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CHARACTERISTICS OF A THERMIONIC CONVERTER WITH A HIGH TEMPERATURE COLLECTOR

By
E. BLUE
J.H. INGOLD

SPECIAL PURPOSE NUCLEAR SYSTEMS OPERATION
GENERAL ELECTRIC
VALLECITOS ATOMIC LABORATORY
PLEASANTON, CALIFORNIA

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SUMMARY

Current-voltage characteristics of a cesium-on-tantalum thermionic converter with a collector temperature comparable to that of the emitter are presented for a variety of electrode temperatures and cesium vapor pressures. The results can be summarized as follows: (1) For emitter temperatures in excess of 2000 K, power outputs of a few watts per square centimeter can be obtained when the ratio of collector temperature to emitter temperature is as high as 0.75 to 0.80, which is the required range for best performance of a radiation-cooled Carnot engine: (2) At temperature ratios above 0.80 the power output is insensitive to changes in electrode spacing for ratios of spacing to electron mean free path greater than 100 at a cesium vapor pressure of 5 torr.

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TESTS MADE BY J. H. Ingold and E. Blue, Direct Electrical Conversion Unit, VAL

COUNTERSIGNED T. M. Snyder Mgr. SECTION Physics Subsection, VAL

BUILDING AND ROOM NO. VAL 105-522 LOCATION P. O. Box 846 Pleasanton, California

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INTRODUCTION

The purpose of this paper is to describe experimental results obtained from a cesium-filled thermionic converter with a collector temperature comparable to that of the emitter. The operating characteristics of such a converter are necessary to the design of STAR-R, which is a radiation-cooled nuclear-thermionic space power supply.(1) In this application, the collectors of the converters would be cooled by radiation of waste heat to space and would, therefore, operate at much higher temperatures than those of typical labroatory converters. At high collector temperature, back emission from the collector becomes important. An analysis(2) of a space-charge-free, collisionless, radiation-cooled thermionic converter in which back emission was taken into account has shown that specific power outputs up to 10 watts/cm^2 are theoretically possible. Until now, there have been no supporting experimental data for converters with collector temperatures in the range of 0.7 to 0.8 of the emitter temperature. However, experiments with cold collector converters have shown that specific power outputs up to 15 watts/cm^2 can be obtained.(3-5) The experiments described below show that a specific power output of 4 watts/cm^2 can be obtained from a cesium-on-tantalum thermionic converter with electrode temperatures of 2255°K and 1785°K, an electrode spacing of 0.7 mm, and a cesium vapor pressure of 5 torr. Preliminary results of a similar nature were reported earlier.(5)

This work was performed on a Development Authorization of the General Electric Company Special Purpose Nuclear Systems Operation.

EXPERIMENTAL PROCEDURE

The converter used in these experiments was of ceramic-metal construction with 0.5" diameter planar tantalum electrodes, both of which could be heated by electron bombardment. A cross-section of the converter is shown in Fig. 1. The converter was baked-out with the electrodes at 2500°K and the tube envelope at 850°K until the pressure was on the order of 10^{-8} torr. During the bake-out, the temperature of one of the electrodes reached the melting point of tantalum so that a small bead of tantalum about 0.8 mm in diameter by 0.2 mm in height developed in the center of the electrode. After seal-off at about 10^{-9} torr, cesium was distilled into the cesium reservoir of the converter from a glass vial which was then removed from the system.

Electrode temperatures were measured with a calibrated optical pyrometer and the true temperature was calculated from the observed temperature using the emissivity of bare tantalum. In this calculation, reflections at the two surfaces of the sapphire window were taken into account, but the effect of absorption in the window itself was neglected. The pyrometer was focused on the cylindrical surfaces of the electrode supports at a point approximately 0.8 mm from the planar electrode surfaces. Electrode spacings were measured with a cathetometer to an accuracy of ±0.05 mm. The cesium pool temperature was regulated by a nichrome heater and a gas cooler, and was monitored with a chromel-alumel thermocouple. Similar thermocouples monitored temperatures at various points on the tube envelope in order to insure the accuracy of the cesium pool temperature determination.

Experimental data in the form of current-voltage characteristics were obtained for various electrode temperatures, electrode spacings and cesium vapor pressures. There was no attempt to optimize these parameters during the experiments. The characteristics were obtained by sweeping the collector with a 60 cps voltage, displaying the characteristics on an oscilloscope, and photographing them for future reference. A circuit diagram is shown in Fig. 2. The guard ring was electrically isolated so that its potential relative

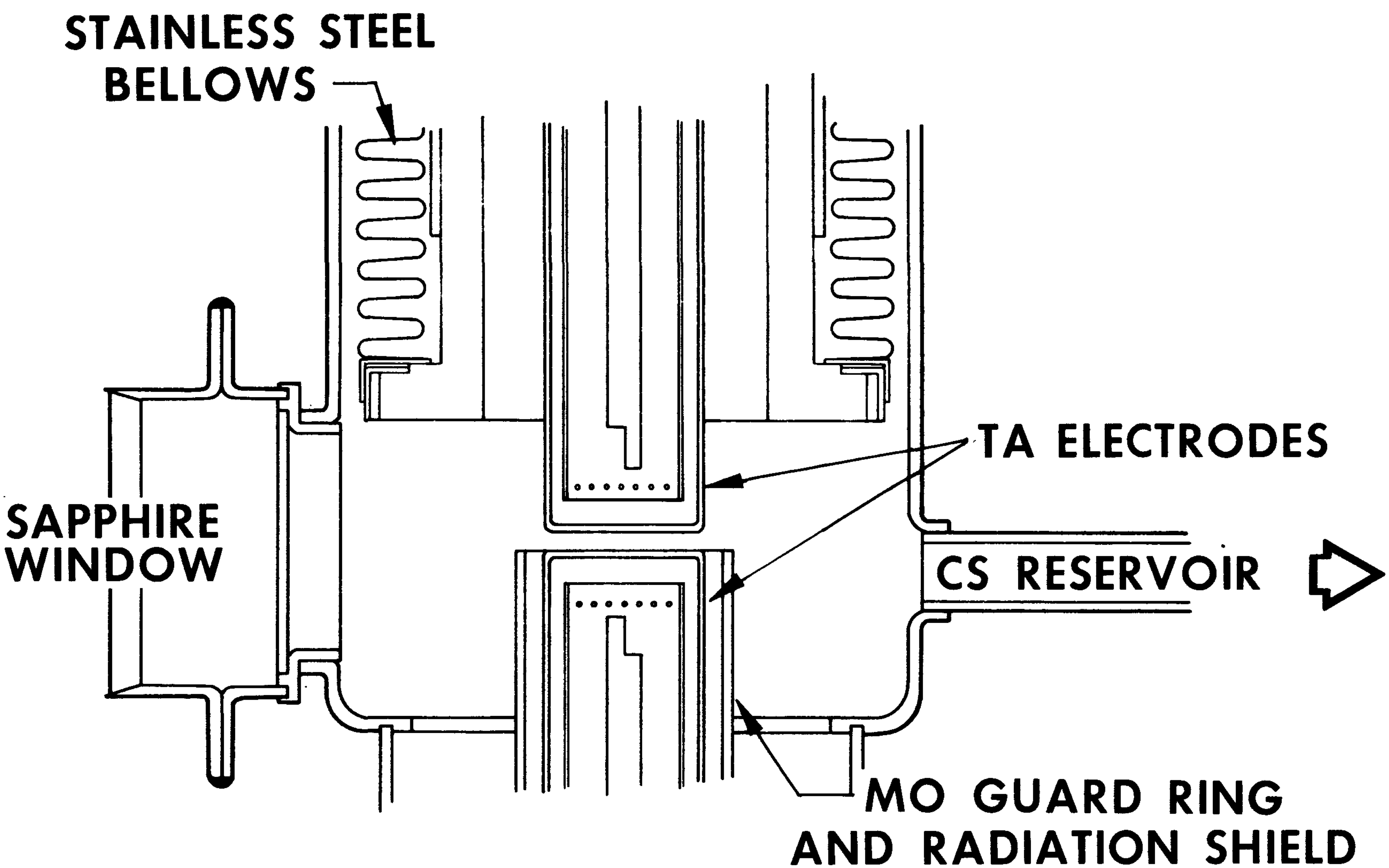

Figure 1. CROSS SECTION OF CONVERTER

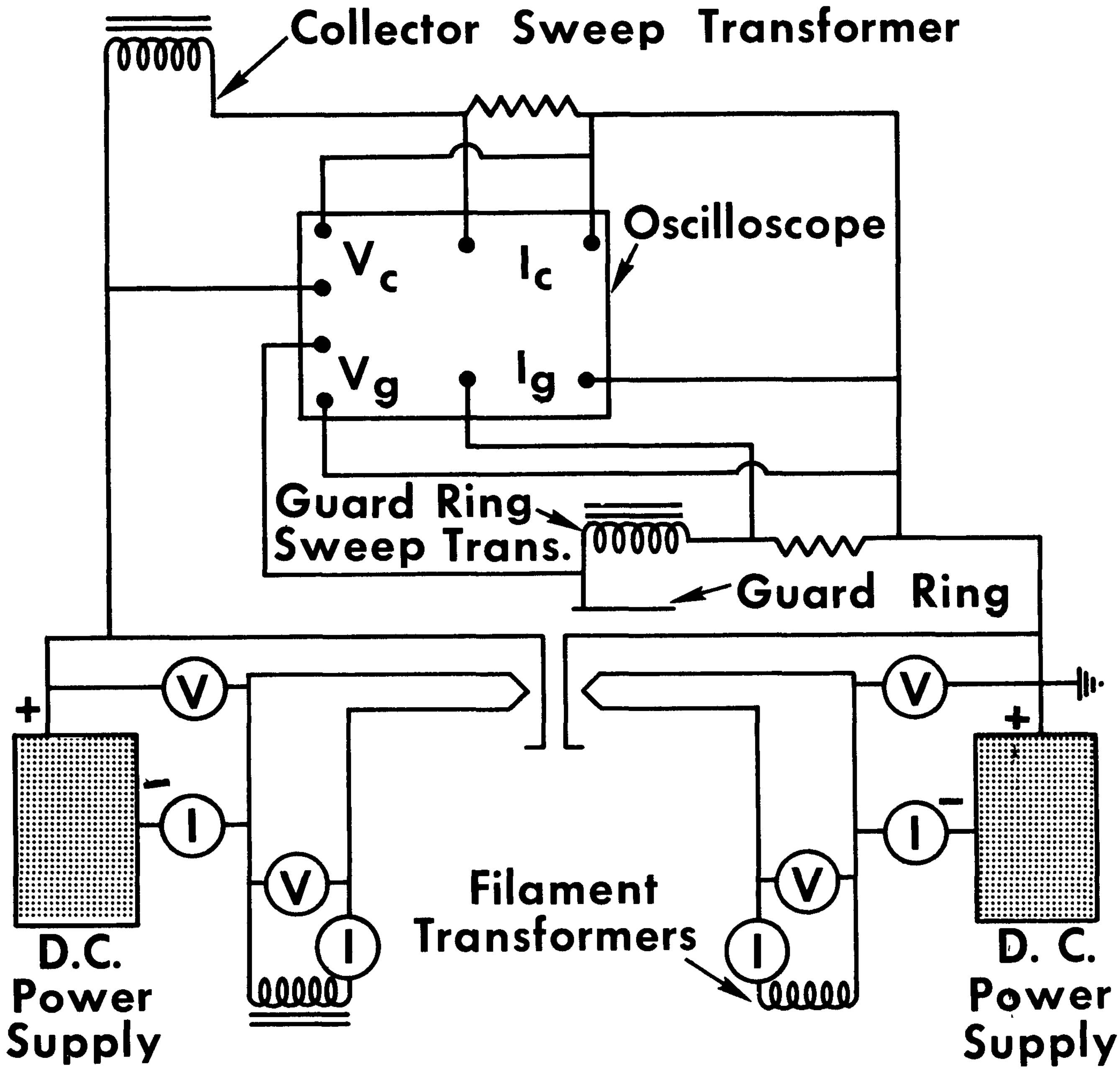

Figure 2. CIRCUIT DIAGRAM

to that of the emitter could be controlled. At high cesium vapor pressures and high emitter temperature where the power outputs were significant, the collector current-voltage characteristic changed very little when the guard ring was successively open-circuited, short-circuited to the emitter, and short-circuited to the collector. This result indicates that the edge effects were unimportant, hence the emitter current densities were accurately known. The data presented below were obtained with the guard ring short-circuited to the emitter.

RESULTS

Current voltage characteristics for an emitter temperature T_e of 1995°K, a cesium pool temperature T_{cs} of 613°K (5 torr) and an electrode spacing L of 0.7 mm are shown in Fig. 3. The parameter here is collector temperature which varied from the emitter temperature to 1493°K, as shown. Figures 4 and 5 show similar current-voltage characteristics for emitter temperatures of 2125°K and 2255°K, respectively. In each case, the lowest collector temperature was that for which no electrical power was being supplied to the collector. In addition, current-voltage characteristics for constant electrode temperatures and spacing, but with varying cesium pool temperature are shown in Figures 6 and 7. Each of the families of curves presented in Figures 3 - 7 was photographed on a single Type 146-L polaroid transparency from which an enlargement was made.

Data similar to those shown in Figures 3 - 7 were obtained for electrode spacings of 0.059, 0.070, and 0.15 cm for the same electrode temperatures and cesium pool temperatures. The corresponding values of the ratio of spacing to electron collision mean free path at 5 torr were 100, 117 and 250 respectively, based on Nottingham's[6] estimate of the mean free path. No significant differences in the current-voltage characteristics were observed, i.e., the observed power output was insensitive to changes in electrode spacing over this range.

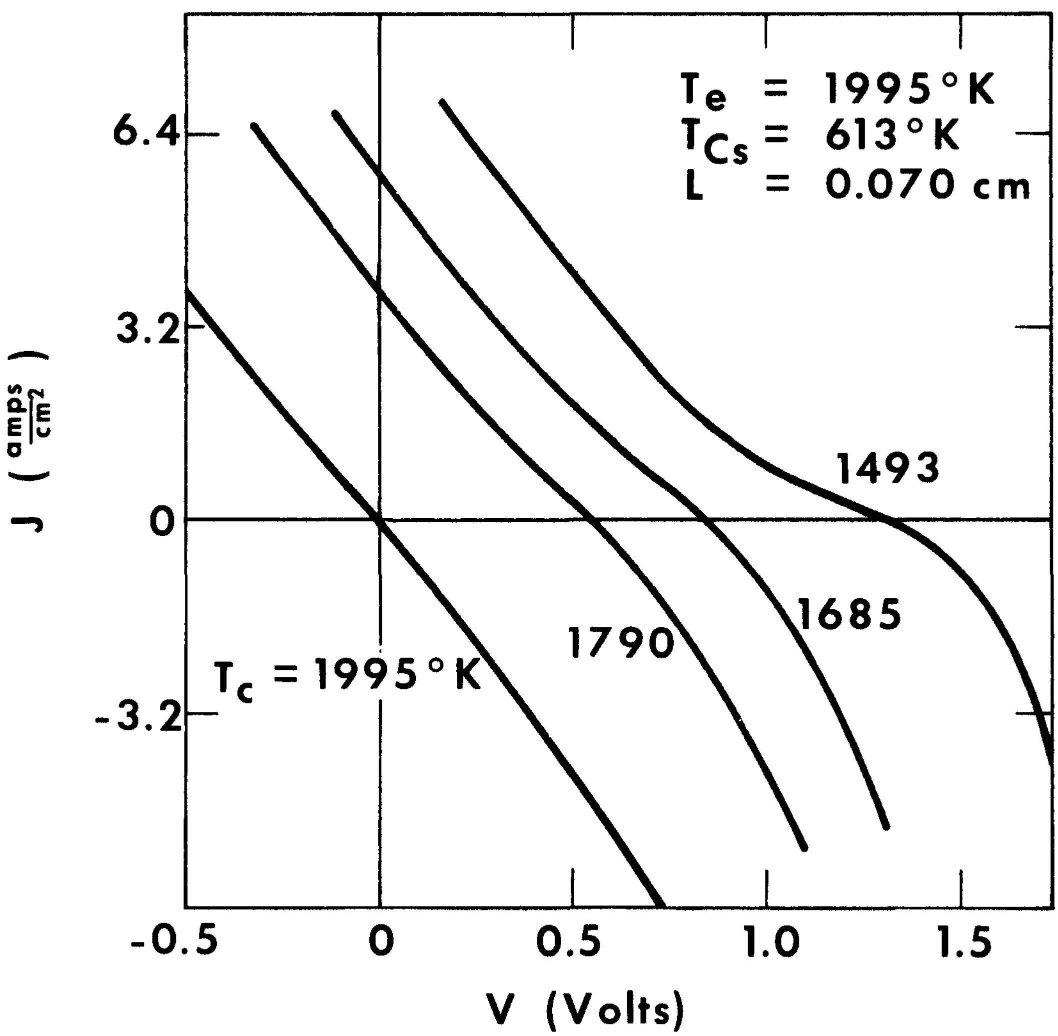

Figure 3.

CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT COLLECTOR TEMPERATURES; Te = 1995°K

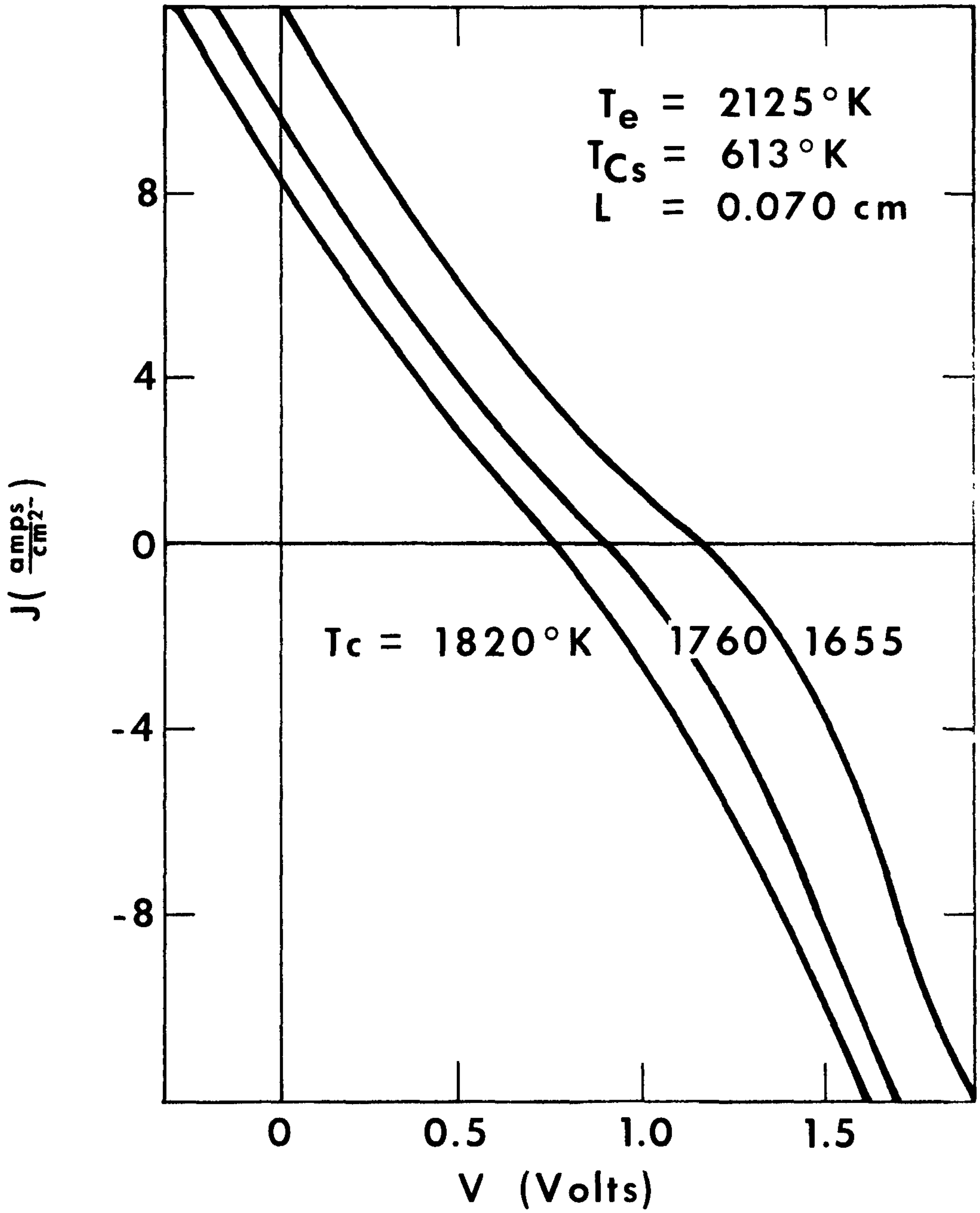

Figure 4.

CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT COLLECTOR TEMPERATURES; T_e = 2125°K

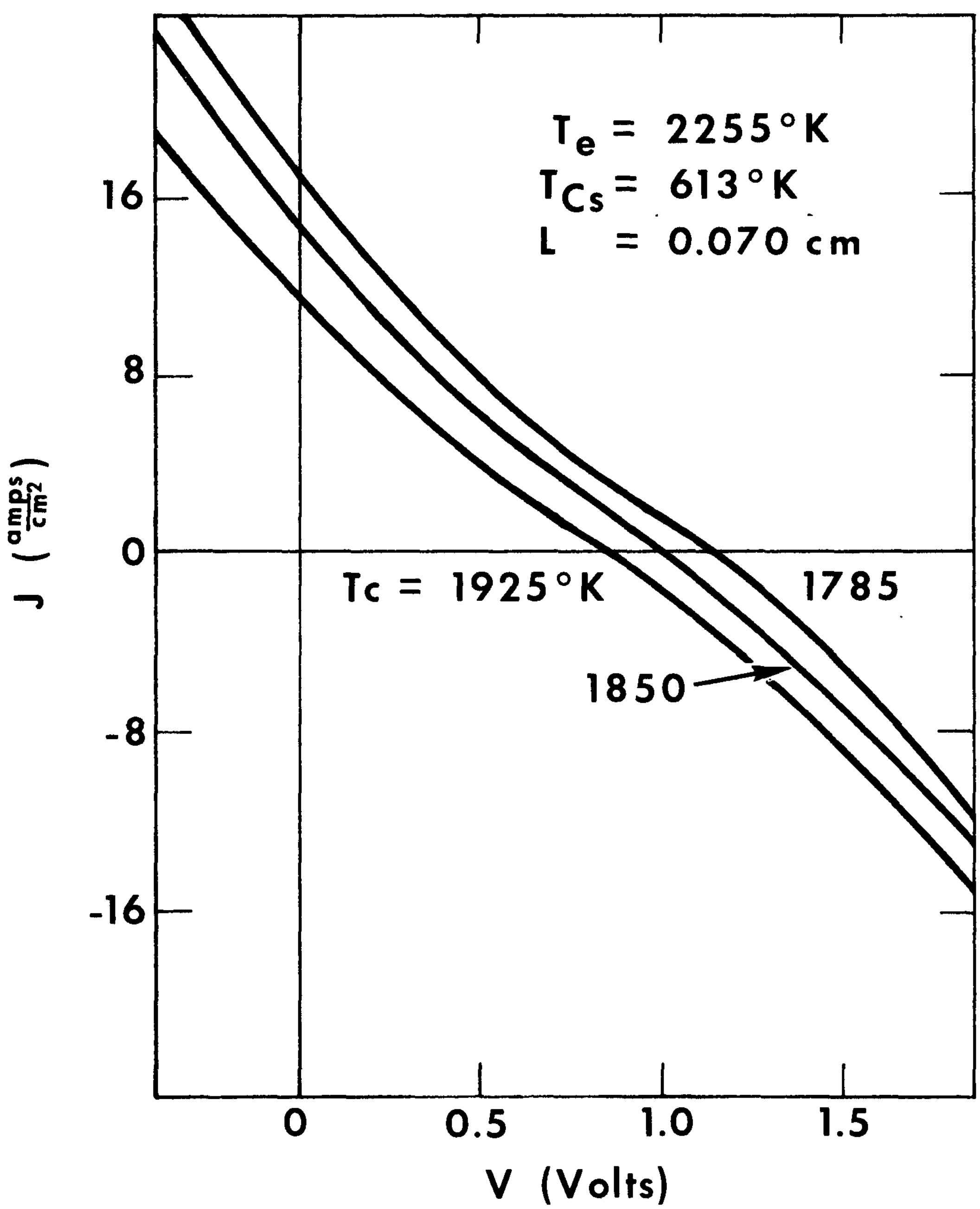

Figure 5.

CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT COLLECTOR TEMPERATURES; Te = 2255°K

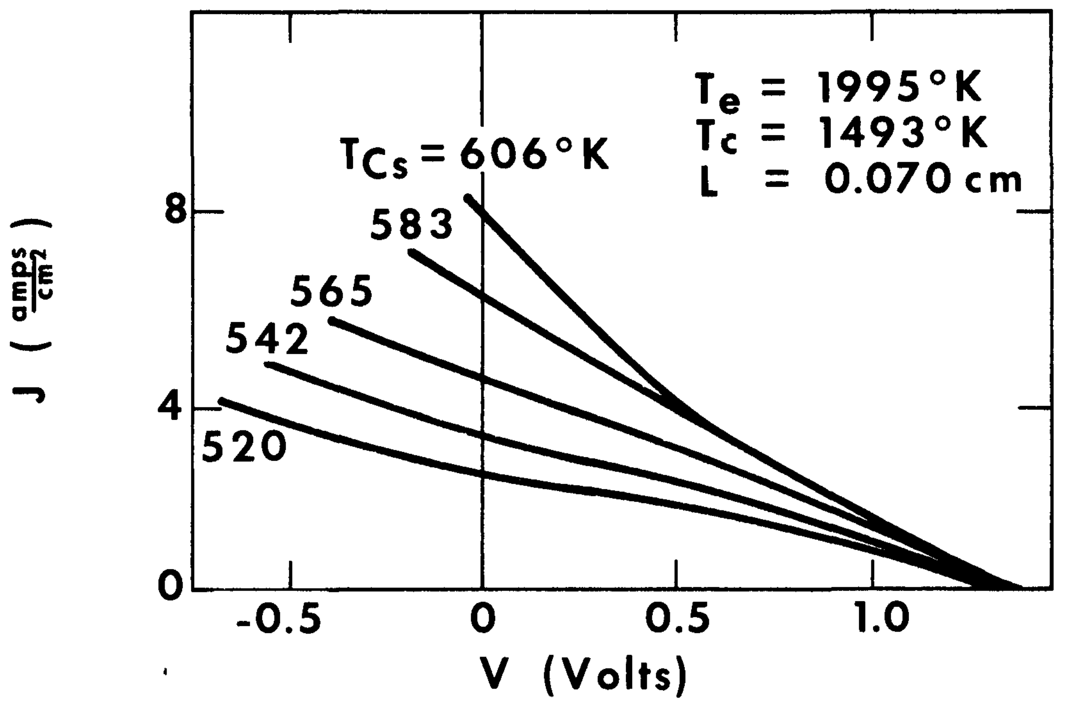

Figure 6.
CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT CESIUM PRESSURES; Te = 1995°K

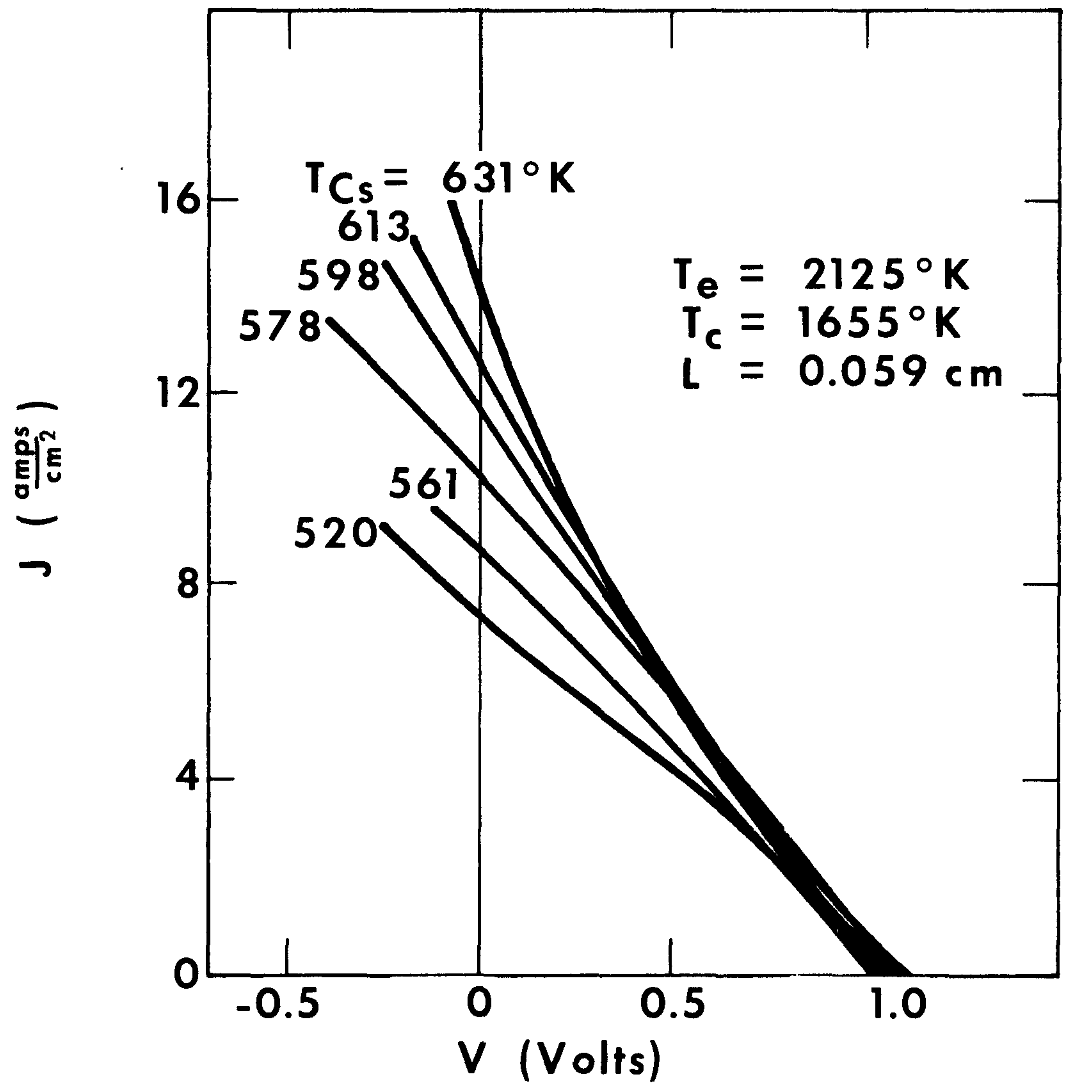

Figure 7.
CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT CESIUM PRESSURES; Te = 2125°K

DISCUSSION

Figures 3 - 5 show that for a given emitter temperature, the shape of the current-voltage characteristic does not depend strongly on collector temperature. Apparently, the main effect of a decrease in the collector temperature in the range covered is to increase the contact difference of potential between the electrodes, so that the current-voltage characteristic is shifted in the direction of higher power output. This effect can be seen graphically in Figure 8, which shows the maximum power output plotted versus collector temperature. These data were repeated at least once (some were repeated twice) and the vertical lines are a measure of the reproducibility of the data. The spread is thought to be due to small variations in parameters such as electrode temperature and cesium pool temperature. Note that the power output goes to zero for equal electrode temperature, in accord with the second low of thermodynamics. Note also that the lowest collector temperatures are in the range of 70 to 80 percent of the corresponding emitter temperature, which is the required range for best performance of a radiation-cooled Carnot engine.

According to Figures 6 and 7, the open circuit voltage between electrodes at fixed temperatures is practically independent of cesium vapor pressure. This means that if the difference in work functions of the electrodes changes with pressure, then the sheath drops change in such a way as to compensate for the change in work function difference. Figure 9 shows the variation of maximum power output with cesium pool temperature. These curves were obtained from current-voltage characteristics such as those shown in Figures 6 and 7. In each case, the highest cesium pool temperature was determined by the coolest region of the tube, which was the base of the emitter support.

During these measurements, it was noticed that the shape of the current-voltage characteristic exhibited a peculiar behavior as the cesium pool temperature was varied. This behavior is illustrated in Figure 10, which

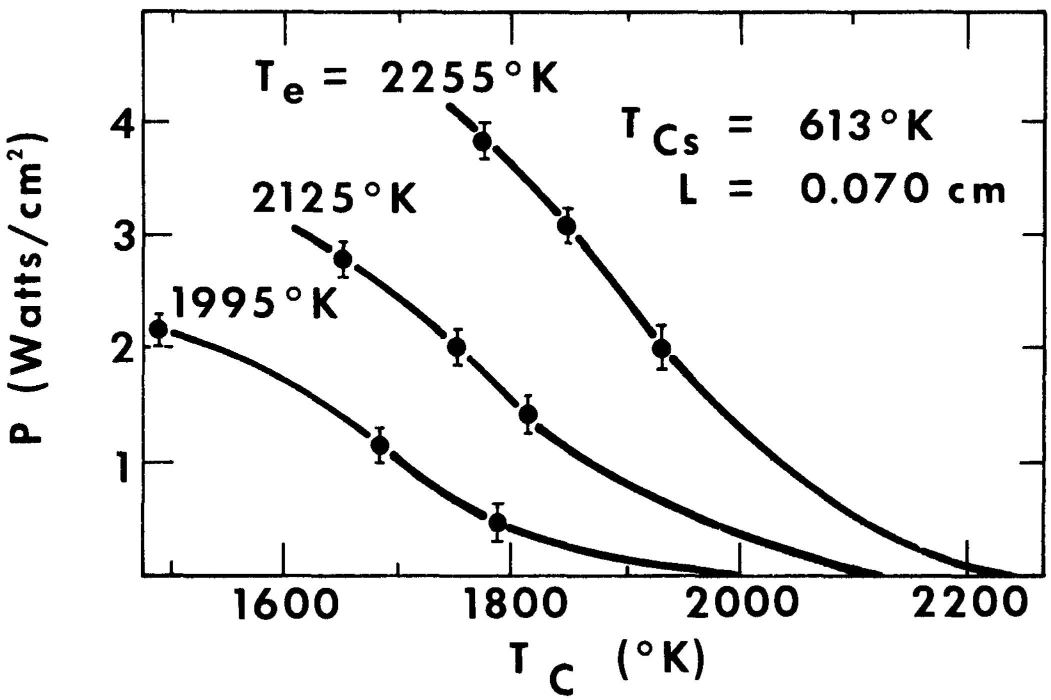

Figure 8.
MAXIMUM POWER OUTPUT
FOR DIFFERENT COLLECTOR TEMPERATURES

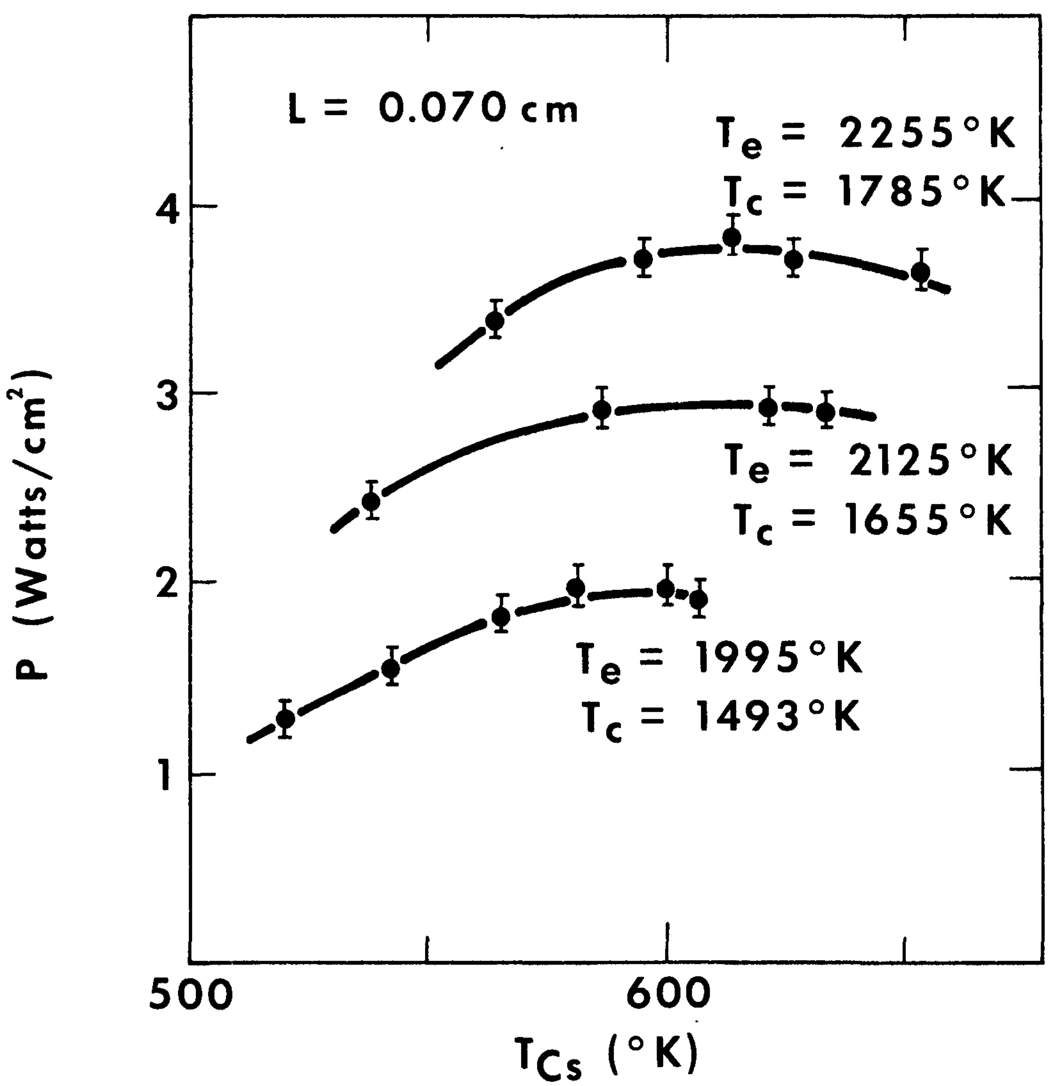

Figure 9.
MAXIMUM POWER OUTPUT
FOR DIFFERENT CESIUM PRESSURES

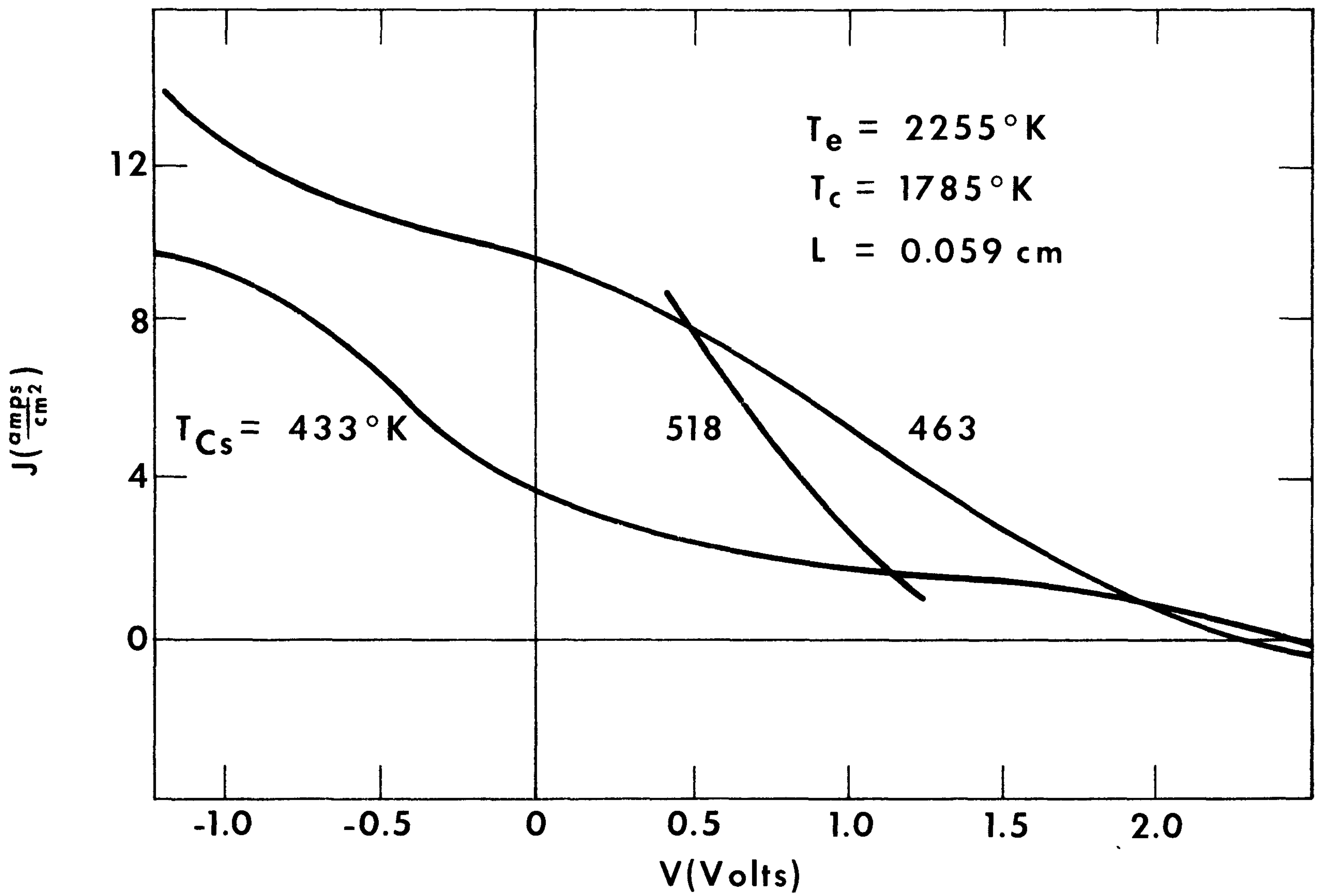

Figure 10. CURRENT-VOLTAGE CHARACTERISTICS FOR DIFFERENT CESIUM PRESSURES SHOWING WALL EFFECT

shows three current-voltage characteristics for constant electrode temperatures and spacing, but widely different cesium pool temperatures. The high pressure curve is, of course, similar to those shown in Figure 5, but the two curves for lower pressures are quite different. The cesium pool temperature was changing rapidly during these measurements so that the values shown are approximate. The peculiarity of these curves is two-fold: (1) The lower pressure curves have much larger open circuit voltages than does the high pressure curve; (2) The power output at a cesium pool temperature of $463^{\circ}K$ is more than twice the power output at either $433^{\circ}K$ or $518^{\circ}K$. This effect has been tentatively diagnosed as a "wall effect", by which it is meant that the tube envelope, which was electrically connected to the collector proper, but was at a much cooler temperature, was playing an important role in the production of electrical power output at low cesium vapor pressure. This conclusion is based on the reasoning that the cool surface of the tube envelope would have a more or less complete coating of cesium so that its work function would be about 1.8 volts. This would account for large open circuit voltages observed at low pressure. This effect can be seen more readily in Figure 11, which shows the approximate variation in maximum power output with cesium pool temperature including the low pressure region. The scatter in the data points is due primarily to the fact that the maximum power was estimated from the current-voltage characteristics while the cesium pool temperature was rapidly changing. In spite of this scatter, however, the peculiar variation of power output with cesium pool temperature is obvious. It is believed that the "wall effect" was unimportant at high cesium vapor pressure (cf Fig. 9).

The result that power output is insensitive to changes is electrode spacing in the range covered is interesting from a practical standpoint. For example, it may be more practical, in terms of reliability, to design a converter to run at high temperature and large spacing instead of low temperature and small spacing. Such an approach would allow for the high radiator temperatures which are required for radiation cooling.

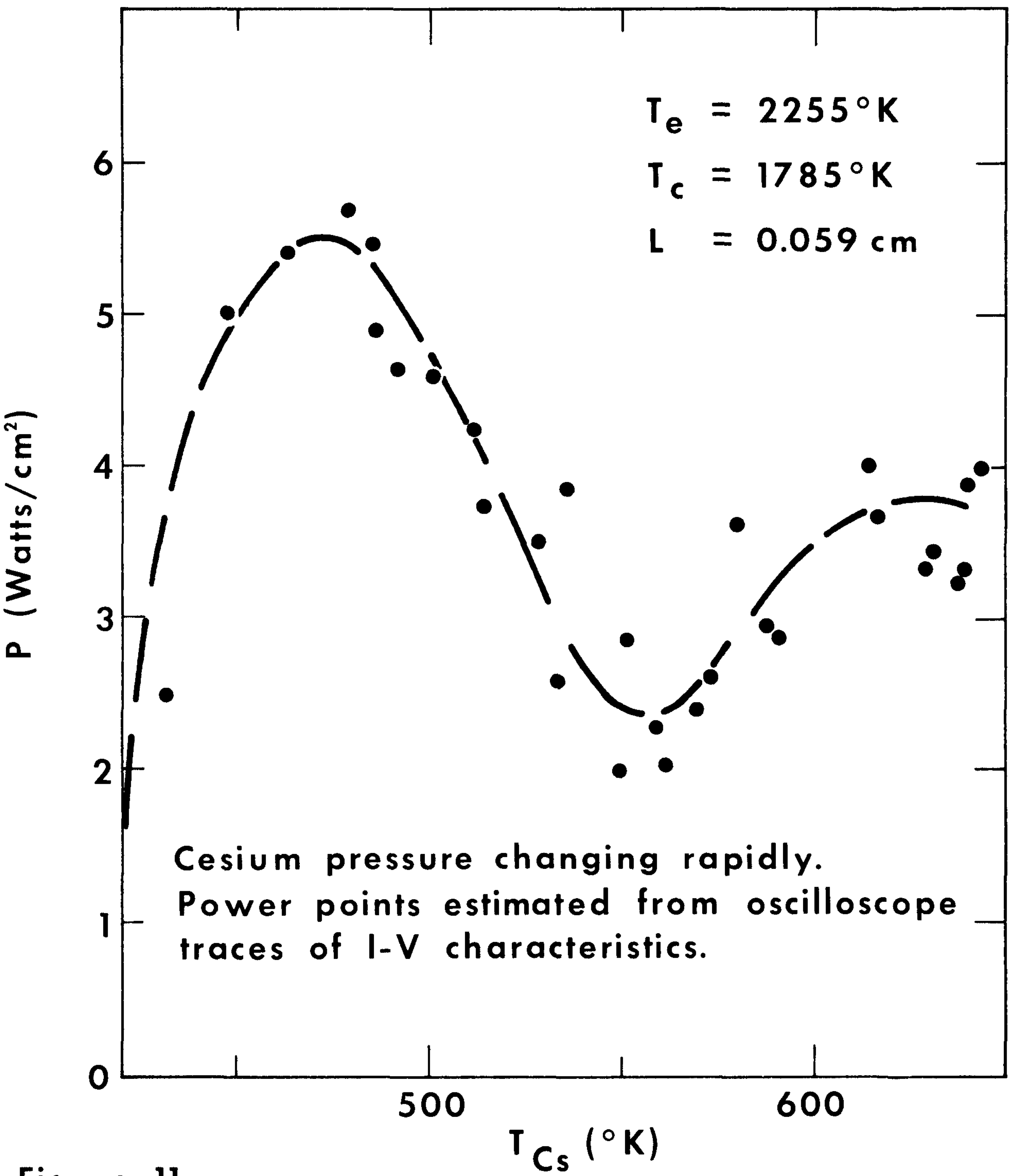

Figure 11.

MAXIMUM POWER OUTPUT FOR DIFFERENT CESIUM PRESSURES SHOWING WALL EFFECT

SUMMARY

Current-voltage characteristics of a cesium-on-tantalum thermionic converter with a collector temperature comparable to that of the emitter are presented for a variety of electrode temperatures and cesium vapor pressures. The results can be summarized as follows: (1) For emitter temperatures in excess of $2000^{\circ}K$, power outputs of a few watts per square centimeter can be obtained when the ratio of collector temperature to emitter temperature is as high as 0.75 to 0.80, which is the required range for best performance of a radiation-cooled Carnot engine; (2) At temperature ratios above 0.80 the power output is insensitive to changes in electrode spacing for ratios of spacing to electron mean free path greater than 100 at a cesium vapor pressure of 5 torr.

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