

500
1K
200   411   10K
200   301   100K
1M
10M
300   c.w.   10⁸
500
10⁹
500
10¹⁰
500
10¹¹
500
10¹²
500
10 mmf
1000 mmf
11 *   90   600
200 10
c.w.
mv
current
10   001   1000
Push to open
case

Type 874 GR coax connector   Type 874 General Radio Coaxial Connector

NOTE: GAIN OF AMPLIFIER IS APPROXIMATELY 5000. BREAKING CONNECTION AT X-X AND INSERTING 2N217 EMITTER FOLLOWER, SHOWN BY DOTTED CONNECTIONS, WILL INCREASE THIS 4-5 TIMES. C-2 MUST BE INCREASED ALSO.

R-12 - 600Ω plus 500Ω ADJUSTABLE. SET SO METER READS .150 VOLTS FULL SCALE IN X10 POSITION.

+26 Volts
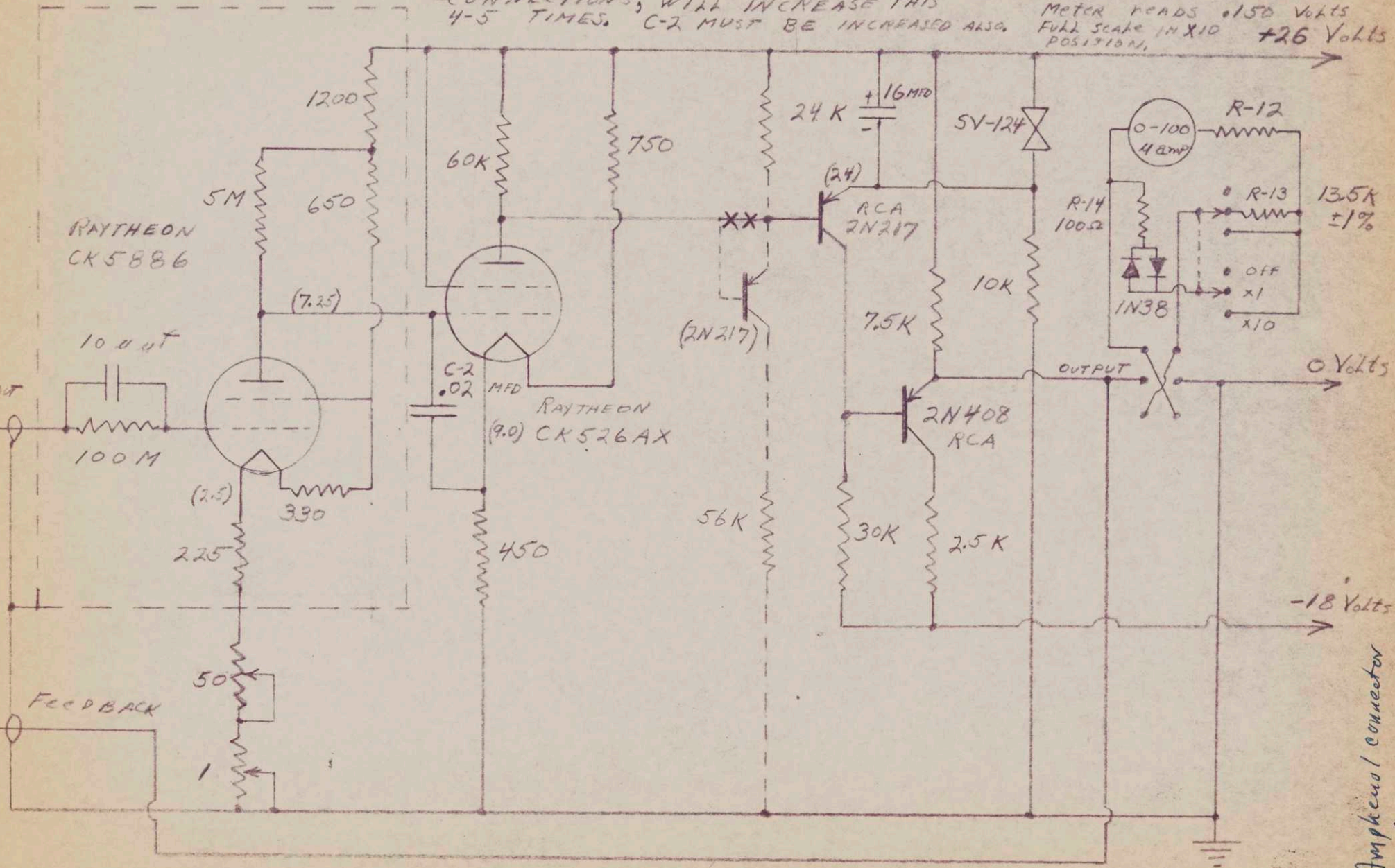
ELECTROMETER AMPLIFIER
REVISED 4   1   JUNE 1959
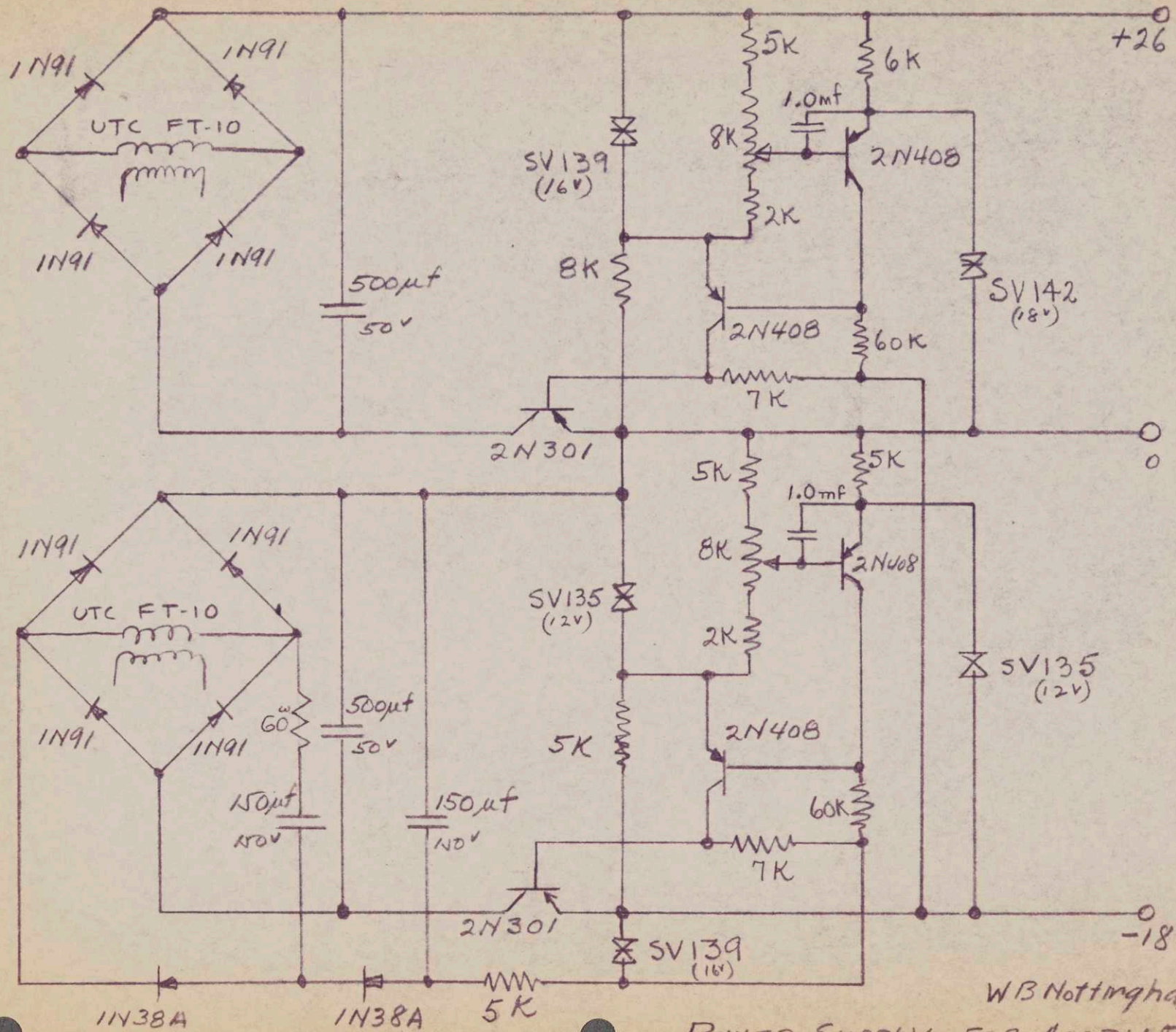
POWER SUPPLY FOR AMPLIFIER

W B Nottingham 7/16/58

EMISSION PROPERTIES
OF MOLYBDENUM BASED ON
HOUSTON'S EXPERIMENTS
AT T_{CS} OF 423°K AND 473°K

Fig. 3

Fig. 4

FIG 5

Fig. 6

Fig. 5
7

EMITTER   COLLECTOR

Fig. 8

EMITTER   COLLECTOR

Fig. 9
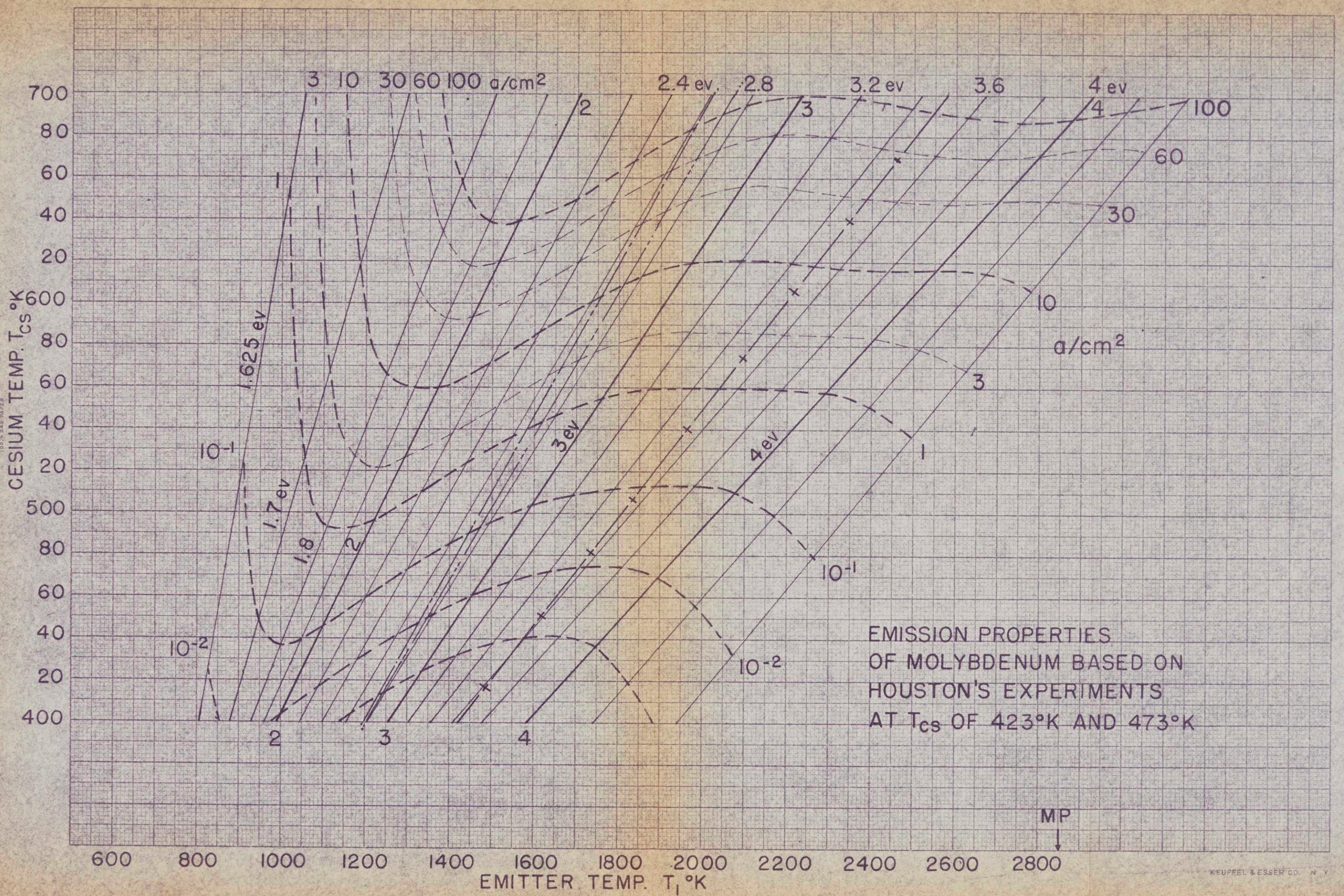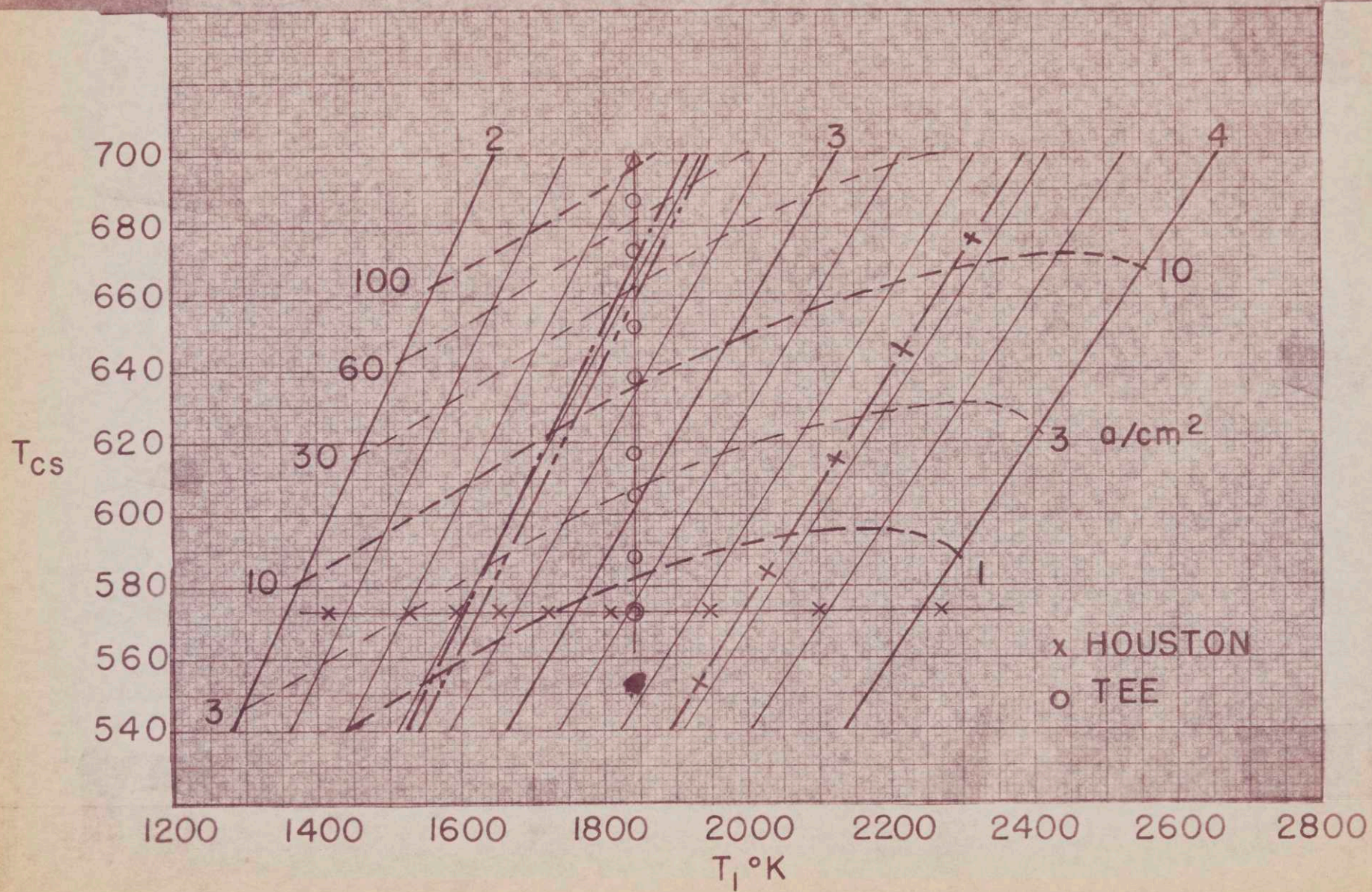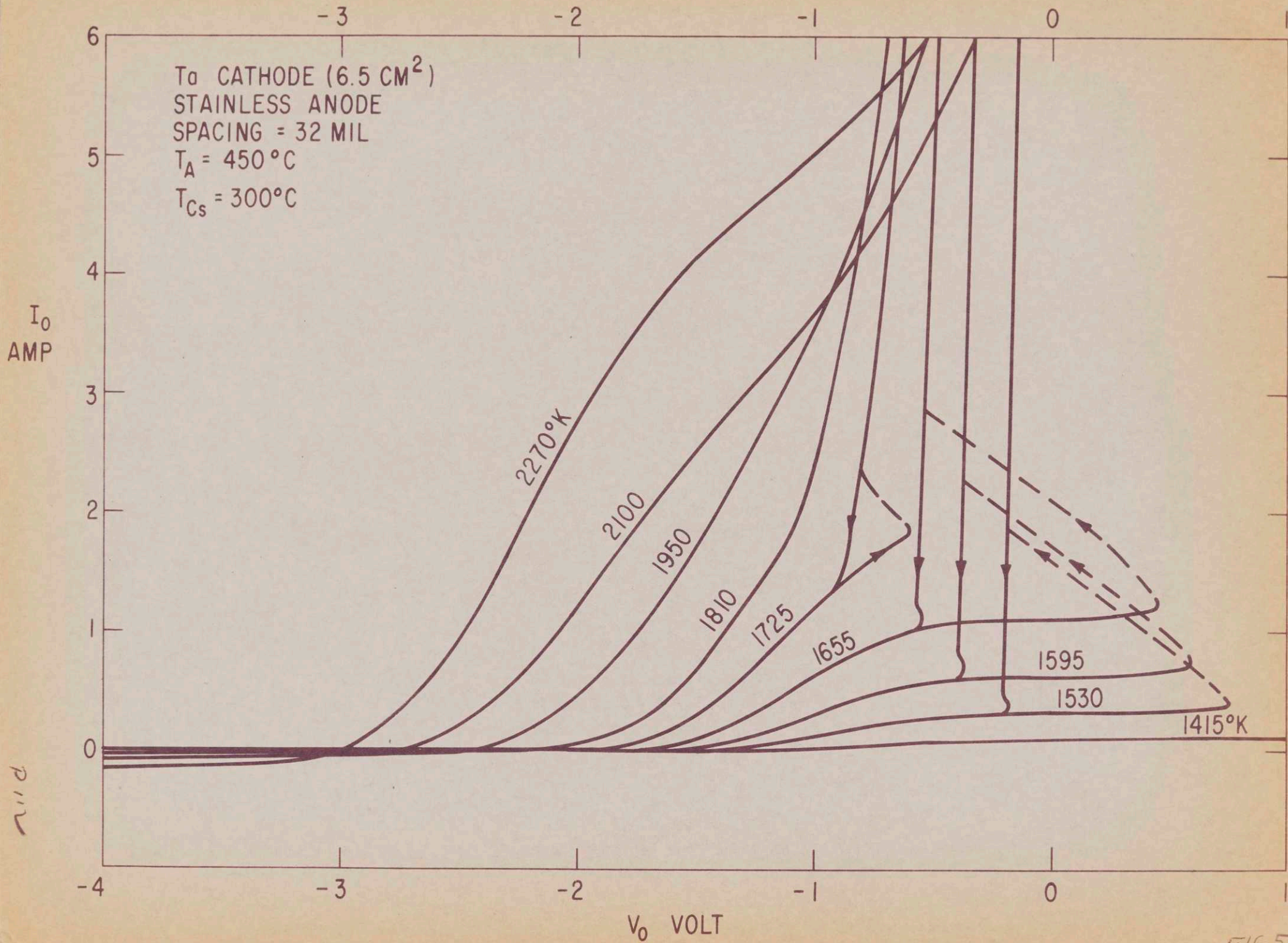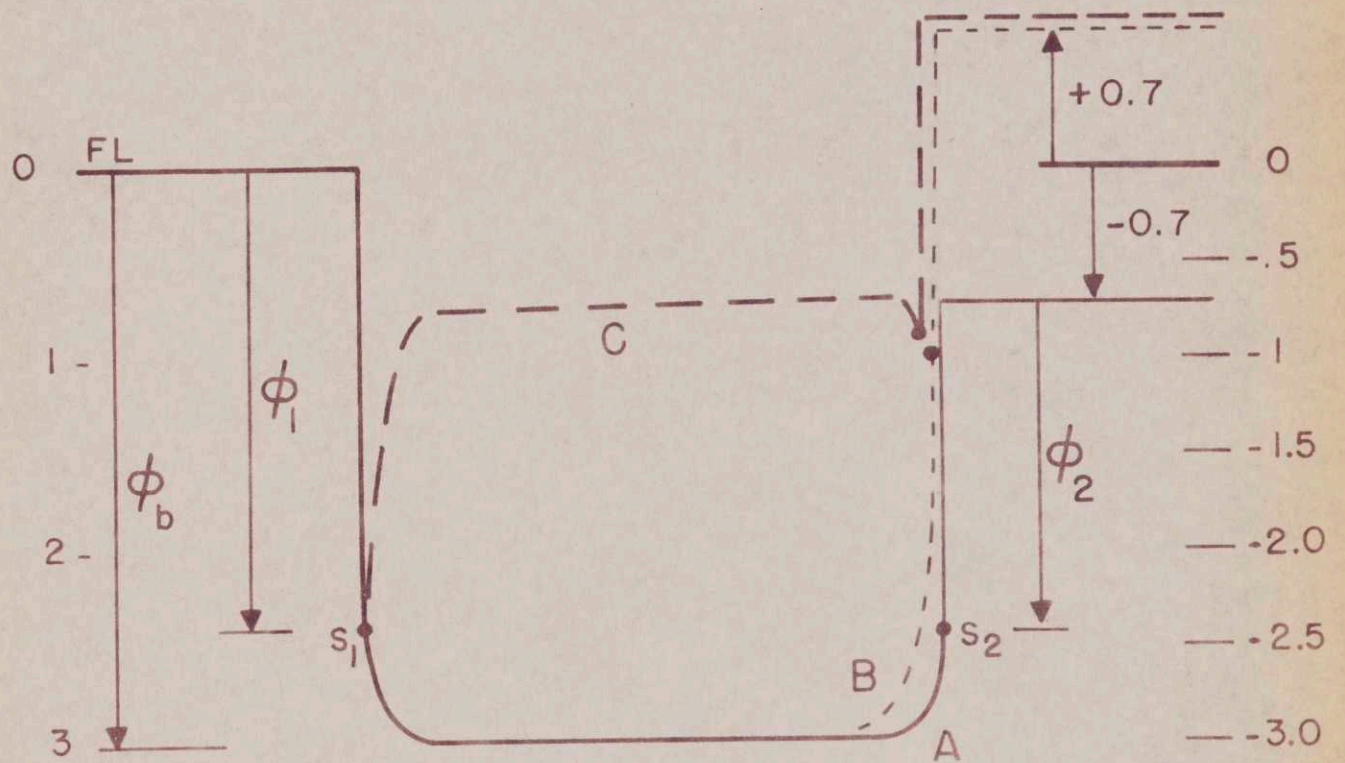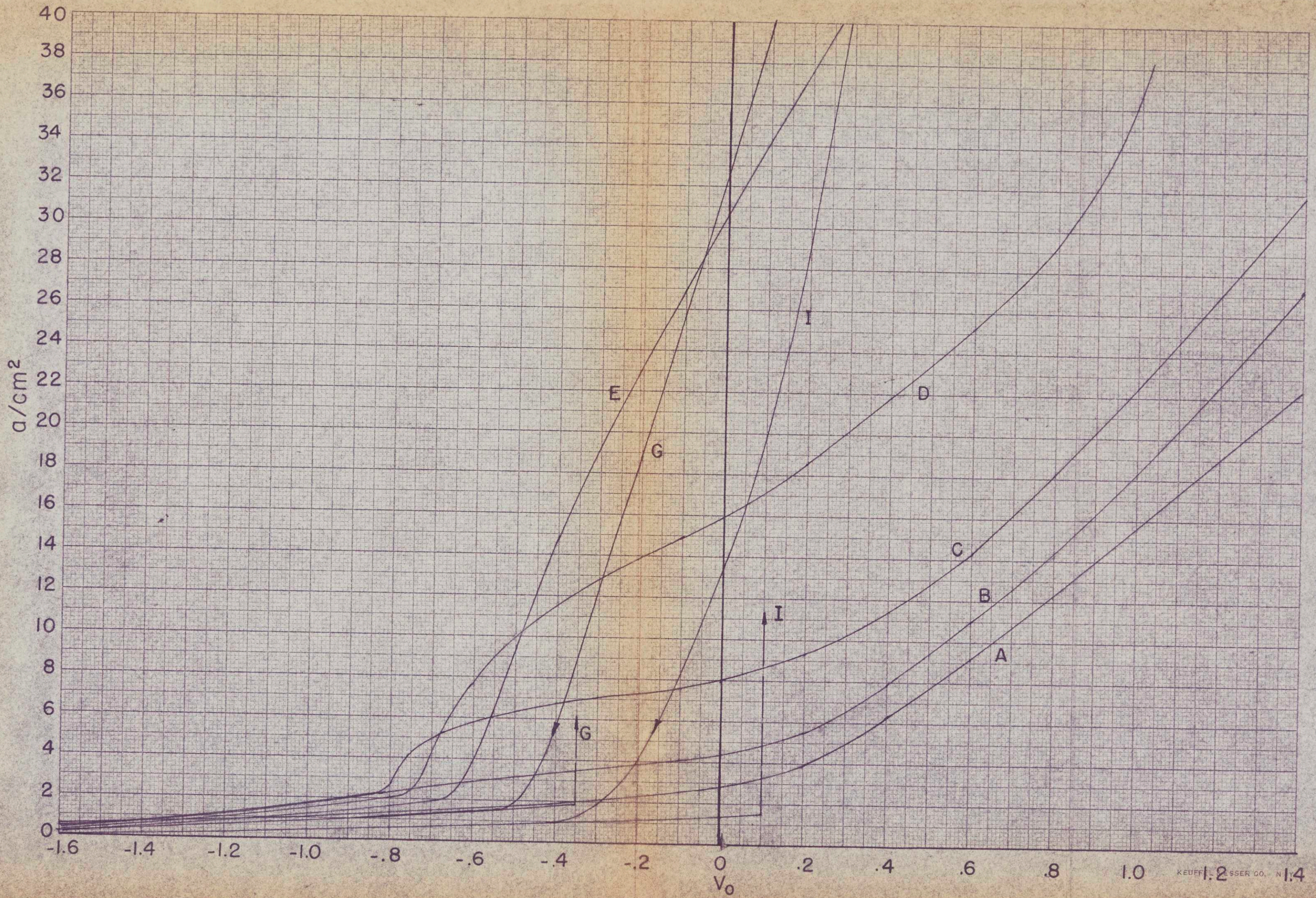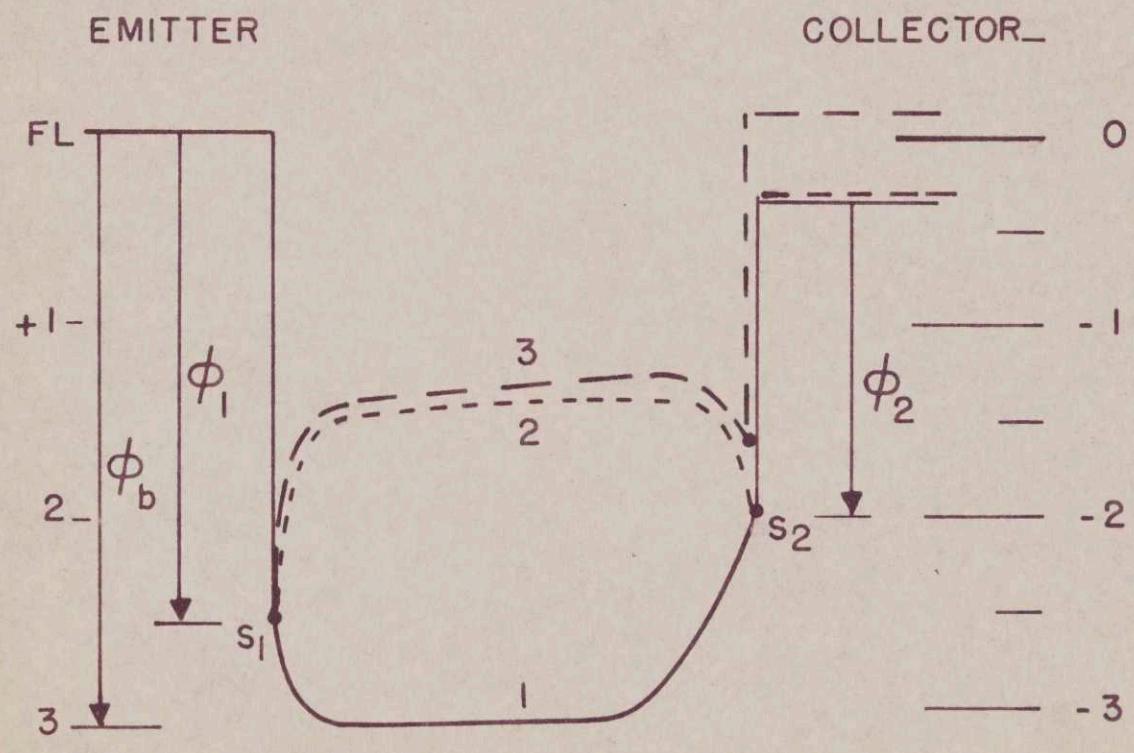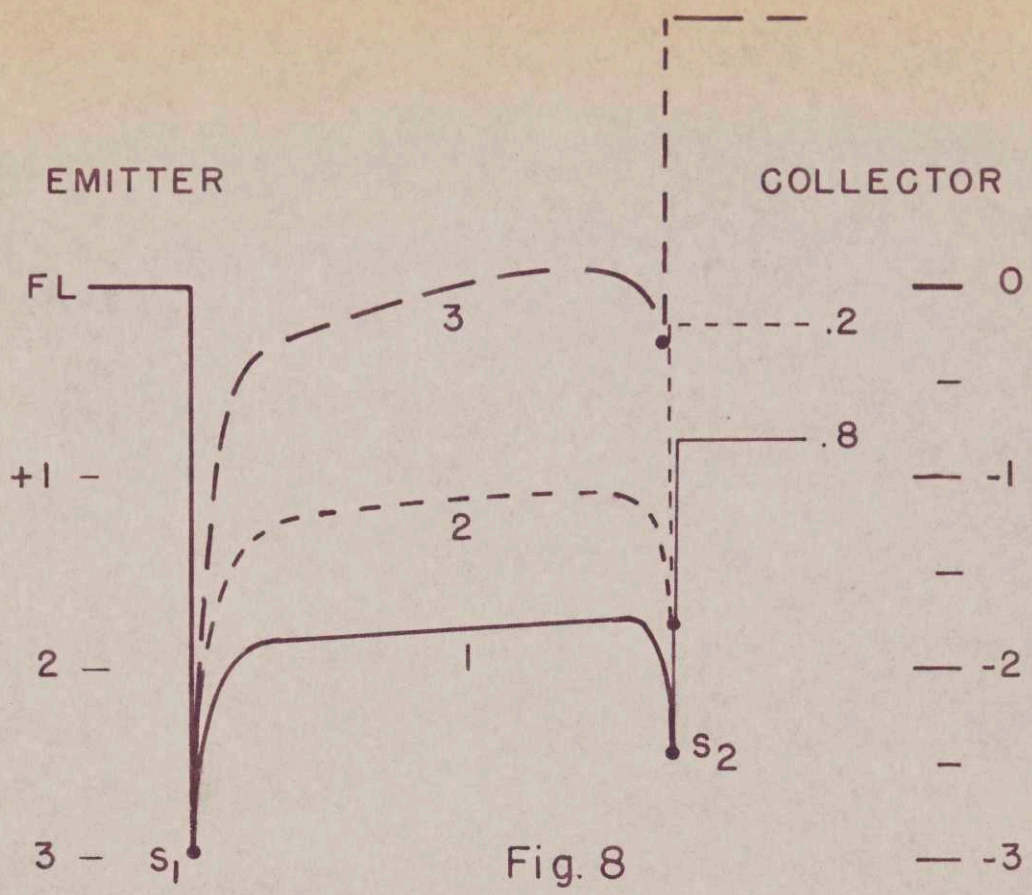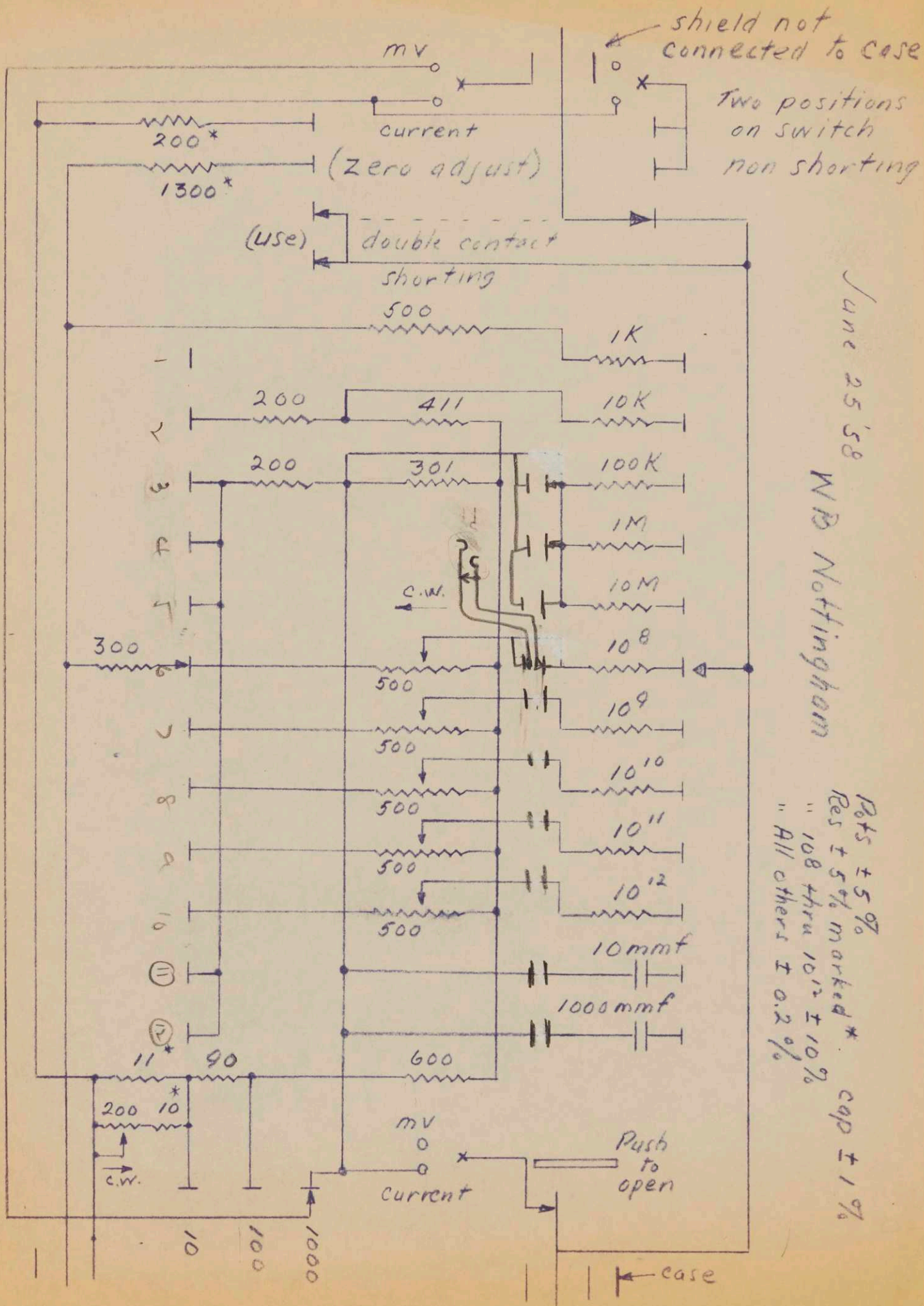
June 25 '58
WB Nottingham

Pots ±5%
Res ±5% marked *
" 10⁸ thru 10¹² ±10%
" All others ± 0.2%
cap ±1%

A Report Related to the Meeting of a
Committee on Thermionic Energy Conversion

held

October 11, 1961

Present were: E. N. Carabateas
G. N. Hatsopoulos
A. W. Mullendore
E. W. Schafer
D. C. White
D. R. Whitehouse
W. B. Nottingham

Some general remarks were made by Professor White to call attention
to two aspects of the need for committee action which were: (1) long-range
considerations on the development of a coordinated program, and (2) the short-
range need for a quarterly report to ARPA.

In order to give a background to the overall appearance of the thermionic
energy conversion program, now in operation on a nationwide basis, the
questionnaire dated August 5, 1960 was passed out. That questionnaire lists
many of the research efforts that should be undertaken and also gives a partial
list of people who are actively engaged at the present time. Copies of the report
dated September 2, 1960 which recorded the results of the questionnaire were
not available in sufficient quantity to pass out. These results were reviewed
however.

After considerable discussion, it seemed that there was a general concensus
of opinion that this group should form a nucleus by means of which the various
independent projects that are going on related to thermionics should be brought
forward and discussed in considerable detail so that coordination now totally
absent can be promoted. Not only should the projects be coordinated but in
many cases it seems as though presently-separated groups could help each
other in many respects. At present, those of us who need help from other
groups have no way of knowing that there are skills and interests that bear
directly on some of these problems.

Drs. Hatsopoulos and Carabateas presented in some detail a report on
the projects now underway associated with the Mechanical Engineering Dept.
Only one of these projects is directly related to the ARPA contract, whereas
the others derive support from other means. The projects mentioned included:

first, conduction of heat by cesium vapor. This scheme involves the measurement of heat flow from a hot surface to a cooler one in high vacuum in order to determine the radiant heat transfer and finally in the presence of cesium vapor at various concentrations to evaluate the heat conductivity of the vapor. Presumably the experimental data will be analyzed in order to try to set up a theoretical understanding of this heat-transfer process as the concentration is changed from that for which the atomic mean-free path is long compared with the spacing to the other extreme of high concentration in which the mean-free path is short compared with the spacing.

A second project relates to the researches of Mr. Norris who is working in two separate areas. In one, he expects to study the volt-current curves of the thermionic diode having plane parallel configuration with a 10 mil spacing and an emitter made of "single crystal" tantalum. Since this is a glass tube, the cesium pressure range for which the study can be made will be limited to relatively low values. It is hoped that useful results will come from this study especially if the experimental data are taken over a suitably wide range of applied voltage. Such data should include measurements with a collector at negative potentials greater than that associated with the open-circuit voltage. This should be done under a variety of conditions and the voltage current curves should be carried through applied potentials of zero and positive values as far as seem to be warranted as the experiment procedes.

The other Norris project relates to the thermionic emission from a single-crystal tungsten wire in cesium vapor.
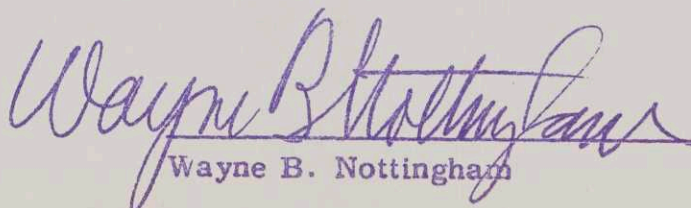
A third study in the Mechanical Engineering Dept. involves the use of a Philips dispenser cathode and the nickel collector. The purpose of this study seems to be to evaluate the concept that even with a low work-function emitter an ion sheath can be maintained after it has generated. The collector used was nickel and the spacing 1/4 inch. The overall objective of this study seems to be a little unclear in that plasma operation with applied potentials out of the converter range were needed to maintain the plasma and as a result a detailed analysis of the observed data along with their evaluation was considered un- necessary. It seemed to this observer that the configuration used was not one particularly adapted to the accomplishment of power generation in the plasma mode from a low temperature emitter and yet the data could have had value.

The fourth research underway is related to the attempt to evaluate the thermionic properties of thoriated molybdenum. In this research the thermionic

emission was observed in a plane parallel structure as a function of the temperature and the applied voltage. The very low maximum temperature to which this specimen was taken would seem to indicate that the usual activation procedure as carried out with thoriated tungsten could not be accomplished. It is therefore very questionable as to what the value of a research associated with the mixture of powdered molybdenum and thoria could accomplish. Such a surface would certainly be extremely nonuniform in its emission capability. After considerable discussion it was not at all clear that the basic objectives described as the motivation for the program were, and how this choice of materials served as the most promising choice to satisfy these objectives.

what

Although no formal conclusions came from this meeting, the suggestion was made that prior to another meeting, approximately two weeks from now, each member should prepare in writing a brief description of projects underway along with an explanation as to why those projects were chosen in favor of others that might have been exploited to satisfy some basic need or objective. These project descriptions are to be hectographed by the individual groups preparing them and supplied to my office for distribution to members of the committee and to such other members interested in this general project. These should be designated by Mr. Schafer.

The review of these projects in this manner might lead to a better coordination and better evaluation of all projects now in operation. It might make future operations more useful if the interested groups would make "seminar" presentations of their ideas so that they can be discussed in a critical manner in advance of any extensive expenditure of time or money. Such critical analysis might serve a number of purposes, one of which would be to call attention to the responsible person or group of previous work or even studies presently underway in other institutions or by other groups. A second purpose would be cooperation between the various groups which could be fostered in this manner since very often the success of an electronics experiment depends on the quality of the materials used in that experiment. Thirdly, once the experiment is well underway, it is possible that complexities that arise in the interpretation of the experiment can be ironed out to some extent by the detailed and critical exchange of ideas that would be stimulated by such presentations.

Wayne B. Nottingham