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TITLE The Power Output and Efficiency of Thermionic Converters Connected in Series and Parallel Circuits - Part 1	S A NO 2036	RECOMMENDED FOR OUTSIDE DISTRIBUTION
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STATEMENT OF PROBLEM

The problem is to obtain optimum and off-optimum performance data on a thermionic converter for use in guiding the series and parallel connected thermionic converter experiments and thermionic power plant design.

ABSTRACT

Optimum and off-optimum performance is experimentally obtained for one of the 10 mil spaced, 7 cm^2 emitter area, cylindrical geometry thermionic converters to be used in the series and parallel connected thermionic converter experiment. The results are presented as graphs of output voltage vs. power input, and power output vs. power input. The current is the major parameter in both cases.

The data in these forms are then easily used to compute the power output of series and parallel connected twin converter circuits where the converters have unequal power inputs. The optimum load conditions under which to operate in these cases is then determined.

The results of the experiment are valuable in guiding the remainder of the series and parallel connected converter experiment and in guiding thermionic power plant design.

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INTRODUCTION

This experiment is the first part of a multidiode * experimental program initiated to determine the extent of some of the problems associated with operating more than one diode in a thermionic power plant. The present experiment is to provide data which can be used to estimate the power output of series and parallel connected diodes with non-uniform power inputs. The problem arises from operating a thermionic power plant which has a spacially non-uniform heat source with a resulting variation of power input to the diodes.

The estimated power outputs for series and parallel connected diodes are to be used to guide the remainder of the experiment when two diodes identical to the one tested are actually operated in series and parallel circuits. If indeed these results confirm the predicted power outputs, then only single diode data will be required to predict performance of diodes with unequal power inputs.

The scope of the report includes a brief description of the diode, the experimental procedure, the results, a physical interpretation of the results, and calculations of the performance of series and parallel connected diodes.

DIODE CONFIGURATION

A cross-sectional view of the diode is shown in Figure 1. Materials and dimensions of importance are listed below:

Emitter - Molybdenum

Collector - Stainless Steel T-304

Cesium Reservoir - Copper

Getter - Titanium

Insulating Vacuum Seal - High Alumina Content Ceramic - MoMn - Cu Braze - Kovar Flanges

Interelectrode Space (cold) 0.0100 ± .0003 in.

Stem Area to Length Ratio - 0.0150 cm

Emitter Area (cold) 7.00 cm^2

EXPERIMENTAL PROCEDURE

The data were obtained mainly as volt-ampere curves for a number of constant

* The terms thermionic converter and thermionic diode are hereafter used interchangeably.

power inputs. Also for convenience or when necessary, data at integral values of the current flux (based on emitter area) were obtained. Running plots of the crude data were maintained in the form of volt-ampere curves at constant power in, and voltage-power input curves at constant current to check the consistency of the data.

The details on the methods of data measurements, errors, and corrections are relegated to Appendix A.

Emitter Temperature and Power Input Limits

The maximum emitter temperature, $(T_E)_{max}$, for good lifetime characteristics is estimated at about 1800°C for molybdenum emitters. In the experiment this limit was used as a guide even though for short periods, data were obtained at emitter temperatures up to 1860°C.

The range of power input over which data were taken extends from about 20 to 42 watts/cm^2. The lower limit was arbitrarily selected due to zero power outputs for currents of interest ($3 \leq J \leq 10$ amp/cm^2). The upper limit was mainly due to the emitter temperature limitations.

Maximization of Power Output

The power output, P, was maximized at $T_E = 1800°C$ by adjusting the collector temperature, T_C, to 750°C, the cesium reservoir temperature, T_{Cs}, to 375°C, and the load for V = 0.72 volts and J = 7 amp/cm^2. At this P_{max} the power input, Q, was 41.1 watt/cm^2.

Off-Optimum Data

Current values of J = 3, 4, 5, 6, 7, 8, 9, and 10 amp/cm^2 were used to provide a reasonable spread of off-optimum power outputs (see data graphs). Besides data taken at $(T_C)_{P_{max}} = 750°C$ and $(T_{Cs})_{P_{max}} = 375°C$, off optimum data for T_{Cs} at 350 and 400°C and T_C at 650°C were obtained.

T_C data at 850°C would have been useful but contract funds expired before the data could be obtained. This data was left until last if in the event difficulties occured with heating the collector to 850°C at low Q values, the remainder of the experiment would not have suffered. Eventually this data should be taken because of its interest in space applications where off-optimum operation on the plus side of $(T_C)_{opt}$ may be desirable for radiator weight conservation.

EXPERIMENTAL RESULTS

The data are presented in Figures 2 thru 7 for T_C = 650 and 750°C, and at T_{Cs} = 350, 375, and 400°C. The constant temperature curves on these figures are derived by plotting T_E data vs. V at constant Q with a subsequent transfer of constant T_E points back to the presented figures.

By cross plotting the results in Figures 2 thru 7 in the form of V vs. Q, with J the parameter, a much more useful form is obtained as shown in Figures 8 thru 13. These results are transformed into P vs. Q graphs (Figures 14 thru 19) by simply multiplying the V and J throughout. This results in directly finding the power output for a given J and Q.

The power output and efficiency are plotted vs. J at $(T_E)_{max}$ = 1800°C in Figures 20 and 21. These plots show the maximum power or efficiency obtainable with the limitation of T_E = 1800°C. It is noted P_{max} = 5.05 watt/cm^2 at J = 7 amp/cm^2, and η_{max} = 12.8% at J = 6 amp/cm^2. From Figure 12 these maximum correspond to $Q_{P\,max}$ = 41.1 watt/cm^2 and $Q_{\eta\,max}$ = 39.3 watt/cm^2.

PHYSICAL INTERPRETATION OF RESULTS

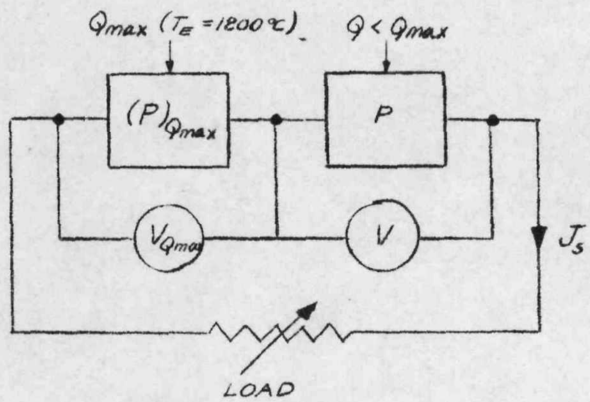
As shown in Figures 20 and 21, the T_{Cs} = 350°C curves fall off rapidly to zero power as J is increased to about 8.5 amp/cm^2 for T_C = 750°C and 7.5 amp/cm^2 for T_C = 650°C. This performance is typical of an emission limited thermionic diode when the saturation current is reached. The operating points at the three cesium temperatures are plotted in Figure 22 on a portion of the Aamodt-Houston J vs. 1000/T_E graph. For the T_{Cs} = 350, 375, and 400°C, emitter saturation currents of 10, 20, and 36 amp/cm^2 are indicated. It is seen then, that the experimental T_{Cs} = 350°C curves saturate very near the emitter saturation current.

The operating points are also plotted on Figure 23, a T_{Cs} - T_E plot to indicate the degree of neutralization and the relative mean free paths. It is seen that all the operating points lie in the ion rich region with β values (1/500 times the ratio of electrons to ions emitted) of about .01, .04, and .1, corresponding to T_{Cs} of 350, 375, and 400°C. The $\frac{d}{\lambda}$ values (ratio of inter-electrode distance to electron mean free path) are 63.5, 106, and 169 respectively.

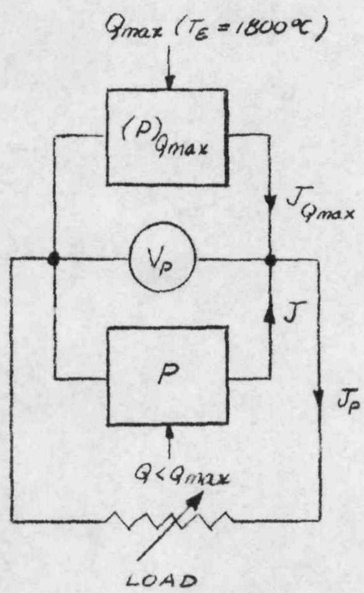
It appears the reason for the lower than optimum performance at T_{Cs} = 400°C is due to the higher values of $\frac{d}{\lambda}$ (i.e., more electron-atom collisions) and higher values of β (i.e., less neutralization).

APPLICATION OF RESULTS

The results will now be applied to the examples of two diodes in series or parallel circuits, schematically shown below.



Two Diodes in Series



Two Diodes in Parallel

The electrical power output and efficiency of the two diodes in these circuits are calculated and graphed in Figures 24 and 25 for values of Q/Q_{max} using the experimental results. The computations are based on the simple laws governing electrical circuits. The series connected diode power is

$$P_s = J_s \left(V_{Q_{max}} + V\right) = \left(P_{Q_{max}} + P\right)_s,$$

and

$$\eta_s = \frac{P_s}{Q_{max} + Q}$$

The parallel connected diode power is

$$P_p = V_p \left(J_{Q_{max}} + J\right) = \left(P_{Q_{max}} + P\right)_p$$

and

$$\eta_p = \frac{P_p}{Q_{max} + Q}$$

As in the experiment, again the maximum allowable emitter temperature is 1800°C. The collector and cesium temperatures on both diodes are to be the same. From the results obtained in this experiment it can be seen that the optimum values of T_C = 750°C and T_{Cs} = 375°C will give the highest power output for the two diodes in either series or parallel circuits if one of the diodes is operating at T_E = 1800°C. (Let it be emphasized the statement just made is with respect to <u>the</u> off-optimum T_C and T_{Cs} temperature data taken thus far. These data are sufficiently removed from optimum T_C and T_{Cs} that the above can be observed. Slight deviations from the optimum T_C and T_{Cs} may increase the performance where one diode operates with $Q < Q_{max}$.)

Examining the results in Figure 18 it is also obvious that for maximum performance from series or parallel connected diodes (which have unequal Q), it is necessary that one of the diodes operate at Q_{max}, with a power output, $(P)_{Q_{max}}$. Notice that Q_{max} is based on $(T_E)_{max}$ = 1800°C and is a function of the current (or voltage, i.e., Figure 12).

Series Connected Diodes

$\underline{P_s}$: Figure 24 shows P_s vs. Q/Q_{max} with J the parameter. A thing of immediate interest is that P_s is directly proportional to Q/Q_{max} in the range of $.8 < Q/Q_{max} < 1.0$ for the values of $(J_s)_{P_{s,\,max}}$. This means if $Q/Q_{max} = 0.8$, then $P_s = 0.8\,(P_s)_{max}$. At $Q/Q_{max} < 0.8$, P_s begins to decrease at a greater rate. Another significant observation is that the optimum value of the current is dependent on Q/Q_{max}. It is seen then for two diodes in series:

$(J_s)_{P_{s,\,max}}$	Limits
7 amp/cm^2	$.92 < Q/Q_{max} < 1.00$
6	$.60 < Q/Q_{max} < .92$
5	$.55 < Q/Q_{max} < .60$

These values of $(J_s)_{P_{s,\,max}}$ may be different for more than two diodes in series.

It can be readily shown that if more than two diodes are operated between $0.8\,Q_{max}$ and Q_{max} and at equal interval fractions, P_s will be decreased by a factor of no less than 0.8. For an example, consider three diodes with power inputs of $0.8\,Q_{max}$, $0.9\,Q_{max}$ and Q_{max}. Using the $J = 6$ amp/cm^2 curve of Figure 24, the corresponding outputs are 3.06, 4.10, and 4.98 watts/cm^2 which totals 12.14 watt/3 cm^2. If all the diodes were operated at $Q_{max} = 39.3$ watts/cm^2, the output would have been $3 \times 4.98 = 14.94$ watt/3 cm^2. The factor the power decreased is $12.14/14.94 = 0.813$.

In a multidiode device, where Q may not vary in a linear fashion as described above, the Q/Q_{max} may, for example, be 0.8, but because Q_{mean} (total Q divided by the number of diodes) may be less than the average value of Q_{max} and Q_{min}, then $P_s/(P_s)_{max} < 0.8$. If $Q_{mean} < \frac{Q_{max} + Q_{min}}{2}$ then $P_s/(P_s)_{max} > 0.8$.

$\underline{\eta_s}$: The efficiency of the diodes in series decreases much less rapidly with Q/Q_{max} than the power output. It is seen in Figure 24 that for a value of $Q/Q_{max} = 0.8$, η_s decreases by only 0.92 or about 1/2 as fast as the power decreases. Below $Q/Q_{max} = 0.8$ the efficiency begins to decrease at a much greater rate. It will also be noted that $(J)_{\eta_{s,\,max}}$ is dependent on Q/Q_{max}.

It is seen for two diodes in series:

$(J_s)_{\eta_{s,\ max}}$	Limits
6 amp/cm^2	$0.9 < Q/Q_{max} < 1.0$
5	$0.64 < Q/Q_{max} < 0.9$
4	$Q/Q_{max} < 0.64$

Parallel Connected Diodes

When comparing the parallel and series results of Figures 24 and 25, the striking difference noticed is that much less power and efficiency is lost for a given Q/Q_{max} in a parallel circuit than in a series circuit.

$\underline{P_p}$: Figure 25 shows P_p vs. Q/Q_{max} with V the parameter. For $Q/Q_{max} = 0.8$, P_p decreases from $(P_p)_{Q\ max}$ by a factor of 0.88 or a little more than 1/2 the degradation of P_s for the same Q/Q_{max}. Also, the rate of decrease of P_p for $Q/Q_{max} < 0.8$ is slower. Another point to notice is the $(V)_{opt} = 0.7$ volt curve applies over the entire range considered ($0.57 < Q/Q_{max} < 1.00$). The V = 0.6 volt curve joins the V = 0.7 volt curve at $Q/Q_{max} = 0.65$.

$\underline{\eta_p}$: The efficiency of the parallel connected diodes decreases by a factor of 0.956 for $Q/Q_{max} = 0.8$. The V = 0.8 volt curve is optimum for $0.73 < Q/Q_{max} < 1.0$. The V = 0.7 volt curve crosses over the V = 0.8 curve at $Q/Q_{max} = 0.73$ and becomes optimum.

CONCLUSIONS

The results will be a useful guide to the remainder of the experiment when series and parallel connected diodes are actually operated.

The results may be of value in estimating the output of a thermionic power plant with non-uniform spacial power distribution until more specific information can be obtained for a particular design.

Appendix A

Measurements and Corrections

Power Input - Readings were taken directly from meters - No corrections were applied.

Power Output - (Voltage and Amperage) Data was read from a 2 point Brown recorder. The recorder was calibrated and corrections were applied. Measurement of the voltage is affected by the location of the potential probes and the probe material. Nickel wire was used for the probes. The collector probe is attached directly, but the emitter probe is connected to a Kovar sleeve with several interposing materials between the Kovar and the molybdenum emitter. The following thermocouples exist: (Nickel and Kovar are assumed to have equal thermoelectric voltages)

	400°C		600°C	700°C		750°C	
Ni	Ko	S.S.	Ni	Mo	(plasma)	S.S.	Ni
−	−	+	−	+		+	−
-5 mv.		+10.8		-22.8		+16 = -1 mv.	

Thermoelectric potentials are given at estimated junction temperatures. If the net effect were actually -1 mv this is indeed an insignificant quantity and less than the error in the voltage measurement. If it is assumed the maximum effect were in the order of 10 mv it is still not a serious error to the data in question.

Emitter Temperature - Emitter temperatures were determined pyrometrically by observing a 31 mil diameter by 90 mil deep cavity in the lower end of the emitter. The window, prism, and pyrometer were calibrated and corrections to T_E data were applied. Corrections for "filament light" in the cavity were not applied because of: 1) difficulty in obtaining a consistent correction, and; 2) the correction's relative unimportance at high temperature ($1650 < T_E \leq 1850$). The emitter temperature in this experiment is used mainly for its limitations which are in the region where the "filament light" is unimportant.

Cesium and Collector Temperatures - Cesium, collector and several other temperatures on the diode were recorded on a 12 point recorder. In addition, T_C and T_{Cs} were controlled by the input of auxillary thermocouples on the collector and reservoir. The thermocouples were not individually calibrated but the same thermocouples were used for the entire experiment. The recorder was checked and found to indicate within the probable error of the thermocouples.

The collector temperature was measured on the outside of the stainless steel cylinder. This does not really affect the usefulness of the data since over the range of power inputs used, the ΔT between the actual collector surface and the outside changes from a maximum of 37°C at $Q = 42$ watts/cm^2 to 21°C at 20 watts/cm^2. This net change of 16°C accounts for less than a 1% change in power output.

Spacing Change Under Operating Conditions - The initial spacing was measured at .0100 in ± .0003. As the emitter and collector are heated, they expand at slightly different rates with a net change in spacing. At T_E = 1800°C and T_C = 750°C the spacing changes to 0.0108 in. At T_E = 1800°C and T_C = 650°C, the spacing changes to 0.0101 in. By corresponding these expansions with the variable spaced diode results, it appears there will be a relative effect of about 5% on the power output data.

Constancy of Performance Over Testing Period - At the beginning and at several times during the experiment an operating point was repeated. There was no measurable power degradation found over the running time of the experiment.

PREPARED BY: J.W. HOLLAND	**ATOMICS INTERNATIONAL** A DIVISION OF NORTH AMERICAN AVIATION, INC.	PAGE NO. OF
CHECKED BY:	MULTIDIODE EXPERIMENTS 7590-2036	REPORT NO.
DATE: 11/6/61	EXP 2 - CYLINDRICAL DIODE - 10 mil sp.	MODEL NO.

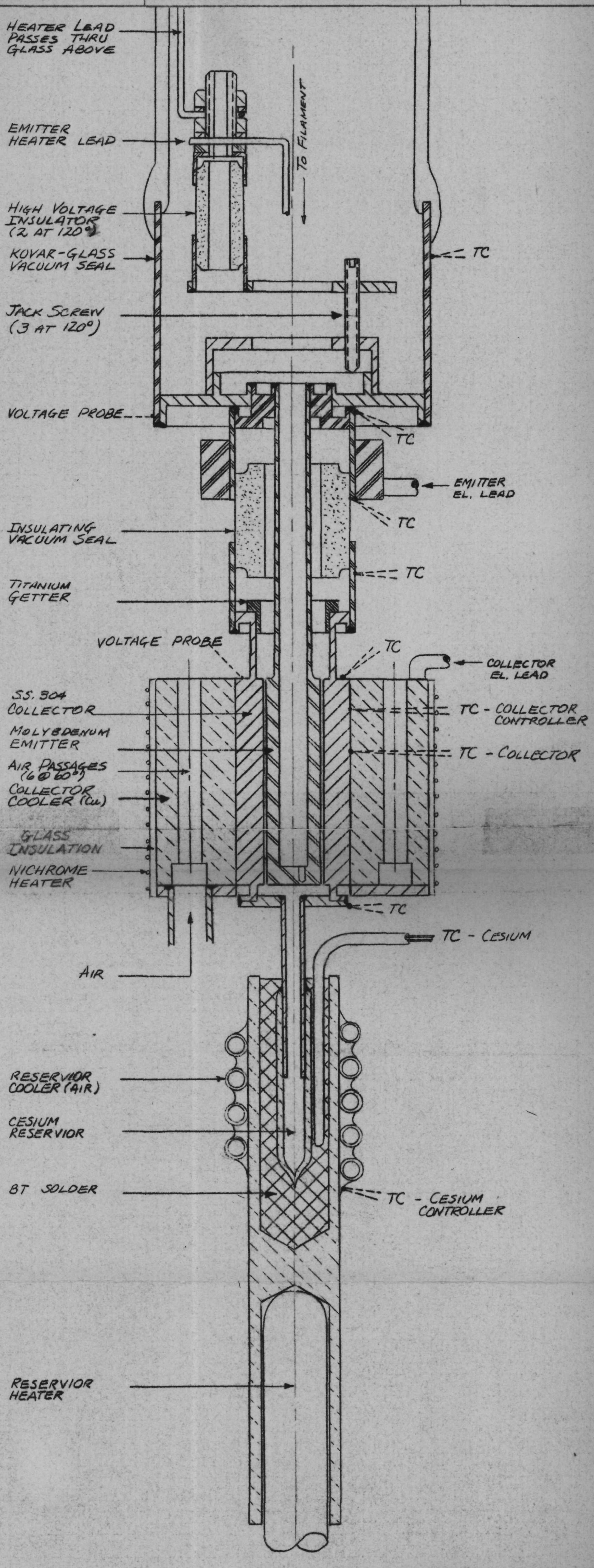


Figure 1
Diode Configuration

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N 152-R-2

Figure 2

Experimental Data Plotted as Amp-Volt Curves at Constant Power Input

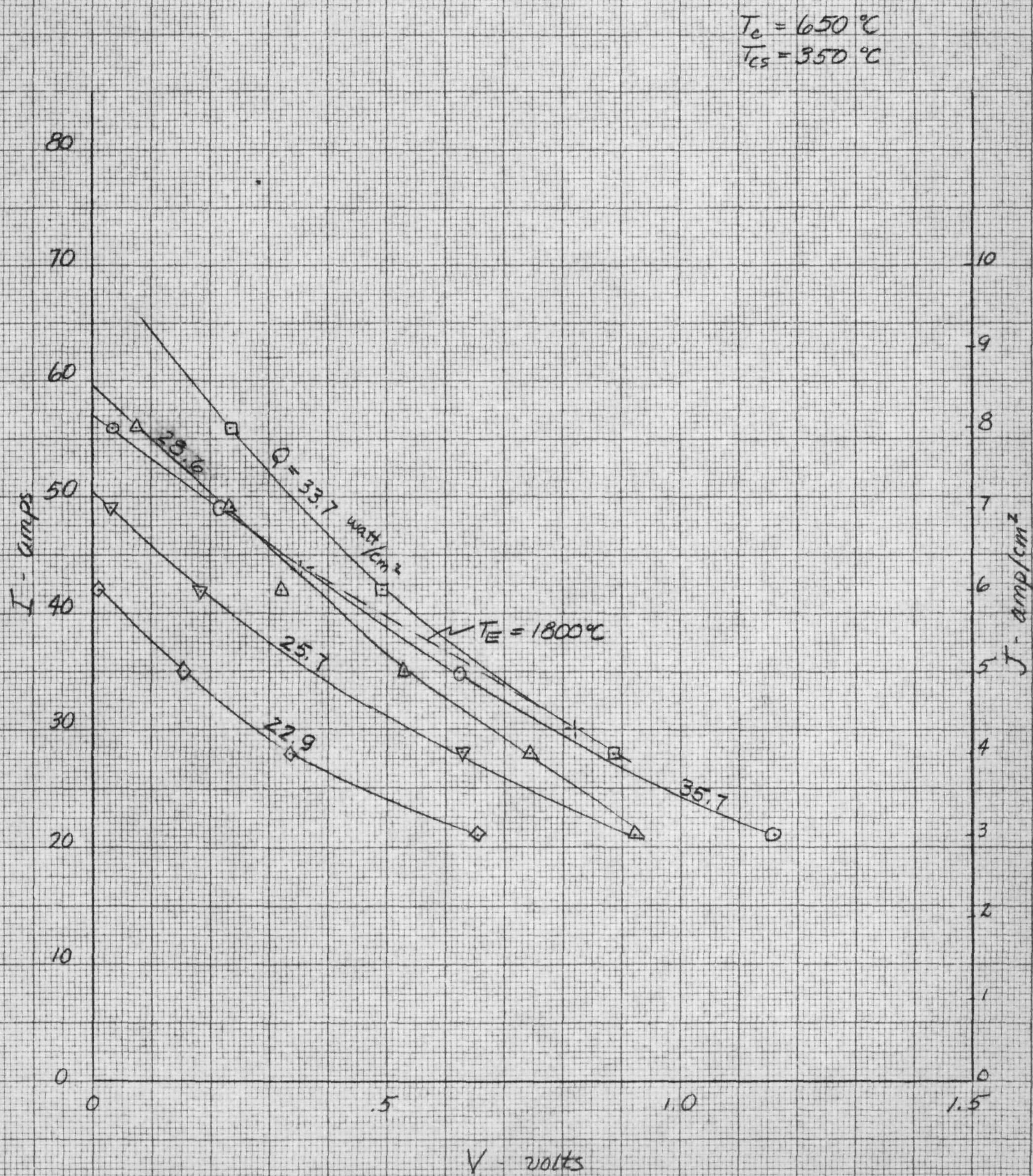


Figure 3

Experimental Data Plotted as Amp-Volt Curves at Constant Power Input

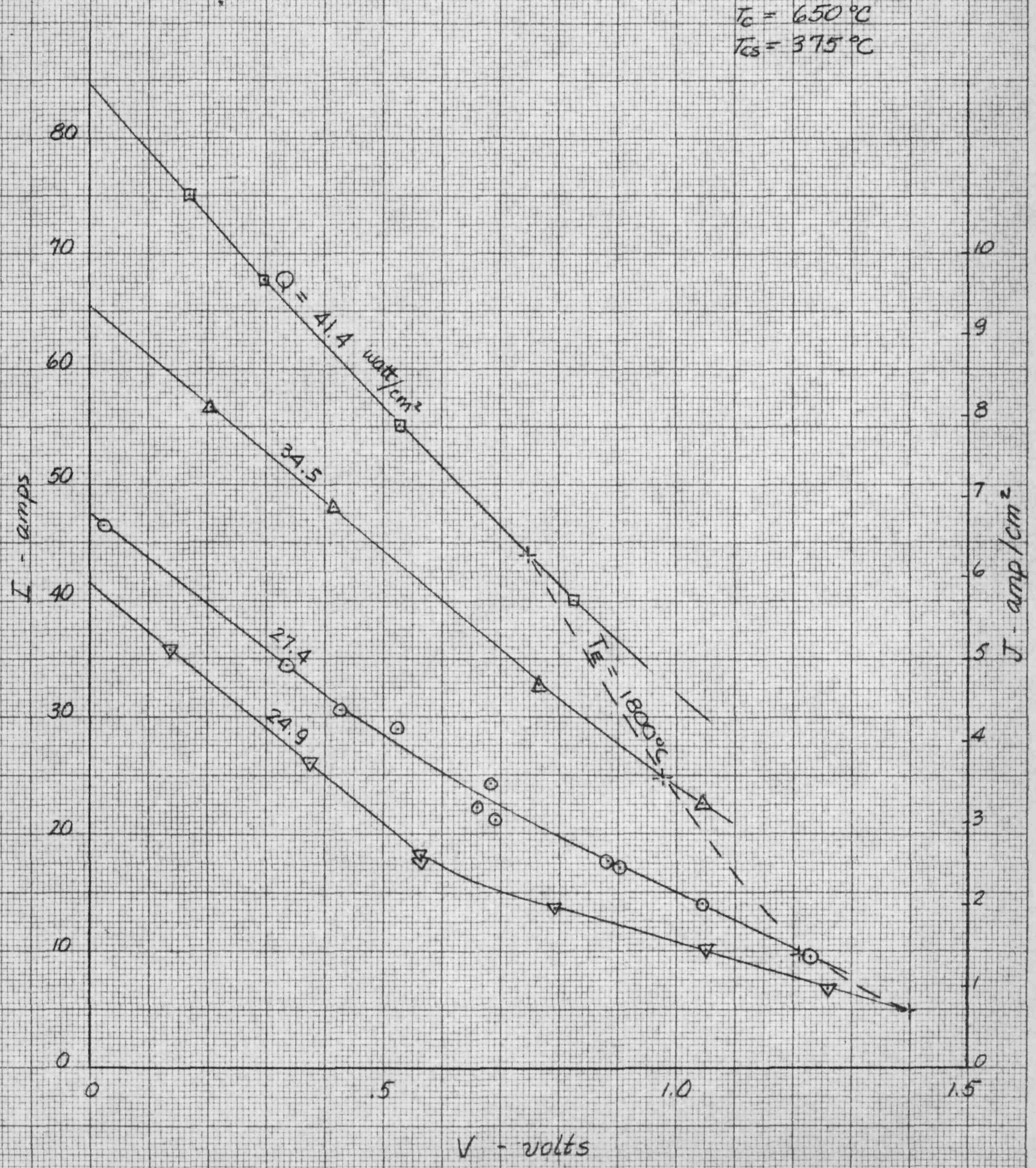


Figure 4

Experimental Data Plotted as Amp-Volt Curves at Constant Power Input

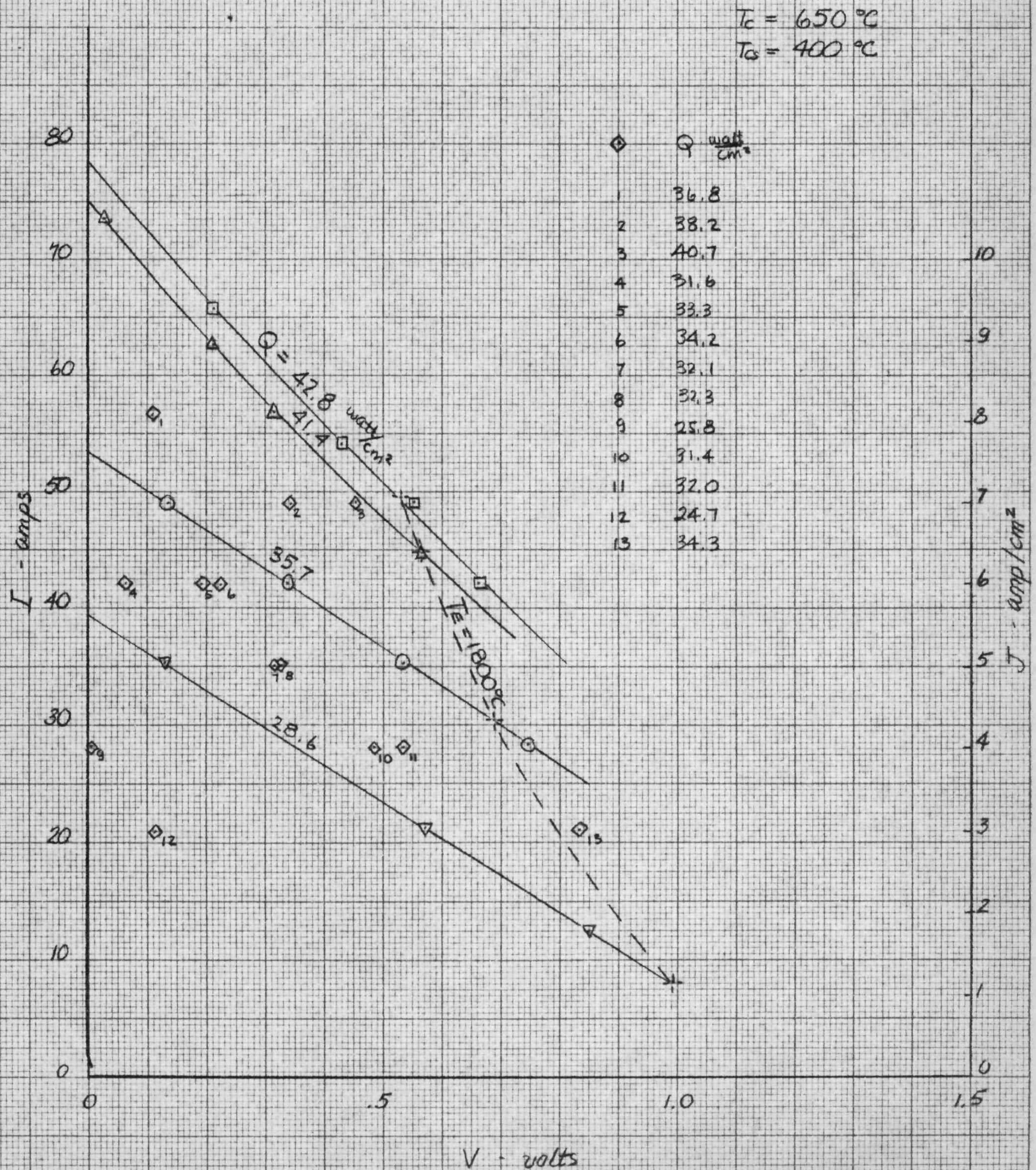


Figure 5

Experimental Data Plotted as Amp-Volt Curves at Constant Power Input

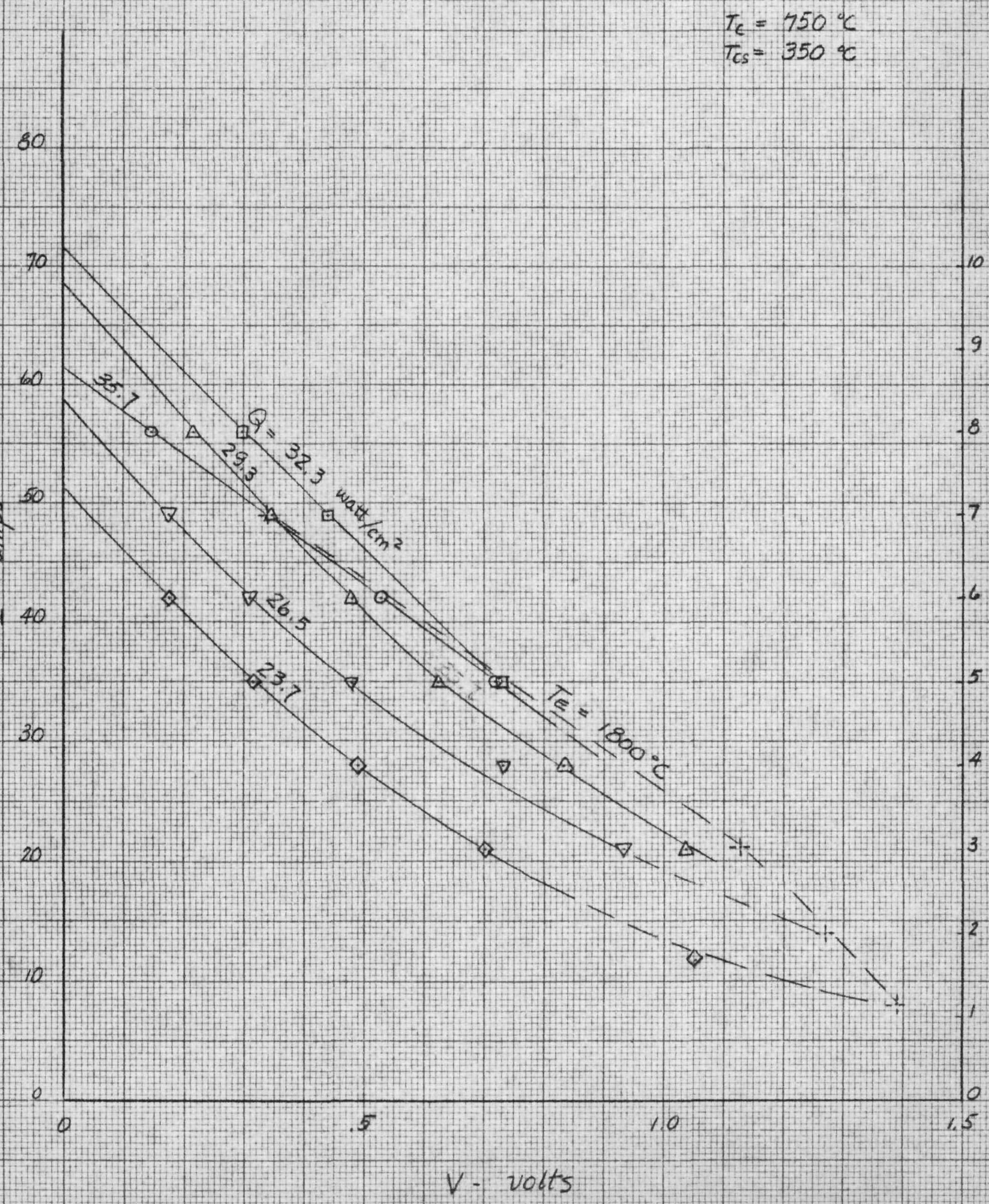
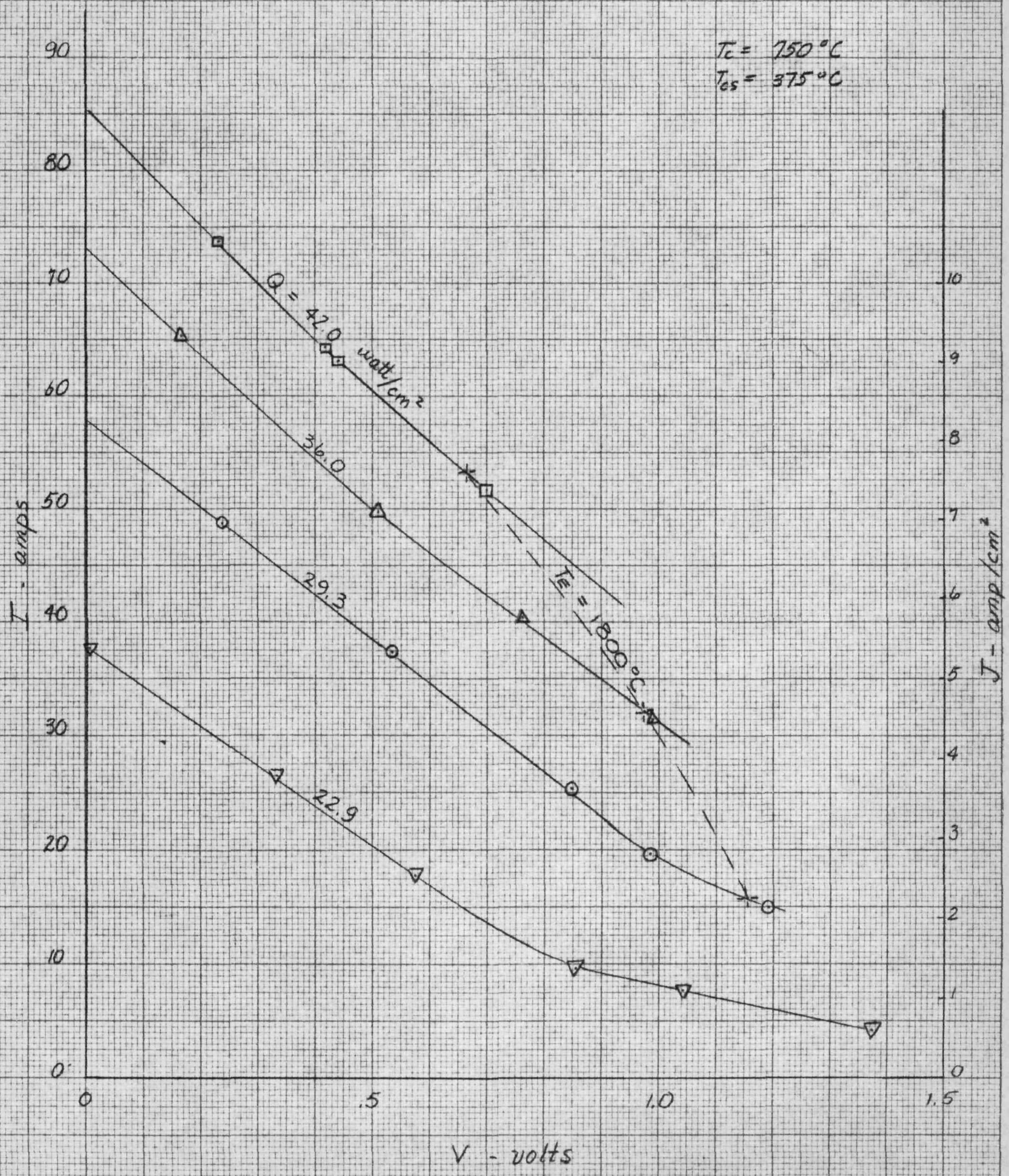


Figure 6

Experimental Data Plotted as Amp-Volt Curves at Constant Power Input



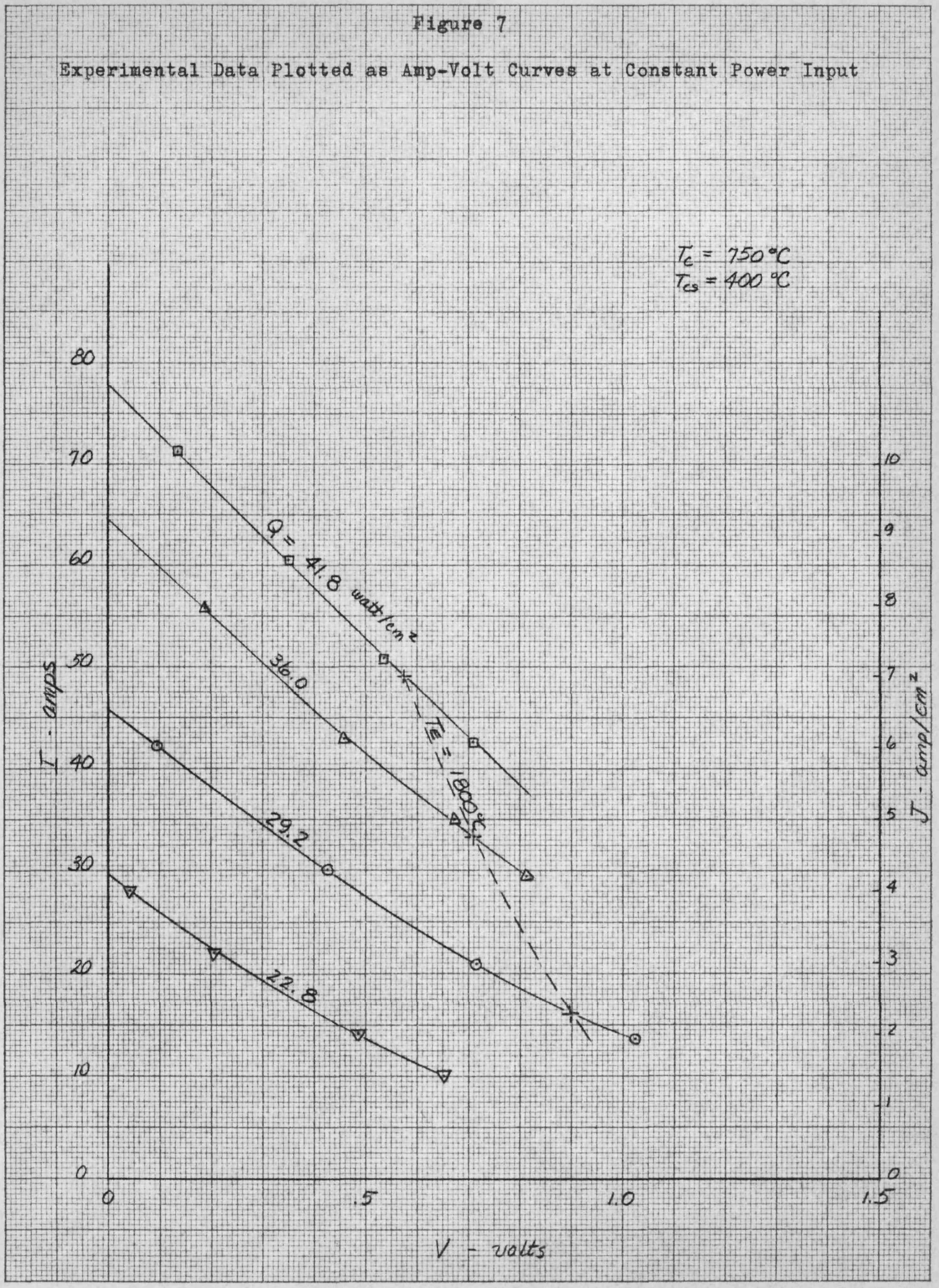


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Figure 8

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

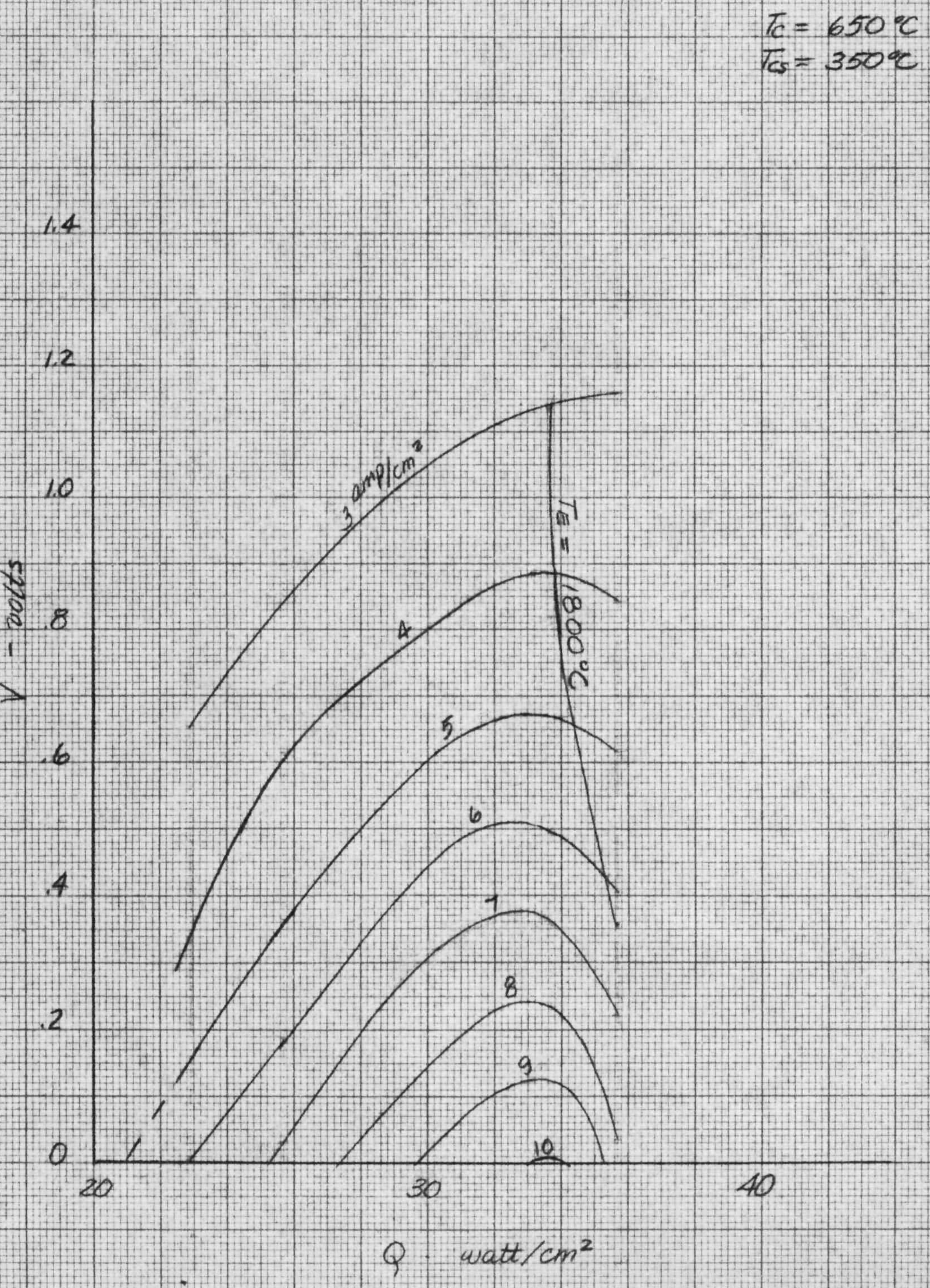

Figure 9

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

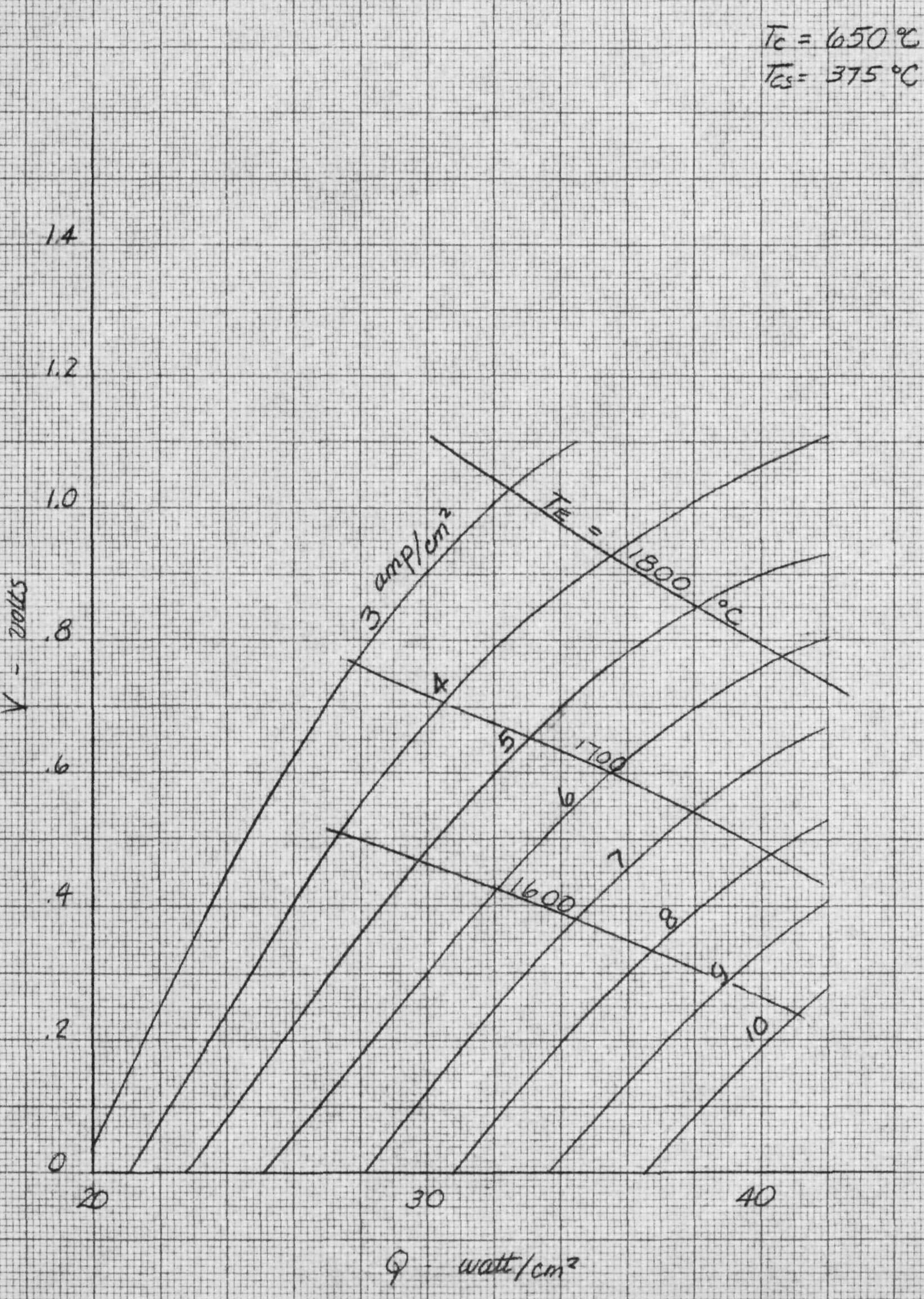

Figure 10

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

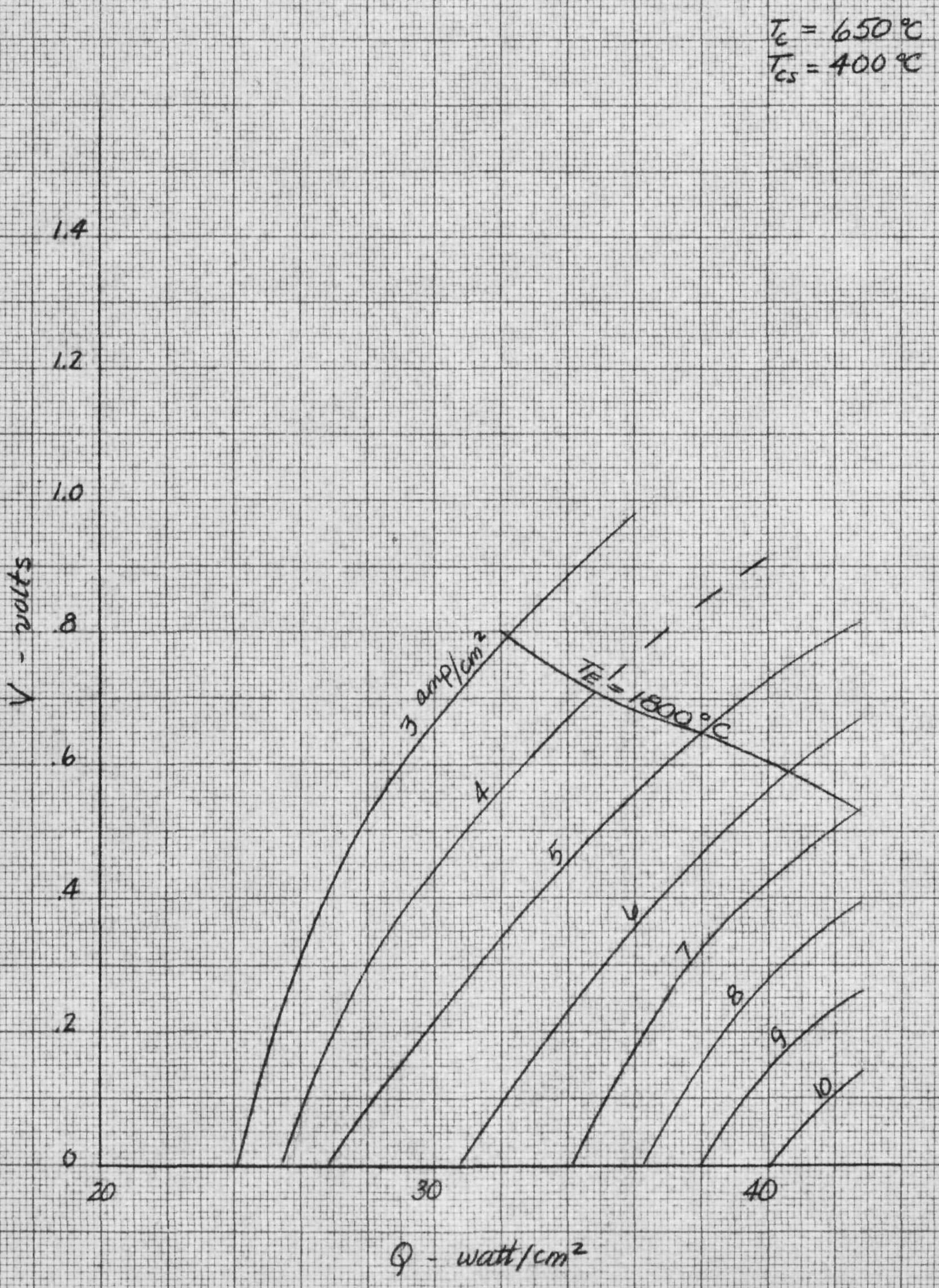

Figure 11

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

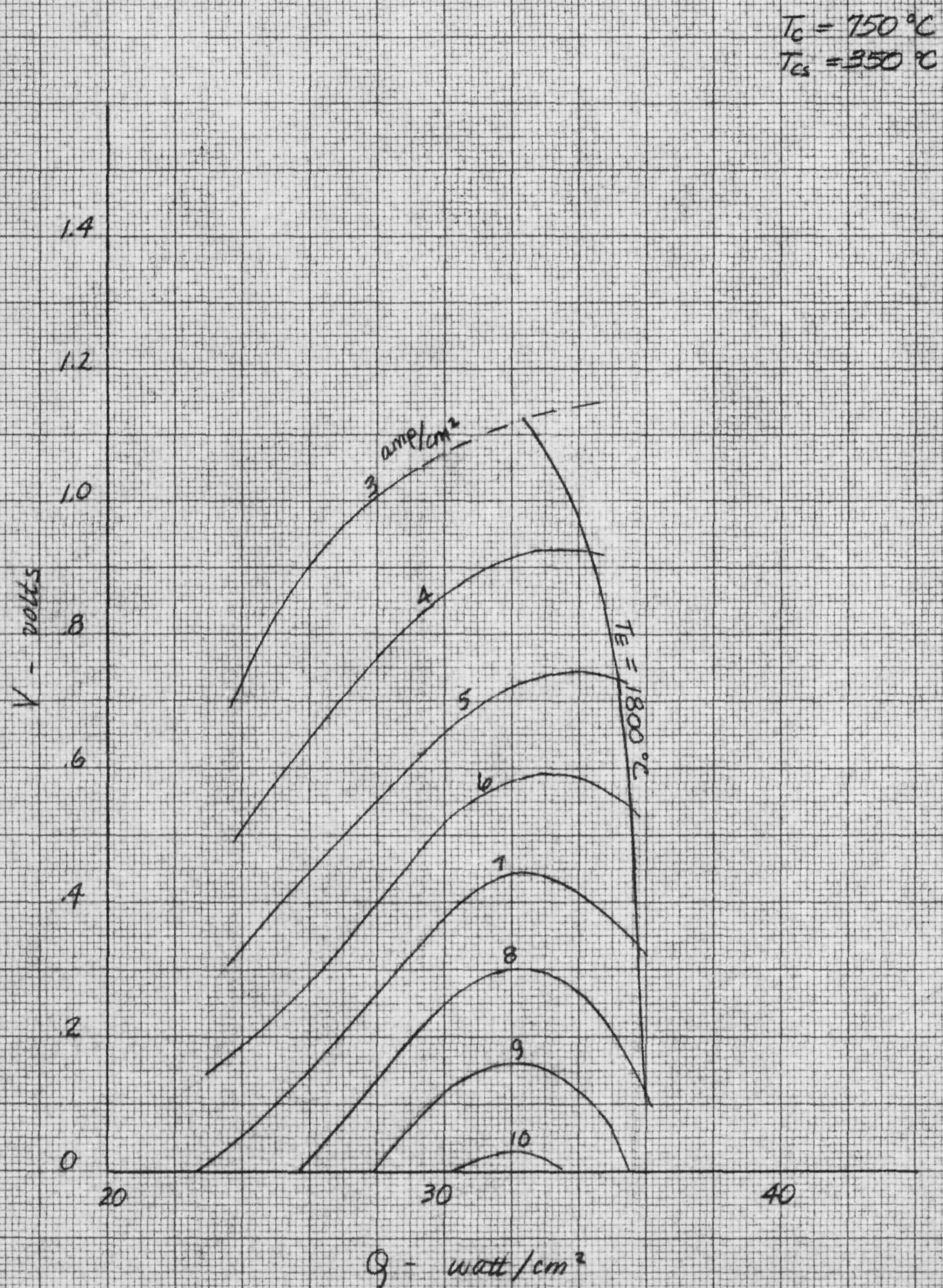

Figure 12

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

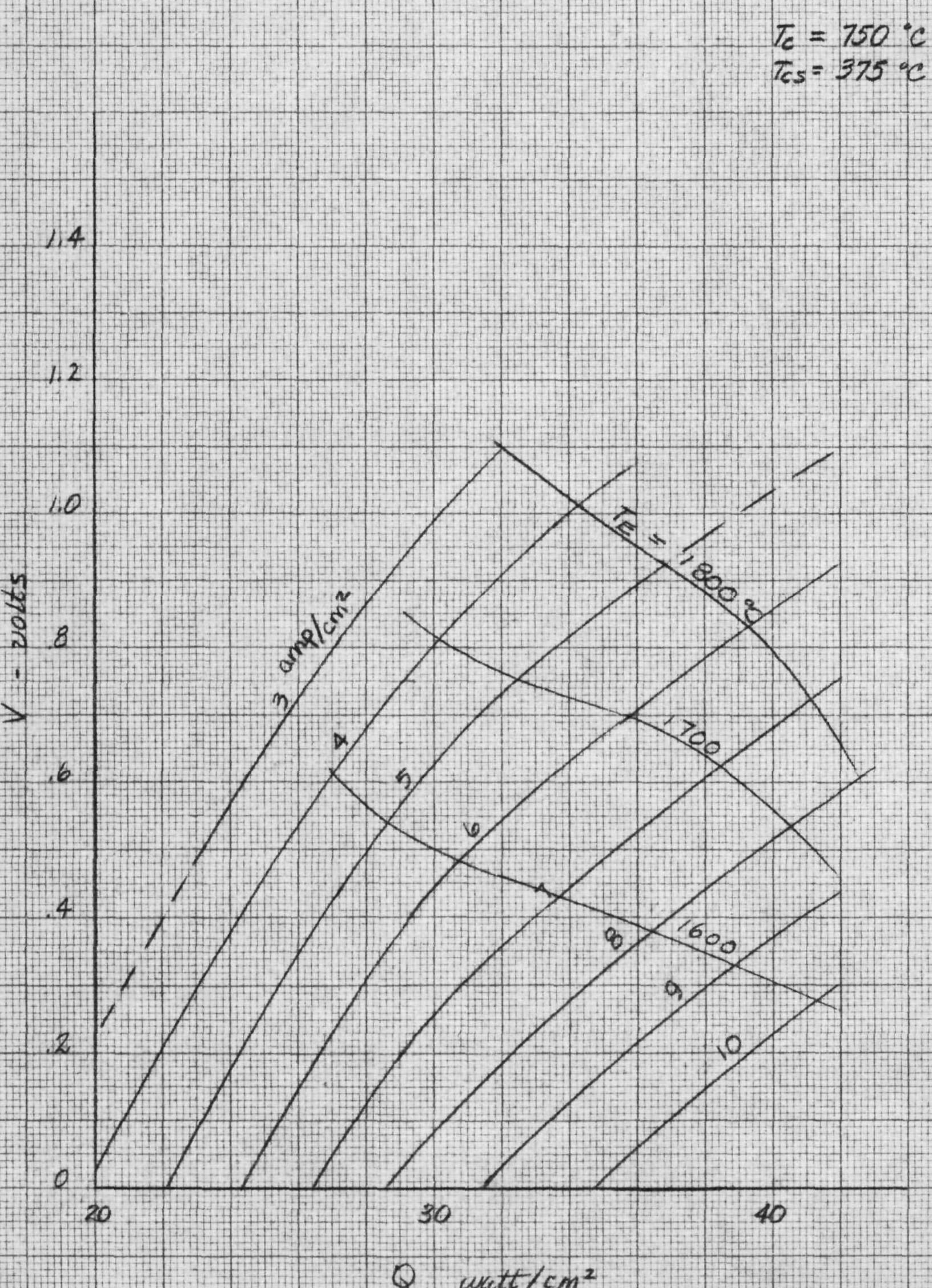

Figure 13

A Cross Plot of the Data in the Form of Volt-Power Input Curves at Constant Currents

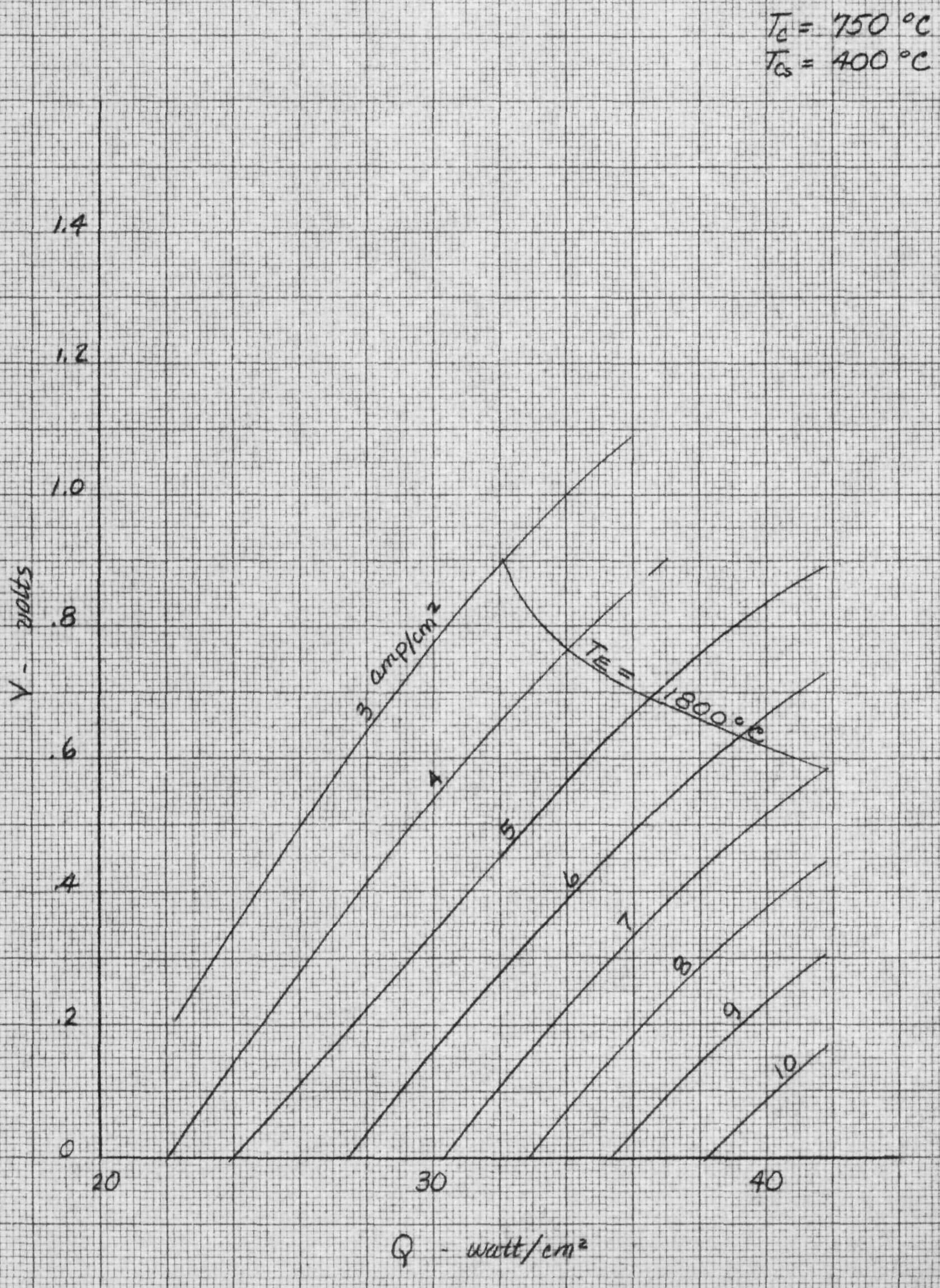

Figure 14

Power Output vs. Power Input at Constant Current

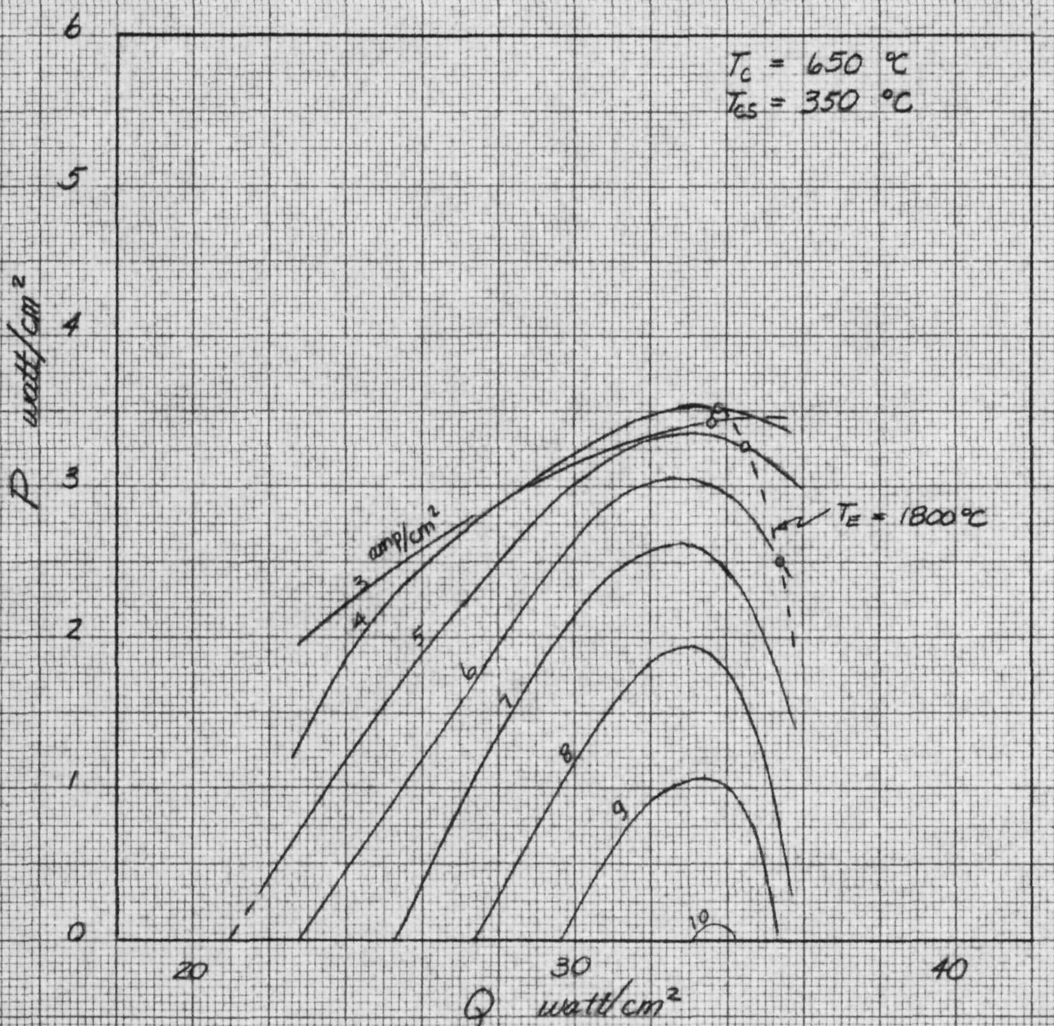

Figure 15

Power Output vs. Power Input at Constant Current

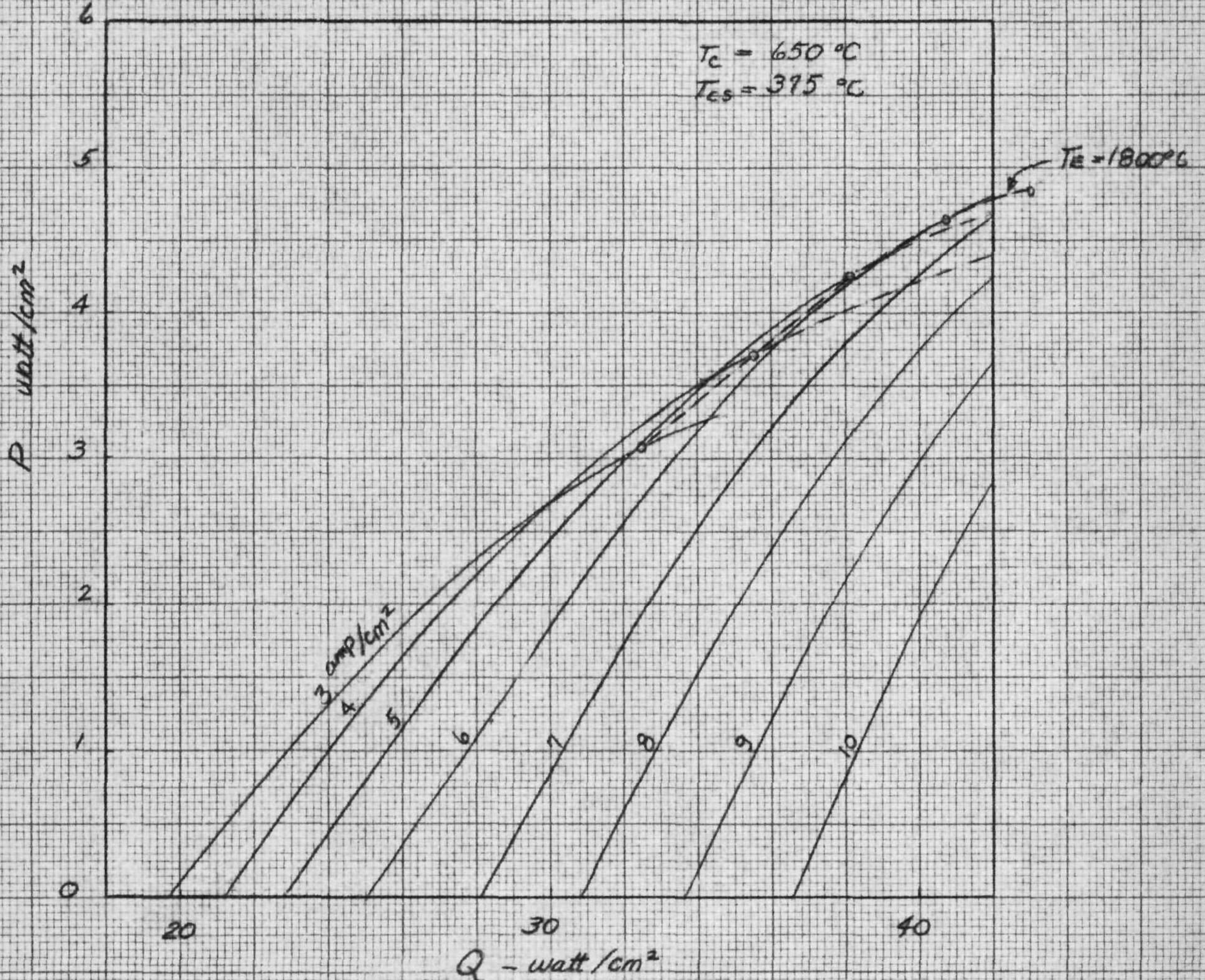

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Figure 16

Power Output vs. Power Input at Constant Current

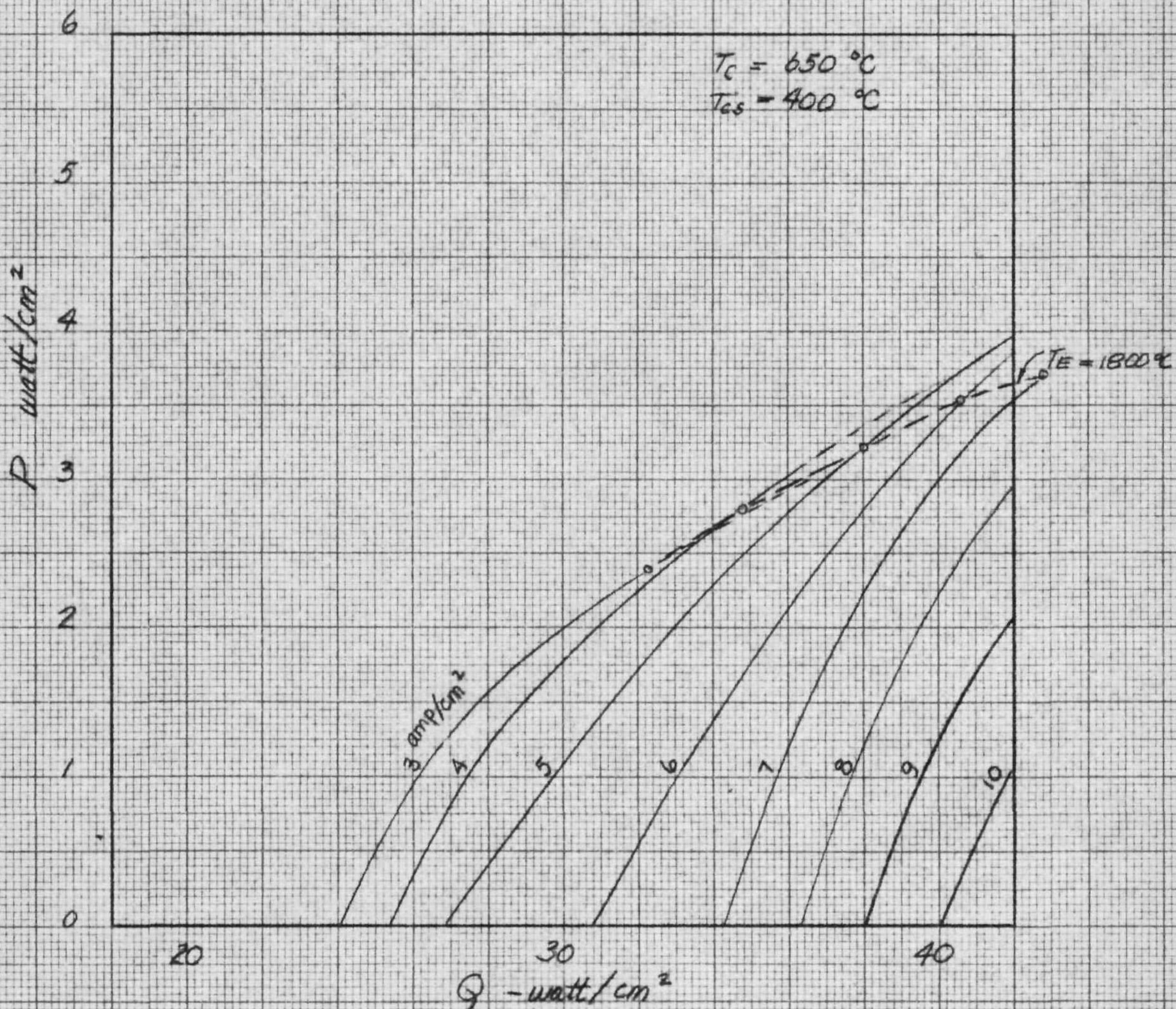

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Figure 17

Power Output vs. Power Input at Constant Current

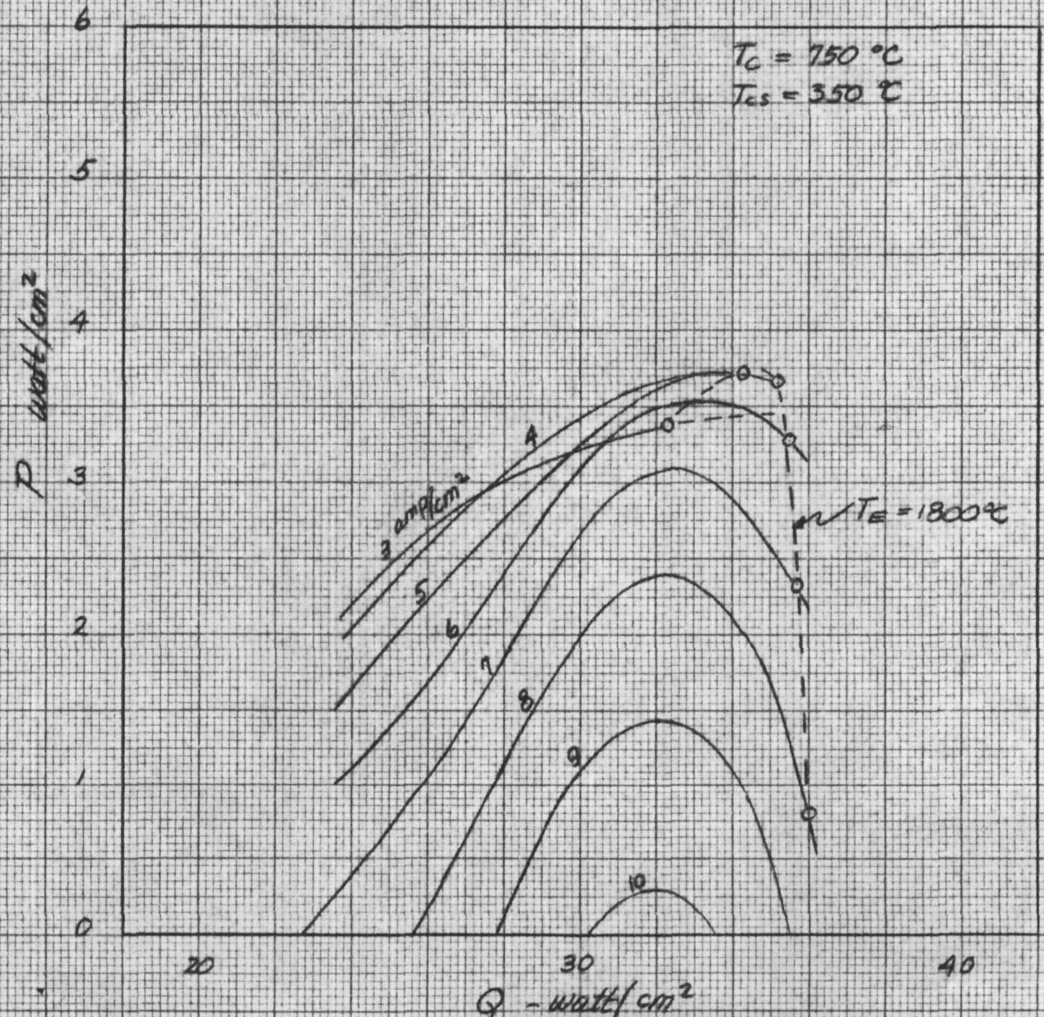


Figure 18

Power Output vs. Power Input at Constant Current

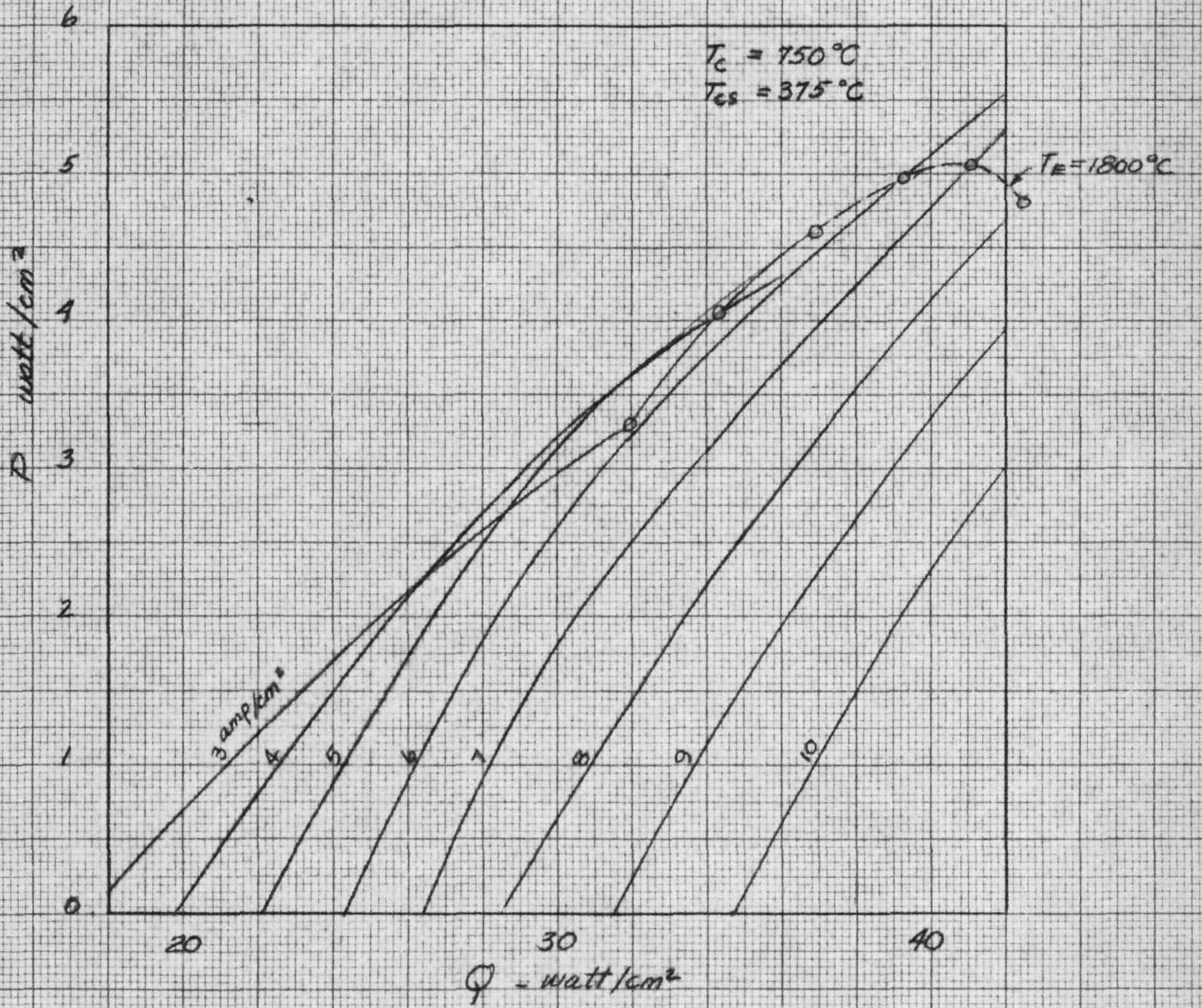


Figure 19

Power Output vs. Power Input at Constant Current

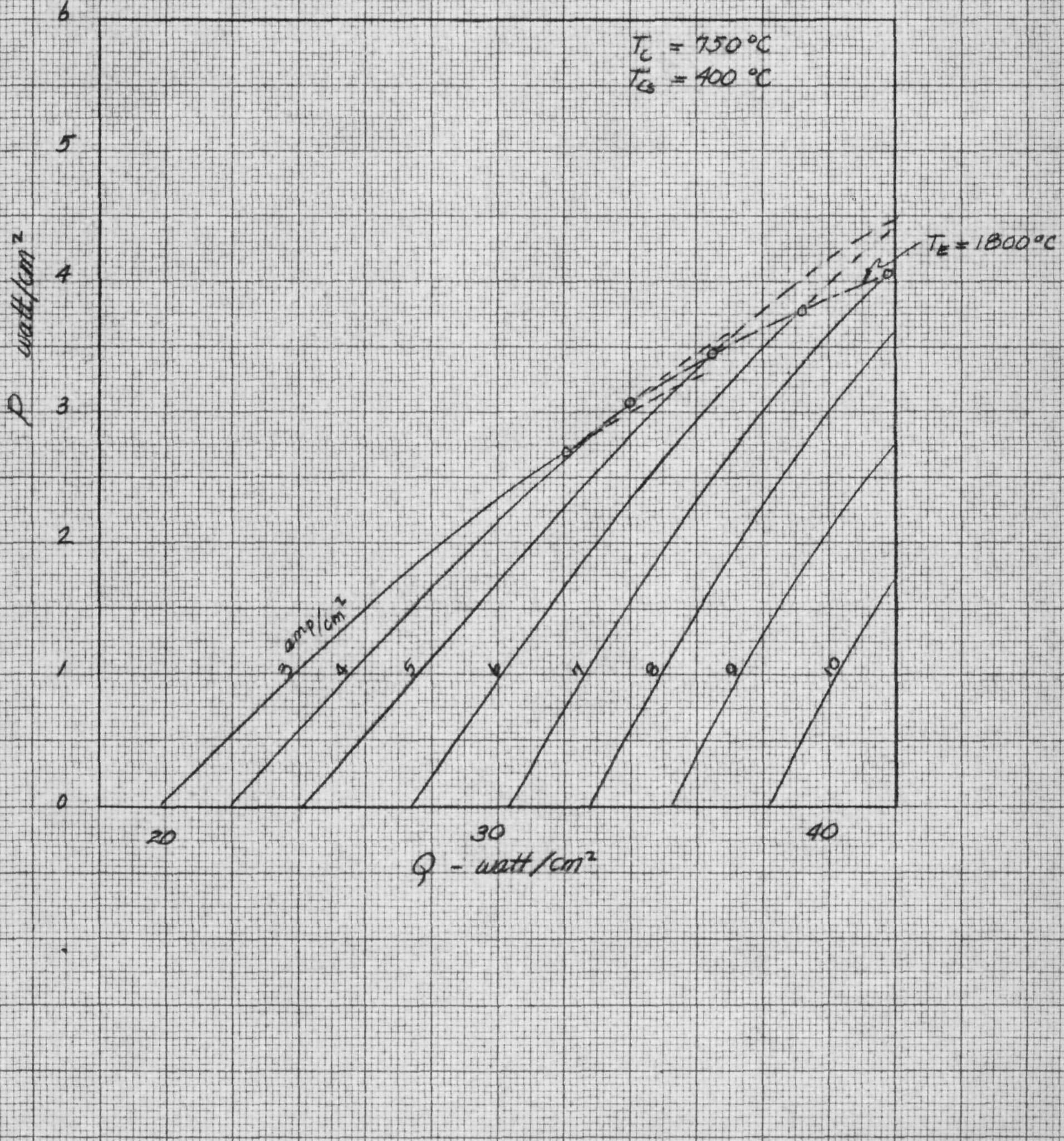


Figure 20

Power Output vs. Current at the Maximum Emitter Temperature, $T_E = 1800°C$

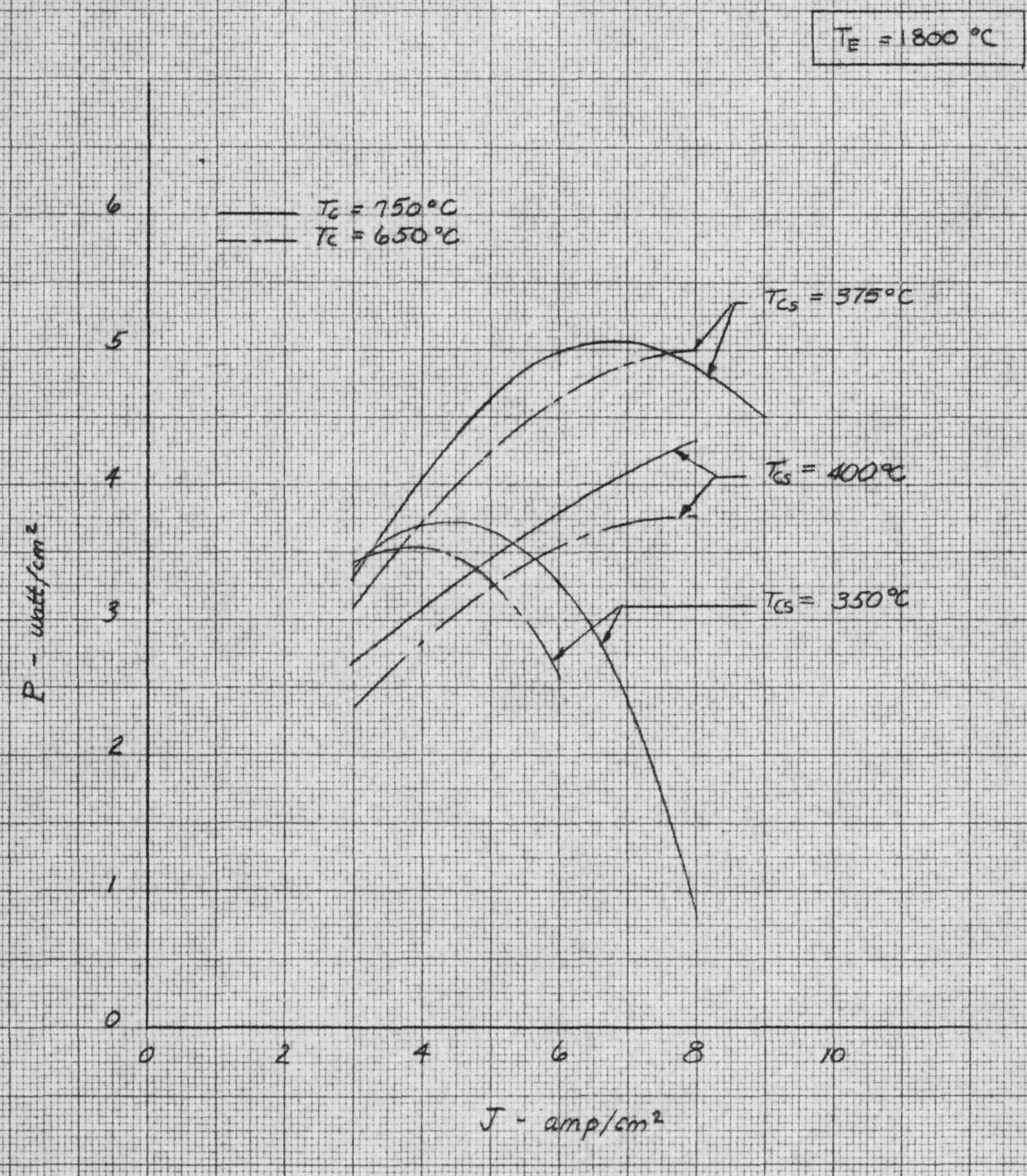


Figure 21

Efficiency vs. Current at the Maximum Emitter Temperature, T_E = 1800°C

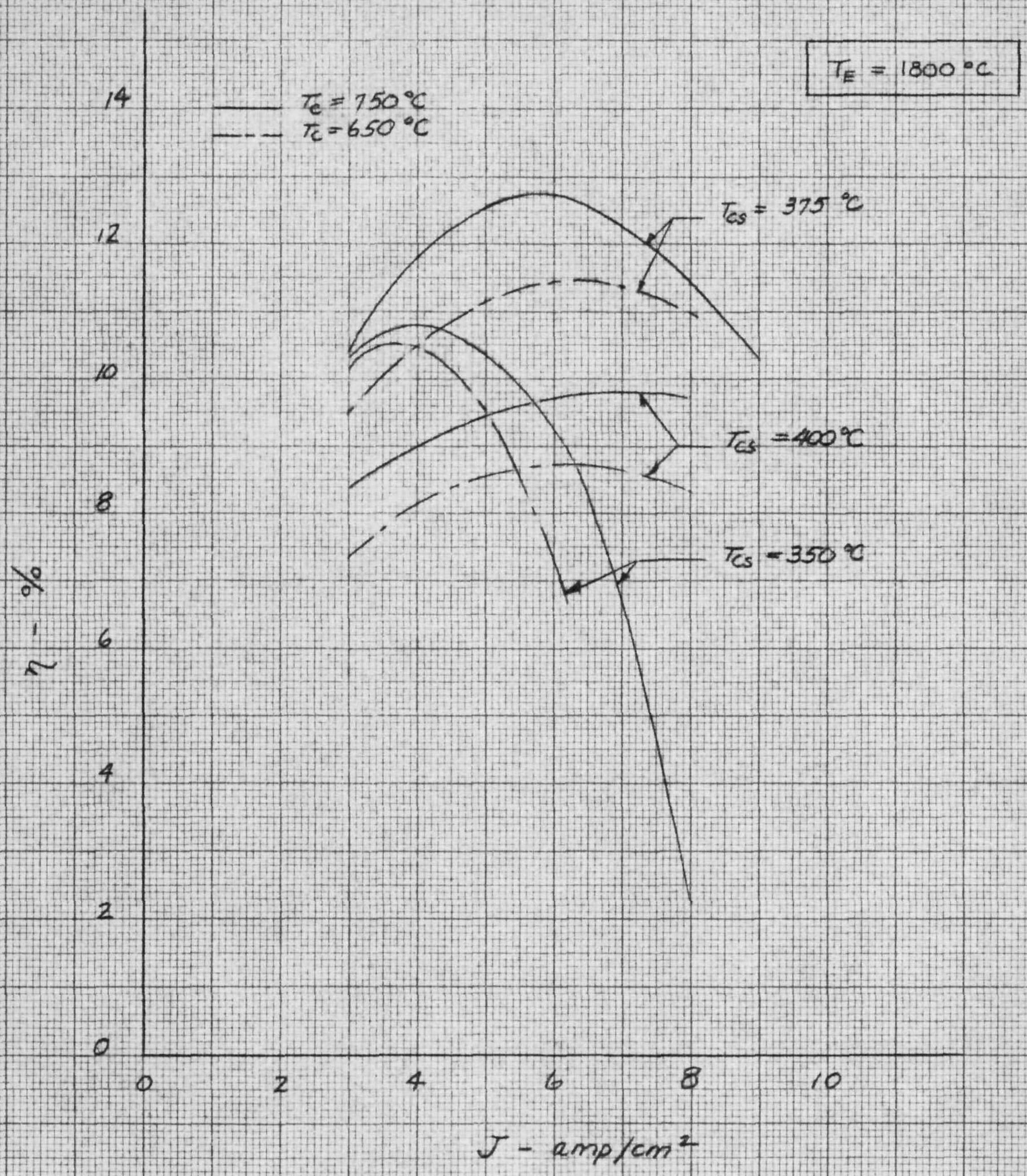
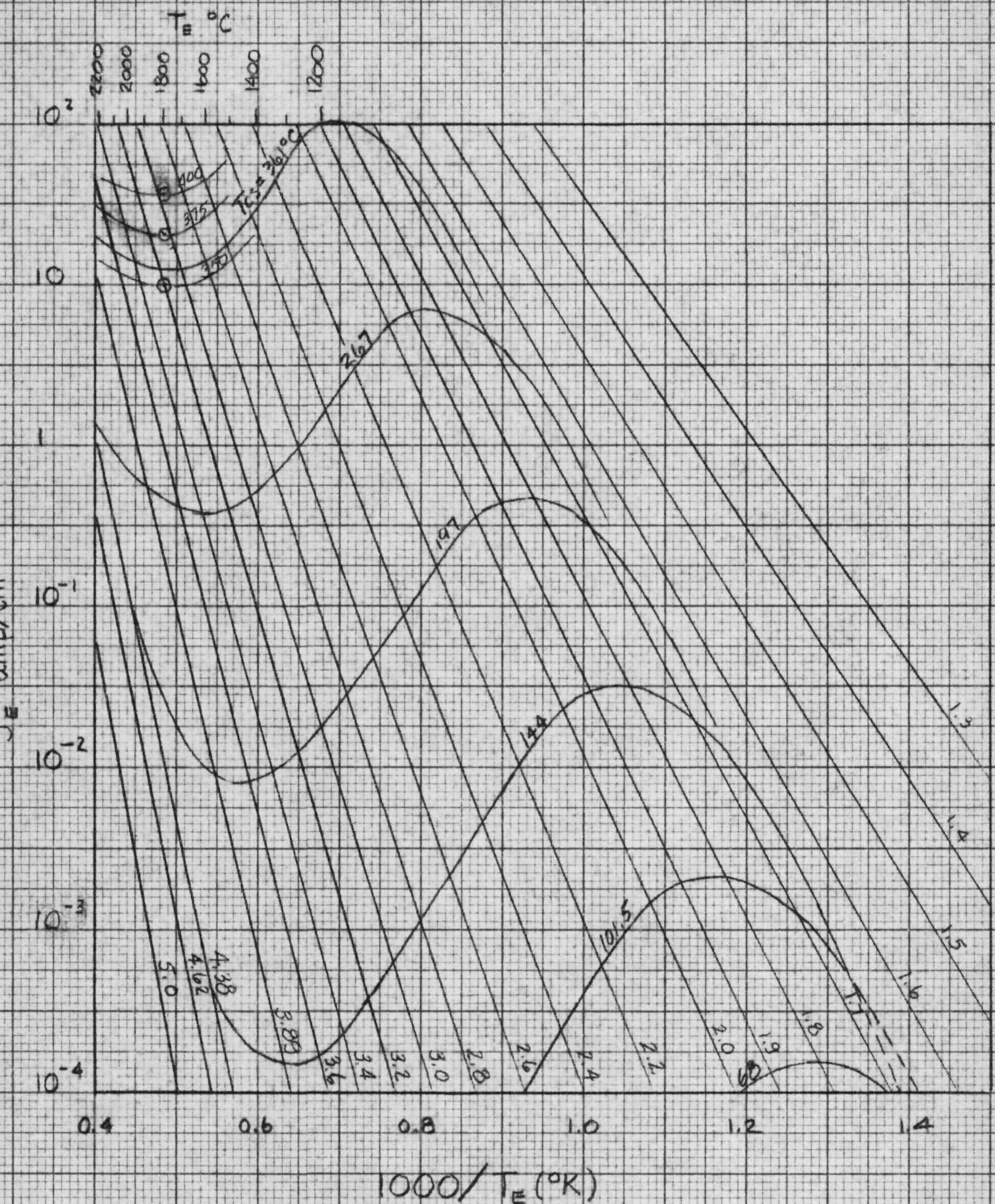


Figure 22

Aamodt-Houston Graph for Molybdenum and Cesium with Experimental Operating Points Plotted at T_E = 1800°C and at T_{Cs} = 350, 375, and 400°C



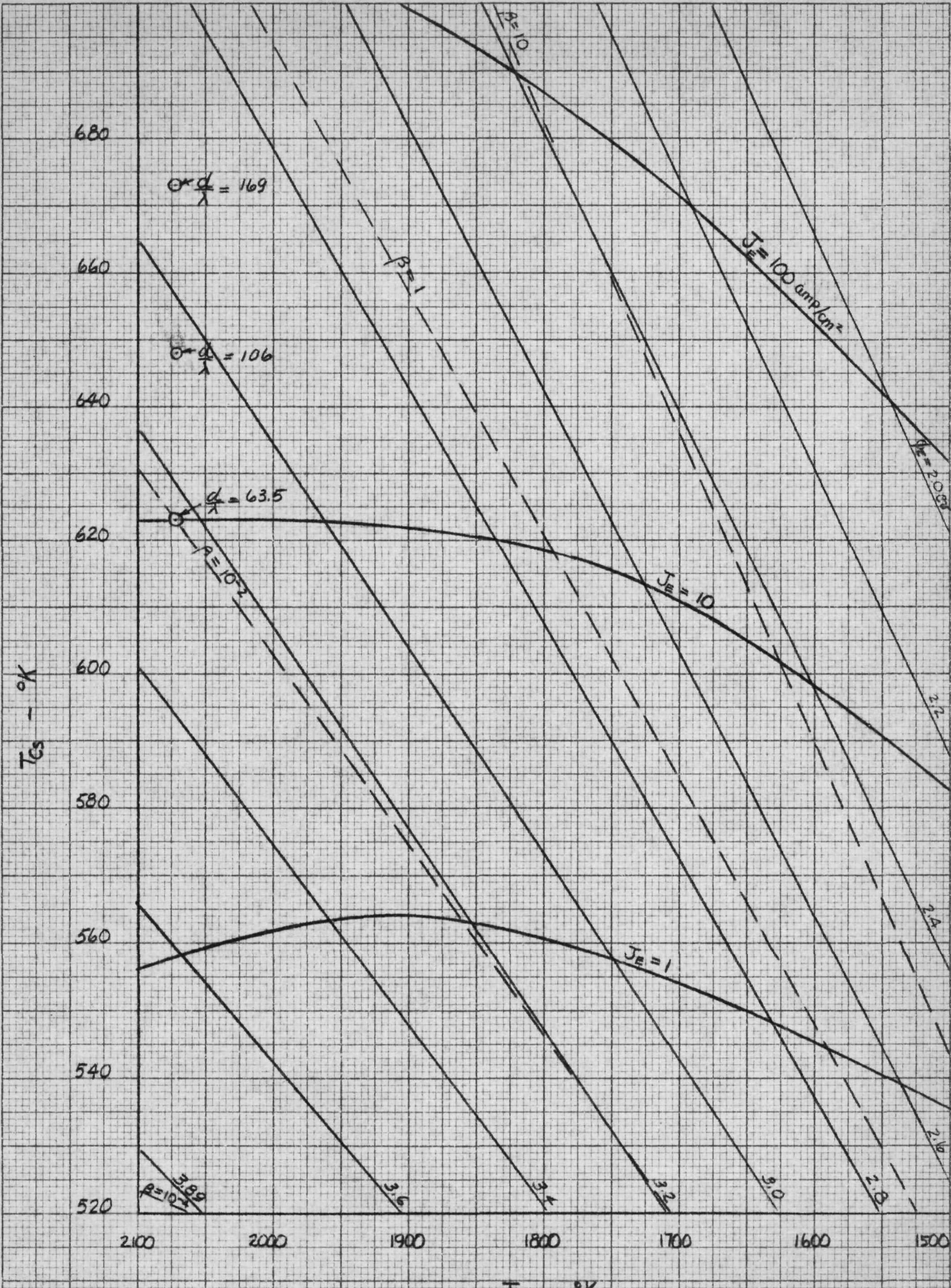


Figure 23

T_{Cs} vs. T_E (°K) Graph With Curves for Degree of Neutralization, Emitter Work Function, and Saturated Emission Currents. The Operating Points With Their Corresponding Values of d/λ are Shown.

Figure 24

Performance of Two Diodes With Unequal Power Inputs Connected in Series

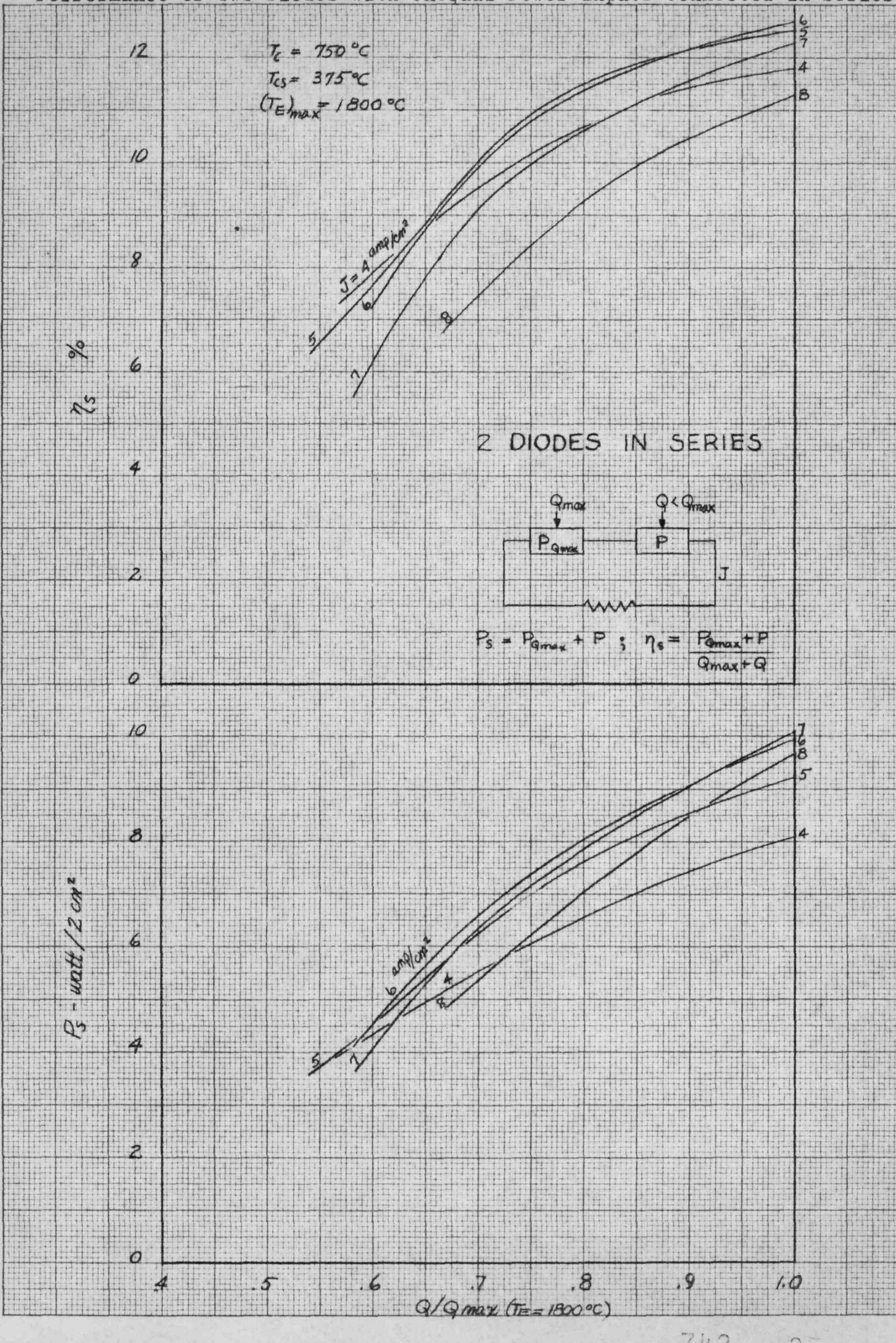


Figure 25

Performance of Two Diodes With Unequal Power Inputs Connected in Parallel