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ELECTRON TEMPERATURES OF THERMIONIC CATHODES

Preliminary Report

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Massachusetts Institute of Technology

January 8, 1959

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Introduction

The energy distribution of the electrons emitted from a cathode of uniform temperature can serve as a means of determining its temperature. The acquisition and interpretation of such data involves the application of suitable experimental techniques and a sufficient knowledge of thermionic emission properties to avoid misinterpretation. It is the purpose of this note to present some of the theoretical background, and the equipment needed for these measurements.

Theory Applicable to Electron Energy Distributions from Plane Emitters

In an idealized plane-parallel structure as illustrated in Fig. 1, the electron current emitted by the cathode and measured by means of a meter in the collector circuit follows the "Boltzmann Law" given as Eq. 1 if the applied potential is sufficiently great in the negative direction to maintain at all times a negative surface charge on the collector.

$$i = i_o e^{-\frac{V}{V_T}} \qquad (1)$$

In this equation i is the observed current; i_o is an empirical constant; V is the applied voltage as indicated on the voltmeter; and V_T is the electron-volt equivalent of the temperature as defined by

$$V_T = \frac{k}{q} T = \frac{T}{11600} \qquad (2)$$

In this equation k is Boltzmann's constant (see attached Table of Constants) for its value); q is the electronic charge; and T is the temperature expressed in ^oK.

With a plane parallel structure of spacing w and an emitter temperature V_T, there is an upper limit to the current density that can flow from the emitter to the collector without its being inhibited by the presence of space charge. The equation for computing this maximum current density is:

$$I_m = 7.729 \times 10^{-12} \frac{T^{3/2}}{w^2} = 9.664 \times 10^{-6} \frac{V_T^{3/2}}{w^2} \quad a/m^2 \qquad (3)$$

An accurate determination of the true work-function of the collector results from an analysis that depends only on the observed I_m, the applied potential V_R and the emitter temperature T. For current densities less than this critical value I_m the Boltzmann equation applies unless the temperature limited saturation emission also falls below this value. In that case the Boltzmann equation applies over the range of voltage for which the electric field between the surface of the emitter and the surface of the collector is retarding for electrons. As the electric field at the surface of the emitter approaches zero, the current no longer rises according to Eq. 1 but within a very small range in the applied voltage, the current becomes practically constant and space charge is of little or no significance over the entire range in applied voltage when the saturation value is less than I_m.

In a practical diode the current measured on the meter generally includes two components that interfere with the direct interpretation of the meter reading as being electron emission current from the cathode. With the applied potential approximately 6 volts negative, the true emission current is so small as to be completely negligible and under that condition the observed current is the sum of the leakage current over the structural surfaces both inside and outside of the tube under test and the photoelectric emission current from the collector itself which is receiving light from the hot cathode. The tube under test should be shielded electrostatically, and also it should be shielded from all sources of light other than that from the hot cathode. For oxide-coated cathodes it is generally true that the true electron emission is negligible over the applied voltage range of -2.5 volts to -6 volts and greater, and therefore within this range the leakage current and the photoelectric current can be measured with sufficient accuracy so that as the electron current takes on a value of only 10 per cent of the background current, the electronic contribution can be determined. As the electron current increases in accordance with Eq. 1, it generally becomes so large that the background current correction may be neglected. These points are illustrated by Fig.. 2.

In order to determine the electron temperature it is not necessary to evaluate the empirical constant of Eq. 1 which is i_o. It is necessary to observe the true electron current over as many orders of magnitude (factors of ten) as possible below the current density value which can be computed from Eq. 3. It is best to plot the observed data on suitably chosen semi-logarithmic paper to establish the fact that Eq. 1 is an accurate representation over the entire range of observation. (See Fig. 3.) Having chosen the best straight line to represent the data, its intercept on the voltage scale at two widely separated orders of magnitude of current serves to determine the electron temperature with accuracy. The arithmetical procedure is illustrated by Eqs. 4, 5, and 6.

$$\log_{10}\left(\frac{i_2}{i_1}\right) = n = \frac{V_1 - V_2}{2.3\ V_T} \qquad (4)$$

$$V_T = \frac{(V_1 - V_2)}{2.3\ n} = \frac{T}{11,600} \qquad (5)$$

$$T = \frac{5040}{n}\ (V_1 - V_2) \qquad (6)$$

A typical numerical example may serve to clarify the above equations. The intercept of the straight line at a current value of 10^{-10}a occurs at a value of V_1 of 1.990 volts. The second intercept V_2 occurs at 1.351 volt for a current of 10^{-7}a. Thus the value of n in Eq. 4 is 3 and the computed value of V_T is 0.0925 volt or the temperature T is 1075°K

<u>General Circuit Description</u>

A generalized circuit diagram is shown in Fig. 4. Note that this figure does not include the precision potentiometer which can be connected by means of a selector switch to measure potentials P_1, P_2, P_3, and P_4. As shown here the heater supply is an 18 volt battery with a suitably variable resistance R_H which will permit a very fine control of the heating current to obtain precisely the desired voltage drop at P_1. Although not absolutely necessary, it is desirable to have a standard resistance in series with this heating circuit so that the precise value of the heating current can be determined. This standard resistance is shown as R_S and should be chosen to permit a four figure determination of the IR drop over the resistance by the connecting of the potentiometer to P_4. During the time required for a single run, it is necessary to have such good stability of the heater power source (to be described in more detail in a later section of this report) that the power input to the heater is maintained constant to four figure accuracy. Note that the potential of the tube grids shown is determined by the potential divider V_g. An isolated 6 volt battery may serve to establish this potential. The way it is shown, a coarse and a fine control are available. The current to the two grids, which are connected together through a 30 ohm resistance, is measured on the Rawson multimeter which has a sensitivity range from 100 microamperes to 1 ampere full scale. The potential used to establish a fixed current value I_g is measured by switching the potentiometer to P_2.

The entire system is maintained at a suitable voltage with respect to the ground connection by the potential divider identified as V_p. Under these circumstances the switch S_1 is closed and the actual value of the potential can be measured with a potentiometer by connecting to P_3. It is often convenient to use the potentiometer itself as this bias control. When this is done the potentiometer is connected directly to P_3 and maintained in operation there while switch S_1 is open. In that manner the precise value of voltage required to bias the cathode with respect to the electron collecting plate is read directly from the potentiometer. The vacuum tube electrometer is one with a feedback loop such that with full scale operation the deviation of the plate potential with respect to ground is significantly less than 1 millivolt. The circuit is arranged so that the output current can be measured on a meter which measures a voltage drop within the feedback circuit. This voltage drop is 1 volt when it corresponds to full scale output. For example, if the current being measured is 10^{-10} amp an input resistance of 10^{10} ohms is used. In case this resistance is as much as 20 per cent high or low with respect to its nominal value, the feedback circuit can be adjusted so that the output meter will nevertheless read precisely full scale when precisely 10^{-10} amp is flowing in the input circuit. Details concerning any of these circuits will be made available to anyone interested.

r = $\sqrt{\frac{2m}{q}}$ $\frac{V_\perp^{1/2}}{B}$ = 3.37 x 10⁻⁶ This is correct

Application of Theory to Practical Structures

Although the above theory applies to a very specialized structure, the electron temperature method of determining cathode temperatures may be applied to practical tube structures that contain many elements and bear little or no relation to a plane-parallel configuration. Data presented in Fig. 3 apply to the receiving tube of Type 12V6GT. These results were first reported to the Seventeenth Annual Conference on Physical Electronics in 1957[1]. The tube under test was mounted in a socket so that a strong magnetic field of about 3000 gauss could be oriented with its field lines along the direction of the short axis of the internal tube structure. The exact orientation of this field is not critical and the strength of the field was such that an electron with a velocity component perpendicular to the field sufficient to correspond to one electron volt of kinetic energy would have a spiral trajectory along a line of force with a radius about this line of force of 16 microns. The general equation for calculating the radius in terms of the electron volt equivalent $V_\perp$ of the energy associated with the transverse component of velocity and the magnetic induction B expressed in webers/m^2 is

?

$$r = 4.77 \times 10^{-6} \frac{V_\perp^{1/2}}{B} \text{ m} \quad (7)$$

The equivalent equation if the magnetic induction is expressed in gauss and the radius expressed in cm is:

x

$$r = 4.77 \frac{V_\perp^{1/2}}{B_G} \text{ cm} \quad (8)$$

Since the thermal energy is of the order of 0.1 ev a field as weak as 300 gauss gives a radius of approximately 5×10^{-3} cm. These figures are given so that the reader can estimate the size of this circle in comparison with the aperatures of the particular tube structure under test. It is

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(1) W. B. Nottingham, Report on the 17th Annual Conference on Physical Electronics, M.I.T. 1957, p. 43

generally not difficult to obtain magnetic fields within practical tubes even of the electron gun type of structure in the range between 300 and 3000 gauss. Under these circumstances the electrons leave the cathode and spiral along the lines of magnetic field toward the collector. In case they do not have sufficient initial kinetic energy associated with the velocity component along the direction of the magnetic field to travel all the way to the collector, they return to the cathode and are re-absorbed there. Thus, in the presence of a moderate magnetic field, the electron current to the collector follows Eq. 1 if not inhibited by space charge.

Usefulness of the Positive Grid

In tube structures that contain one or more grids, it is generally advisable to connect the available grids together and operate them at a suitably chosen positive potential of not more than one or two volts applied with respect to the cathode. The purpose of this positive potential is to minimize the influence of space charge in the immediate neighborhood of the cathode. In most examples, the electron current collected on the grid system may be varied from 50 microamperes to 2 milliamperes without influencing the current measured at the collecting plate more than one or two per cent. If the grid is made too positive, however, and an observation is made with a high retarding potential, that is, a small current received at the plate, it is not unusual to find the observed plate current to be extremely dependent on the grid voltage, and the current may be 100 to 1000 times greater than expected. Analysis shows that under these circumstances electrons are oscillating back and forth near the grid space and are exchanging energy with each other, thus producing some abnormally high electron energies that are in no way characteristic of the cathode temperature. For a given tube type, a skilled observer should determine the maximum grid voltage that can be used without the generation of these oscillations. At any lower voltage, the oscillations do not occur. A second cause of oscillations in multi-grid tubes results from a capacity-inductance relation between the grids themselves if they are simply connected together at the socket. It is best to connect a small resistance of the order of 20 to 30 ohms directly in series with each individual grid connection before the grids are tied together. This resistance dissipates energy and lowers the probability that an internal oscillation will develop.

To summarize this section, the cathode temperature in a practical tube may be determined by operating the tube in the presence of a strong magnetic field with the current flowing to the grid system held at a suitable constant value while the current to the collector is measured as a function of the applied potential difference between the cathode and the collector itself. Corrections must be made for leakage current and photoelectric current before the true electron current to the collector is plotted on semi-logarithmic paper as a function of the applied voltage. The temperature is determined by Eq. 6.

General Remarks With Regard to the Circuit and Its Arrangement

It is not worthwhile to use the electron temperature method unless the necessary steps are taken to ensure the control and measurement of the important quantities. Specifically, the heater power must be maintained constant to such a high degree of accuracy that deflection meter measurements of the power input are not sufficiently accurate. Since it is generally necessary in order to eliminate spurious pickup to heat the cathodes by direct current, the heater current and the drop in potential across the heater can be measured with the help of a precision potentiometer. A more expensive device which may also be used is the digital voltmeter which can be obtained that reads directly to four figure accuracy. Not only is it necessary to maintain the heater power constant, but it is necessary to measure the applied voltage on the electron receiver to an accuracy better than one millivolt. This requirement, therefore, also calls for four figure accuracy. For most purposes other voltages and currents can be measured with good, but inexpensive, equipment. A list of needed equipment is given below.

When the measurement laboratory is located in a sufficiently favorable environment so that high frequency disturbances do not invade the area, simple shielding of most of the parts used in the experimental arrangement is sufficient. This easy solution to the interference problem cannot be used in all cases, and therefore this note warns the reader that misleading results may come because of such interference unless special precautions are taken. The method used by the writer under such circumstances involves the entrance of power from the ac supply line along a single line to a shielded one-to-one power transformer such as Freed Transformer IT-2 or IT-3 or UTC-R-74. This transformer then becomes the center for all equipment branches. Leads are brought from this center coaxially to each important element of the circuit. Since the elements themselves must have cross connections, the only method for completing these connections is to do it by bringing all leads coaxially to the power center so that the connections can be made there. If this is not done, loops that become coupled electromagnetically to the outside disturbances give trouble when powerful high frequency fields are present in the measurement area.

List of Desirable Instruments and Their Properties

Although the equipment described in the following list of items has never been assembled in its complete form for the purpose of electron temperature determination, the individual parts needed have been constructed. There is every reason to believe that when these are assembled, they will serve their purpose. It is part of our M.I.T. electronics program to make such an assembly in the near future. The items needed are listed and a brief description is given for each.

Stable Power Supplies

Inspection of Fig. 4 shows that it will be convenient to have 3 stable supplies for the operation of the circuit not including the supply for the potentiometer. This total of four can be reduced by combining V_g and V_p in a manner that would permit the use of a single supply for these two. Still further reduction in the number of units needed would be to combine the filament supply also to obtain its power from the same source. Our present experience depends on these supplies all being storage batteries maintained in good condition in order to have the necessary stability. An engineered unit could undoubtedly derive the power needed from a well-regulated transistorized, low voltage, high current supply system.

The power supply for the potentiometer falls in a different category since it must of necessity be completely independent so that the potentiometer can serve a multiplicity of purposes. The potentiometer which we have used in the past requires a supply voltage of approximately 24 volts and a current of approximately 0.2 amp. The shielded potentiometer which we are recommending in this report will require approximately the same voltage but will operate with the current through the potential divider of 0.01 amp. A brief description of this potentiometer is given in the next section.

Potentiometer for Four Place Accuracy

The Leeds and Northrup Type K potentiometer can serve to give an accuracy of potentiometer readings to 5 or even 6 significant figures. Unless the potentiometer is modified in the factory for high voltage operation, it does not measure directly more than 1.6 volts. Our laboratory has a number of modified units which measure to 16 volts and these are found very convenient and desirable for our work. The disadvantage even of this instrument is that it is not properly shielded. We have, therefore, undertaken to design and build a potentiometer capable of measuring up to 21 volts and based upon component parts that are easily available. This potentiometer when finally constructed will have three ranges of which the high range has a maximum value of 21 volts; the medium range 2.1 volts; and the low range 0.21 volt when the unit is powered by our transistorized 26 volt supply. The output of this supply may be reduced so that we will have again three ranges, each one a factor of ten lower than those just mentioned. This unit is being constructed and therefore has not been tested. Details may be obtained as soon as we have had some experience with this design. The cost of the potentiometer and the power supply will probably be considerably less than the Leeds and Northrup potentiometer alone. We desire and expect at least four figure accuracy.

Associated with the potentiometer is a selector switch which allows it to be used for a multiplicity of purposes already mentioned in an earlier section of this report.

Grid Current Meter

Under most circumstances the precise value of the grid current is not important. Any good meter will serve the purpose. We use Rawson multimeters since for some studies we may be interested in reading with reasonable accuracy currents as small as 10 microamperes and currents as large as 10 milliamperes.

If electromagnetic disturbances must be contended with, the meter must be housed in a shielded box and precautions already mentioned followed strictly.

Micro-Microammeter

We have designed and used a semi-transistorized micro-microammeter which has its own stabilized power supply and amplifier unit and an input unit. These are integrated in such a manner as to permit considerable flexibility. A device which is recommended has a current measuring range from 10^{-14} to 10^{-3} amp. Over the range from 10^{-12} to 10^{-3} it is scaled precisely in factors of ten. The input resistances on the very small current range are associated with individual gain control potential dividers which permit this accurate scaling in spite of the deviations from nominal values that occur first in the choice of input resistors and their ultimate aging. Details concerning these circuits can be made available in the future.

Tube Mount, Adaptors and Wiring

The tube mount should be non-magnetic and shaped so as to fit into a suitable magnetic field. This field in many cases can be produced by a fixed magnetron magnet, but in other cases it may be better to create the magnetic field with an electromagnet. The individual using this method of temperature determination must decide details of this kind. The fact that magnetic materials are often used in practical vacuum tubes does not interfere with the usefulness of this method and the suggestion that magnetic materials be eliminated from the tube mount applies mainly so that the strong magnetic field will not be by-passed and distorted by these external elements. The tube must be shielded both electrostatically and all external light from the room eliminated. If this is not done, electron currents in the very low range cannot be measured with the required accuracy.

Care should be exercised in the design of adaptors so that a basic circuit can be used for many tube types since leakage currents must be minimized and objectionable loops which can couple with external interfering sources must be eliminated if possible. Since many commercial establishments where this method of operation might prove to be very useful are located near sources of strong high frequency electric fields, a maximum skill in electrical layout must be exerted in the design, construction and location of all of the equipment so that interference can be reduced far below that which in many other devices would be tolerated.

Concluding Remarks

This report has been prepared to indicate at least some of the requirements that must be satisfied in order that reliable measurements can be made for the determination of cathode temperatures. The user of this method must face the fact that either the job must be done carefully or it is not worth doing at all. When done carefully it becomes one of the best ways of determining cathode temperatures and can be applied to practically any tube structure. Data obtained by this equipment either serves to give an excellent determination of the temperature or in case this fails, it will give valuable information concerning gross non-uniformities of the cathode. Even in the presence of gross non-uniformities considerable temperature information can be obtained although the interpretation of the data is not a routine exercise[2].

In the course of the next few months it is hoped that a prototype assembly of all of the units described in this report will be available in our laboratory for inspection in order to demonstrate the usefulness of this method of temperature determination.

It is anticipated by the writer that a number of laboratories will be interested in acquiring equipment of the type described here for laboratory purposes, and that as experience is gained with its use additional developments will be made to permit a really rapid acquisition of data so that temperature determinations will be made in

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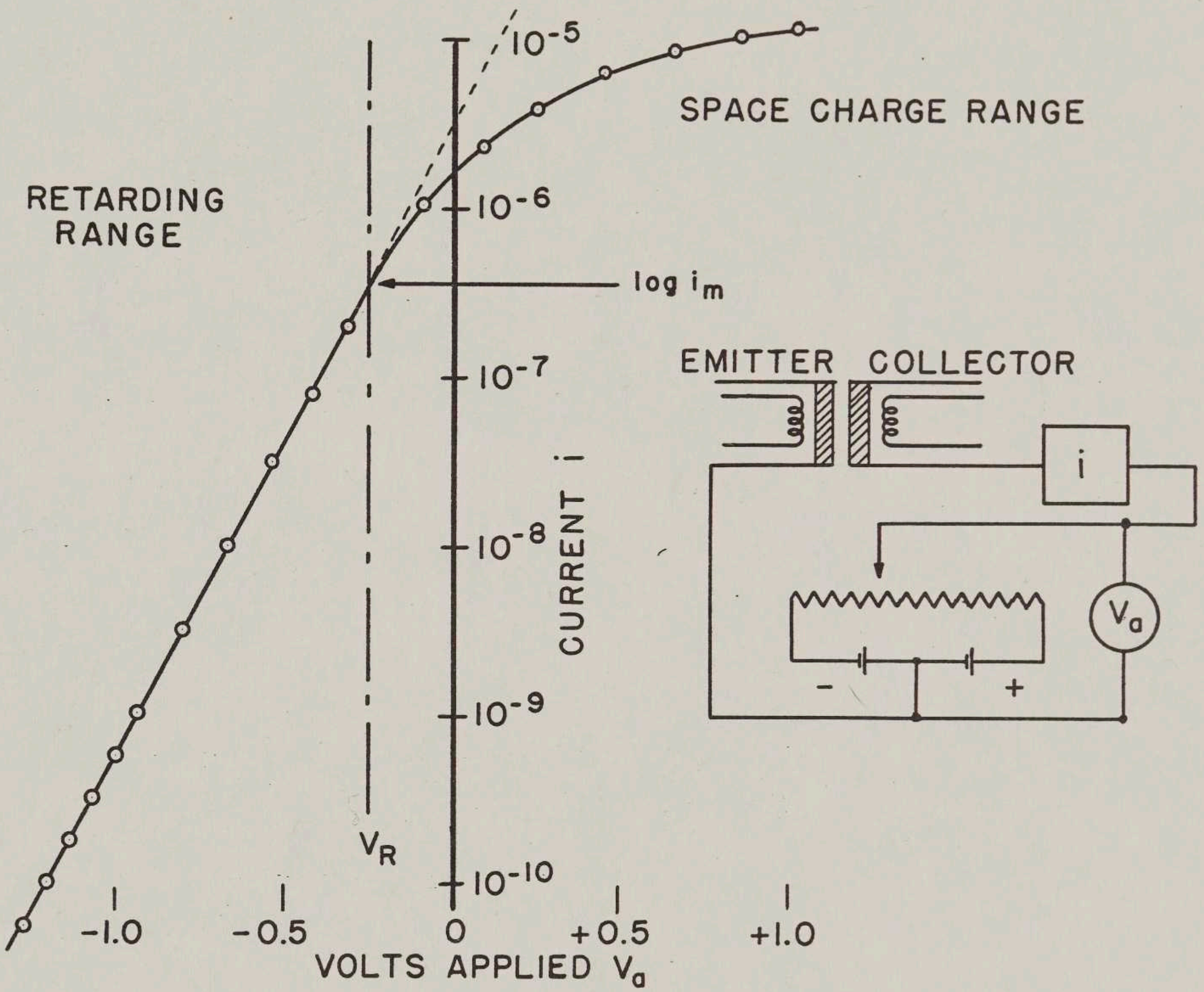
(2) W. B. Nottingham, "Thermionic Emission", Handbuch der Physik, volume 21, 1955, p. 142

a matter of seconds instead of a matter of minutes. In general the equipment described here requires the observer to spend three to five minutes on each temperature determination after the tube under test has stabilized under the operating conditions for which the temperature is being determined. Good electron temperature measurements have been made over the range from 550°K to 2000°K by these methods.

Although the actual cost of parts for assembling equipment for electron temperature measurements is not really great, the assembly of these parts into an integrated working unit can require considerable time and can be done more efficiently if a single organization were to undertake the building of a number of custom designed units. The Dunn Engineering Associates, Inc. of Cambridge, Massachusetts has expressed an interest in this possibility and it is anticipated that as soon as the prototype system has been finished which we expect to use in connection with our laboratory research that they will be in a position to offer to outsiders a product built by them to meet the requirements of this work.

Table of Constants

	m.k.s.	c.g.s.
Boltzmann's constant (k)	1.3804×10^{-23} joule/degree	1.3804×10^{-16} erg/degree
Electron Charge (q)	1.6021×10^{-19} coulomb	4.8029×10^{-10} statcoulomb
Electron Mass (m)	9.1083×10^{-31} kg	9.1083×10^{-28} gm
Planck's Constant (h)	6.6252×10^{-34} joule-sec	6.6252×10^{-27} erg-sec
Temperature Equivalent of 1 ev (q/k)	11,606 coulomb-degree/joule	----------------
0.4343 q/k	5040 coulomb-degree/joule	----------------
Ice Point	273.16°K	273.16°K



RETARDING RANGE
SPACE CHARGE RANGE
10-5
10-6
10-7
10-8
10-9
10-10
CURRENT i
log im
VR
-1.0
-0.5
0
+0.5
+1.0
VOLTS APPLIED Va
EMITTER
COLLECTOR
i
Va
-
+

Fig. 1

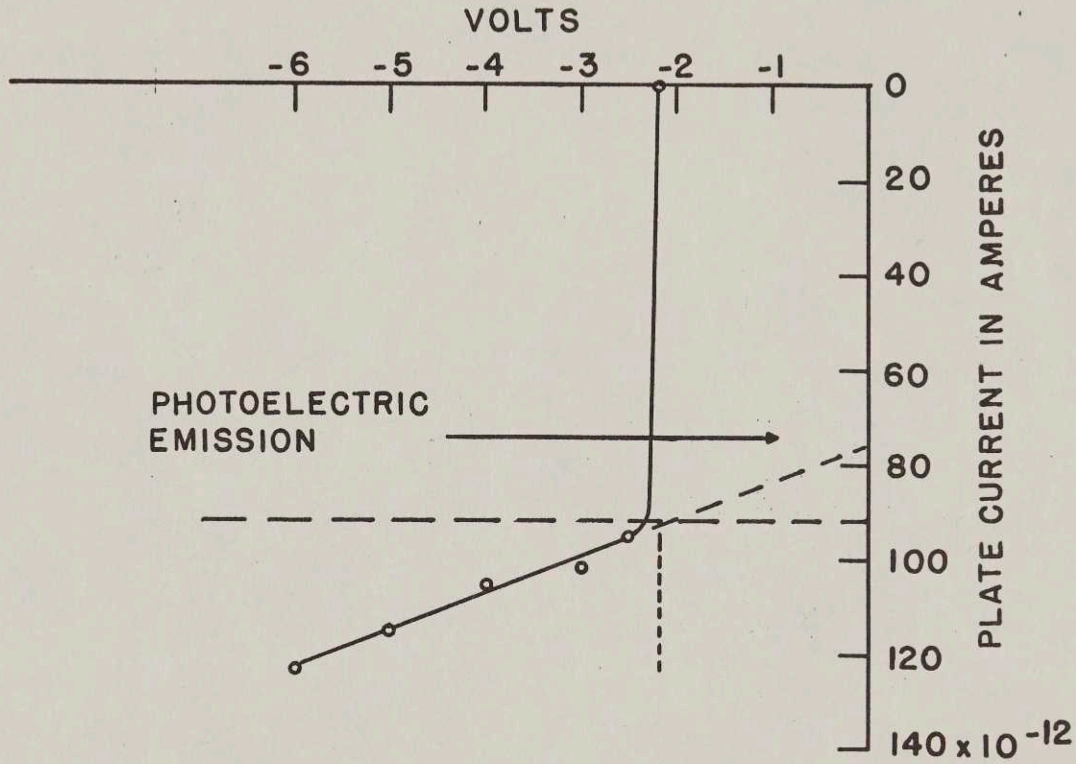


Fig. 2

Example of currents observed with high negative potentials. Heater 12.6 v; temperature $1125^{\circ}K$; leakage resistance 1.3×10^{11} ohms; photoelectric current 7.6×10^{-11} amp.

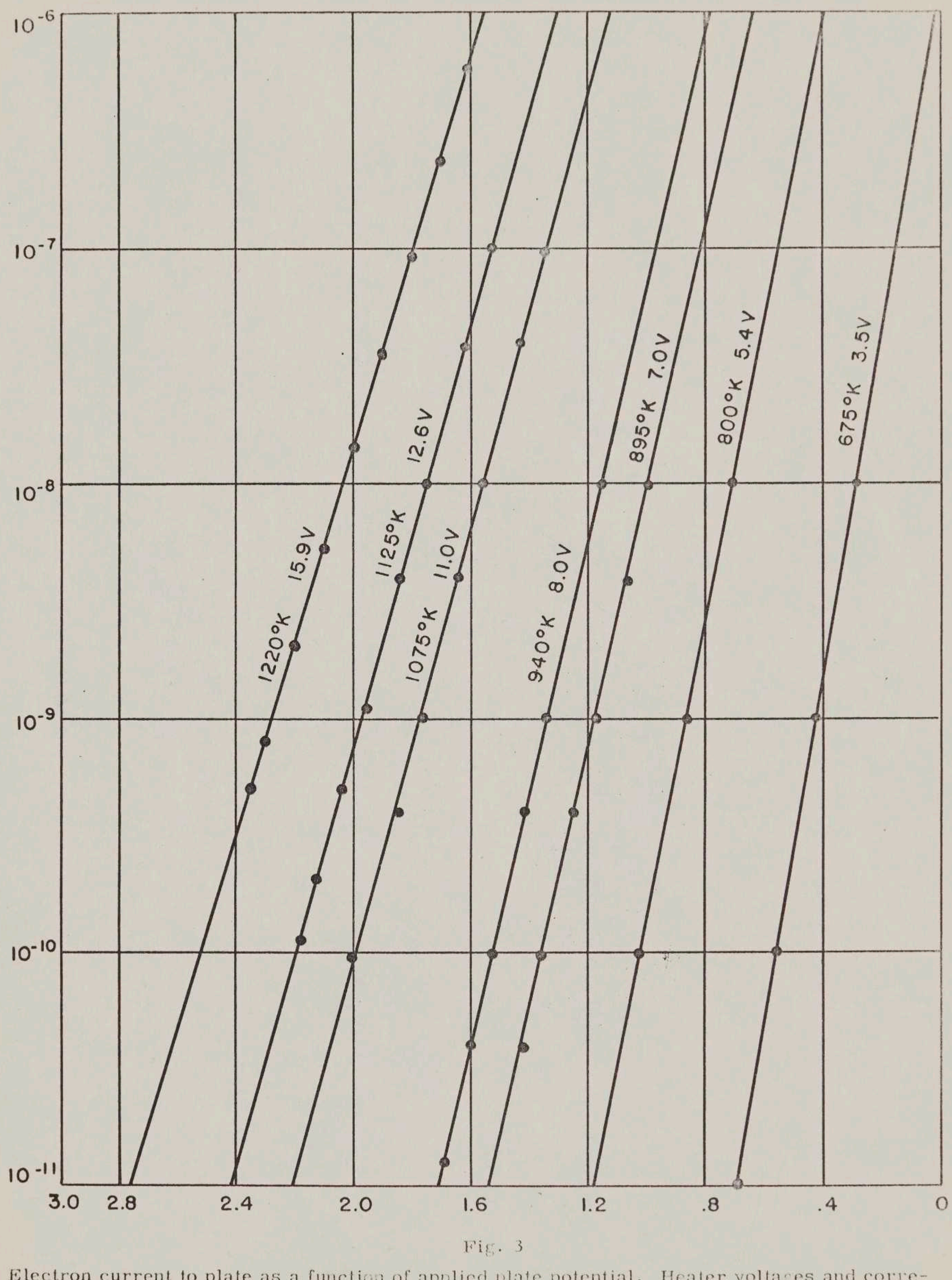


Fig. 3

Electron current to plate as a function of applied plate potential. Heater voltages and corresponding temperatures shown on each line.

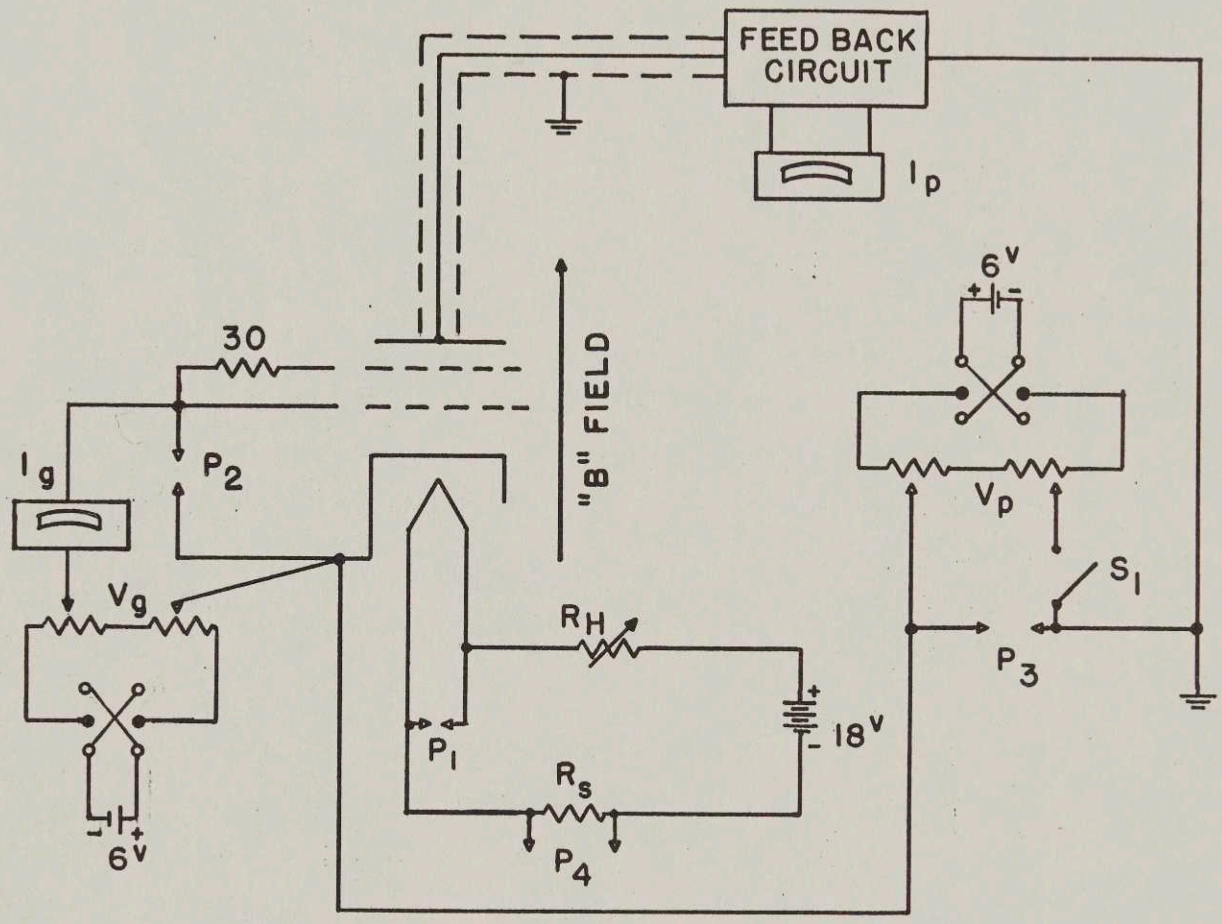


Fig. 4

Circuit for measurement of the electron energy distribution.
Adaptation specifically for tube type 12V6GT.

Supplement to Preliminary Report on

ELECTRON TEMPERATURES OF THERMIONIC CATHODES

A report on the electron energy distribution and its measurement as a means of evaluating thermionic cathode temperatures was prepared and dated January 8, 1959. On page 11 of that report the importance of equipment layout was emphasized. A supplementary statement on this subject has been requested.

The detecter needed to measure the very small currents involved in an energy distribution study usually makes use of a dc amplifier containing such nonlinear components as vacuum tubes and transistors. In general, ac pickup put into these nonlinear elements result in a dc output which interferes with the accuracy of measurement. All such interference must be carefully avoided.

In many commercial instruments the measurement of a current is accomplished by having the current flow through a high resistance which in turn results in a deviation of the potential of the electron collecting element unless the loop gain of the feedback circuit is sufficiently high to make this deviation negligible. It is therefore very important that the observer has a clear understanding of the properties of his detecting instrument so that corrections can be made to offset this difficulty. In some cases, the correction cannot be made with suitable accuracy and results of observations with that instrumentation are likely to be in error.

In some laboratories energy distribution measurements have been made without the control of the electron trajectories that can be accomplished by having a suitably strong magnetic field present. In practical tubes, it is very rarely possible to obtain accurate results without the use of a magnetic field. The reason for this difficulty is that a considerable variation in applied potentials must be used in order to determine the electron energy distribution. If this variation in applied potential results in an alteration in the electron trajectories, then faulty results will be obtained. If one first establishes a true temperature by studying a given tube type with a magnetic field and then determines the correction necessary to correspond to observations in that particular tube type without a magnetic field, routine measurements may be made.

Wayne B. Nottingham