AN APPLICATION OF LANGMUIR-TAYLOR DATA
TO THE THERMIONIC CONVERTER, 1960

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(TEE-7002-8)

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by

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Foreword

This technical report was first prepared in September 1960, when it was hoped that additional experimental data might soon become available so that the results of these calculations could be more accurately assessed. Although plans are well under way to make an experimental evaluation of this analysis, so much interest has been exhibited in it that it is now being presented as a brief technical report. Comments from recipients of this report will be appreciated.

Abstract

Nothing new in the way of experimental data is presented in this technical report. Its purpose is to show that alternate ways of presenting the Langmuir-Taylor data and its equivalent can very well be of considerable practical interest to the designer of a thermionic converter of the cesium diode type. Principally, the analysis applies to the alteration of the emitter work-function as determined by the temperature of the emitter and the temperature of the cesium concentration control. The basic starting point is the Taylor-Langmuir paper. Final results permit one to determine approximate values for the thermionic emission capability of a tungsten surface operated at any specified temperature between 1200 and 2400°K and a cesium-bath temperature in the range of from 500 to 640°K. The ratio of the ion production and the corresponding electron production is analyzed, and an area of operation is defined in which the current density can be large and yet have a sufficient ion production not only to neutralize space charge but to create an ion sheath over the emitter to accelerate the electrons into the highly ionized plasma region of the diode.

TABLE OF CONTENTS

Section	Title	Page
1.0	INTRODUCTION	1
2.0	DISCUSSION OF THE TAYLOR-LANGMUIR DATA	1
3.0	DEFINITIONS	2
4.0	ADDITIONAL DERIVED RESULTS	5
5.0	MINIMUM IONIZATION NEEDED FOR SPACE-CHARGE NEUTRALIZATION	6
6.0	CONCLUDING REMARKS	7
7.0	REFERENCES	8

LIST OF ILLUSTRATIONS

Figure	Title
1	Effective work-function of tungsten for various cesium condensation temperatures based on Taylor-Langmuir data
2	Current density as determined by the effective work-function and the emitter temperature
3	Lines of constant effective work-function and current density as determined by the cesium control temperature T_{Cs} and the emitter temperature T
4	Ratio of electron current to ion current for selected cesium control temperatures

1.0 INTRODUCTION

Taylor and Langmuir studied the evaporation of ions and electrons from tungsten in the presence of cesium vapor [1]. In the use of Taylor-Langmuir data, certain facts not widely recognized must be kept in mind. First, the tungsten used was not only polycrystalline but it also exhibited a wide range in true work-function in the absence of cesium. It has been established that electron-emission properties in the presence of cesium are sensitive to the underlying crystalline structure [2]. A second fact is that the actual range in cesium condensation temperature and tungsten temperature used for the study was very limited. The maximum cesium temperature was 302°K (29°C). Interpolation and extrapolation formule were developed by Langmuir to extend his results to higher pressures. An extrapolation extending over an additional three orders of magnitude of atom arrival rate has been carried out by Wilson [3]. Present needs demand data in the pressure range 10^6 higher than the maximum used by Taylor and Langmuir. Although the acquisition of new experimental data applicable to the cesium condensation temperature range of from 500°K to 625°K and a tungsten temperature range of from 1200°K to 2600°K would resolve the uncertainty with regard to the applicability of the Taylor-Langmuir data to present-day problems, a research objective that included the study of other materials than tungsten and a control of the crystallographic nature of the underlying surface would be of much greater value. In the meantime, it may be of some interest to see what can be accomplished on the basis of the Taylor-Langmuir data combined with the introduction of a new approach to its analysis.

2.0 DISCUSSION OF THE TAYLOR-LANGMUIR DATA

During and shortly after the researches of Taylor and Langmuir, investigations at M.I.T. by Johnson, Martin, Robinson, and others indicated very strongly that the tungsten samples used by Taylor and Langmuir were not dominated by the 110-surface as claimed by Langmuir.

Taylor and Langmuir state on page 424, "Actually after heating to 2900° during ageing, a tungsten filament becomes etched and develops dodecahedral crystal faces (110) in which there are 1.425×10^{15} tungsten atoms/cm^2." There are two reasons to doubt this statement. First, our thermionic emission patterns, observed from single crystals of tungsten after an equivalent heat treatment, always showed a great nonuniformity in work-function and practically no thermionic emission from the 110-direction. The much more recent work of Hutson and others has established that the work-function associated with the 110-direction must be 5.3 electron volts or more. Thus, the second reason for disbelief of the statement that the surface is dominated by 110-areas is that Taylor and Langmuir used an effective work-function of 4.62 to represent their electron-emission data. With this work-function associated with a thermionic constant of 120, one obtains the usual average emission current density so often observed to have a Richardson work-function of 4.52 and a Richardson thermionic constant of 60 amp deg^{-2} cm^{-2}.

Taylor and Langmuir in their Fig. 8 show experimental results that are basically significant in that they show the concentration of cesium atoms as a number per unit area on a tungsten surface as a function of the atom arrival rate and the tungsten temperature. The condensation temperatures associated with the recorded arrival rates cover the range of from 235 to 284°K.

3.0 DEFINITIONS

Although the "true work-function" of a surface is defined as the energy difference between the Fermi level of a substance and the energy state of an electron just capable of electron emission with negligible excess kinetic energy, the "effective" work-function is the value of the symbol ϕ_e which yields the same electron current density at a given emitter temperature as would be obtained from

an idealized surface of a uniform true work-function equal to the effective work-function. Thus, if the effective work-function is known for a practical emitter, which may nevertheless be very nonuniform in its properties, then the current density obtained is given by the relation

$$I_e = 120 \times 10^4 T^2 \exp\left(-\frac{\phi_e}{\overline{V}}\right) \quad \text{amp/ m}^2. \qquad (1)$$

The new symbol introduced here is defined as the electron-volt equivalent of temperature given as

$$\overline{V} = \frac{kT}{q} = \frac{T}{11600}. \qquad (2)$$

The evaporation rate of cesium atoms from liquid cesium can be deduced from an empirical equation which gives the vapor pressure of cesium over a very wide range in temperature. On the assumption that the arrival rate of cesium at a hot surface is equal to the evaporation rate at the nearby liquid surface of cesium, the following equation may be written:

$$\mu_{Cs} = 7.48 \times 10^{33} T_{Cs}^{-1} \exp\left(-\frac{8910}{T_{Cs}}\right) \quad \text{atoms m}^{-2} \text{ sec}^{-1}. \qquad (3)$$

If every atom that arrives at a hot surface converts into an ion, then the ion emission current density would be given by

$$I_{Cs} = 1.2 \times 10^{15} T_{Cs}^{-1} \exp\left(-\frac{8910}{T_{Cs}}\right) \quad \text{amp/m}^2. \qquad (4)$$

The probability that a cesium atom will be converted to a cesium ion at the hot surface depends on the temperature of the surface and on its true work-function. The effective work-function of a surface generally represents some average, difficult to assess in terms of the component true work-function values. There are conditions especially associated with effective work-functions that are less than the ionization potential for which it is of secondary importance to use the actual true work-functions instead of the effective work-function. On that basis, the

following formula will be used to relate the ion production rate to the atom arrival rate:

$$I_+ = \frac{I_{Cs}}{\exp\left[(V_i - \phi_e)/\overline{V}\right] + 1}. \qquad (5)$$

Equations (1), (4), and (5) may be combined to yield an expression for the ratio I_e/I_+, which is

$$\frac{I_e}{I_+} = T^2 \exp\left(-\frac{\phi_e}{\overline{V}}\right)\left[1 + \exp\left(\frac{V_i - \phi_e}{\overline{V}}\right)\right] T_{Cs} \exp\left(\frac{8910}{T_{Cs}}\right) \times 10^{-9}. \qquad (6)$$

If the difference between the effective work-function and the ionization potential is sufficient in units of $\overline{V}$, then the following logarithmic expression applies:

$$\ln \frac{I_e}{I_+} = 2 \ln T - \frac{2\phi_e - V_i}{\overline{V}} + \ln T_{Cs} + \frac{8910}{T_{Cs}} - 20.73. \qquad (7)$$

Although the emitter temperature T and the cesium bath temperature T_{Cs} are independent variables under the control of the experimenter, the effective work-function ϕ_e is dependent on these two temperatures and also on the emitter material itself. The curves of Fig. 1 have been drawn with the hope that they represent the relationship between the emitter temperature and its effective work function for various values of the cesium condensation temperature. High accuracy cannot be claimed for these curves since they depend on such an extensive extrapolation from the original data of Taylor and Langmuir. They are used to demonstrate the method of analysis proposed here, and at the same time they help to define the temperature ranges most likely to be of interest.

The solid lines in Fig. 2 relate the temperature of the emitter to its work-function for various electron current densities as expressed by the following equation:

$$I_e = 3.52 \times 10^9 \exp\left(-\frac{\phi_e + 0.328}{\overline{V}}\right) \quad \text{amp/cm}^2. \quad (8)$$

This equation is derived from Eq. (1) and is quite applicable for the temperature range of from 1400 to 2400°K. For the easy calculation of the temperature associated with a given work-function and current density, the following equation may be used:

$$T = 5040 \frac{\phi_e + 0.328}{9.5 - \log_{10} I_e}. \quad (9)$$

Note that in these two equations the current is expressed in amperes per square centimeter.

The dashed lines of Fig. 2 represent a superposition of the solid lines of Fig. 1 on the solid lines of Fig. 2. It is interesting to note how nearly these lines parallel each other, indicating that, over a considerable range of emitter temperature and in the presence of cesium characterized by these condensation temperatures, the emission current density remains nearly constant because as the temperature increases, the corresponding increase in work-function holds the electron current density constant.

4.0 ADDITIONAL DERIVED RESULTS

No additional data are needed to present the information contained in Fig. 3, which relates the emitter temperature and the cesium temperature for various values of constant work-function or for various values of constant emission density. Note, for example, that if the emitter effective work-function is to be maintained at approximately three volts as the emitter temperature is increased from 1600 to 2100°K, then the cesium temperature must be increased from 500 to 650°K. Note also that if an emission current density of 40 amp/cm^2 is to be maintained, then the cesium temperature must be decreased as the emitter temperature is increased. Ten amperes per square centimeter can be expected with an emitter temperature of 1900°K and a cesium temperature of about 580°K.

5.0 MINIMUM IONIZATION NEEDED FOR SPACE-CHARGE NEUTRALIZATION

Since the square root of the mass ratio ($\sqrt{M/m}$) is 492 for cesium, an ion production which is equal to the electron emission current density divided by this factor must be obtained as the minimum for space-charge neutralization. Figure 4 is a graphical representation of the application of Eq. (7) combined with the work-function dependency exhibited by Fig. 1. Since the natural logarithm of 492 is 6.20, the dotted line in the figure represents the demarcation between the area above the line, for which insufficient ionization is available, compared with the region below the line, for which more than enough ions are produced to satisfy the minimum requirement. These data are sufficient to establish the corresponding dotted line in Fig. 3. Note that to the left of this line there is insufficient ionization, whereas to the right of the line the minimum is exceeded.

Two numerical examples may be of interest as this presentation is related to that of the "General Theory"[4] in that there is Eq. (6-7) which applies to the theory of emitter-sheath space-charge formation. This example involves the following choice of parameters:

$$T = 1950°K,$$

$$T_{Cs} = 624°K,$$

$$\phi_e = 2.7 \text{ ev},$$

$$u = \frac{2.7 - 3.9}{0.168} = -7.15,$$

$$H_2(u) = -7.15,$$

$$I_e = 40 \text{ amp/cm}^2.$$

These values correspond to a point in Fig. 3 very close to the intersection of the dotted border line and the line for emission current density of 40 amp/cm^2. The ion sheath potential calculated for this case is 0.13 volt. The approximations involved in the formation of

the basic equation used for this calculation are so poor that it is fair to say that this injection potential is substantially zero and is therefore in agreement with the choice of a point on the dotted line of Fig. 3 that is critical in that the ionization is adequate for neutralization but no more.

The second choice of parameters also corresponds to the same current density. These parameters are

$$T = 2320\,^{\circ}K,$$

$$T_{Cs} = 608\,^{\circ}K,$$

$$\phi_e = 3.3 \text{ ev},$$

$$u = \frac{3.3 - 3.9}{0.2} = -3.0,$$

$$H_2(u) = -3.03,$$

$$I_e = 40 \text{ amp/cm}^2.$$

The computation here leads to a sheath potential of 1.06 volts and this in turn to an electron temperature after injection into the plasma of 11,300°K. Such a result not only indicates that an adequate generation of positive ions exists for the neutralization of space charge, but it would also seem to indicate that an injection sheath could be formed to give the electrons a high random motion that would correspond to a temperature above 6000°K, perhaps as high as 10,000°K.

6.0 CONCLUDING REMARKS

It has been the purpose of this paper to present a way of analyzing emission data so as to have a direct bearing on the design of a thermionic converter. In terms of the detailed evaluation, it is all dependent on the validity of the relations shown in Fig. 1. If better data were available, then the whole treatment could be redone following these suggestions and more valid design information would be available. It would appear from this study that, with an emitter operating at 2400°K and a cesium condensation temperature near 620°K, something approaching 80 amp/cm^2 might be realized with a maximum available voltage near 1.6. After some

losses are taken into consideration, an optimistic analysis would lead to the belief that 100 w/cm^2 output power is not unrealistic. The collector should operate at a temperature not much in excess of 1100°K to minimize the back emission. A rough estimate of the minimum radiation loss would be 80 w/cm^2 and an electron cooling of 300 w/cm^2. These figures suggest an efficiency of 26%. Figures of this kind show sufficient promise to warrant a far more diligent effort to acquire the basic data of well-substantiated reliability compared with that used in this report and incorporated in Fig. 1.

Associated with the suggested choice of a cesium condensation temperature of 620°K is the estimated mean-free path of 5 μ. If the distance between the emitter and the collector is between 50 and 100 μ, it may nevertheless be possible to operate the converter in a practical manner in that the high-energy electrons injected across the emitter sheath may be able to maintain the required ionization density to maintain good conductivity with relatively little loss of output voltage in the intervening space. One logical approach in terms of the construction of a device is to choose the smallest practical spacing consistent with an emitter operation near 2400°K and bring up the cesium condensation temperature to the highest practical value, preferably near 620°K. If spacings as small as 50 μ prove difficult to achieve, then lower cesium pressures and lower current densities will be indicated.

7.0 REFERENCES

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"Adsorption of Cesium on Various Crystallographic Surfaces of Tungsten As a Function of Temperature," B.S. Thesis, M.I.T. Physics Dept., 1960.

3. V.C. Wilson, Chap. 7 of Direct Conversion of Heat to Electricity, J. Kaye and J. Welch. New York: Wiley and Sons, 1960. See Fig. 7-6.

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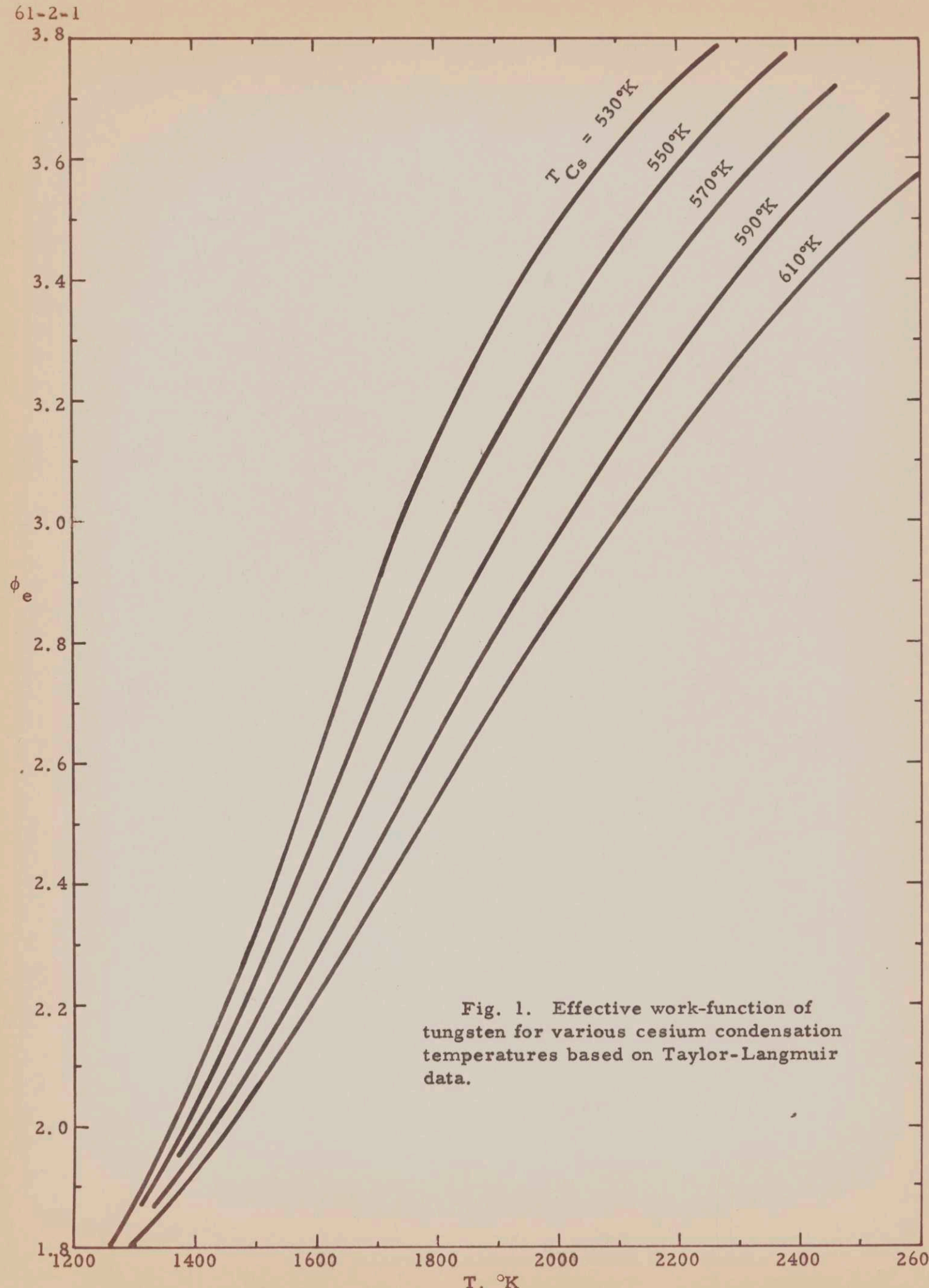

Fig. 1. Effective work-function of tungsten for various cesium condensation temperatures based on Taylor-Langmuir data.

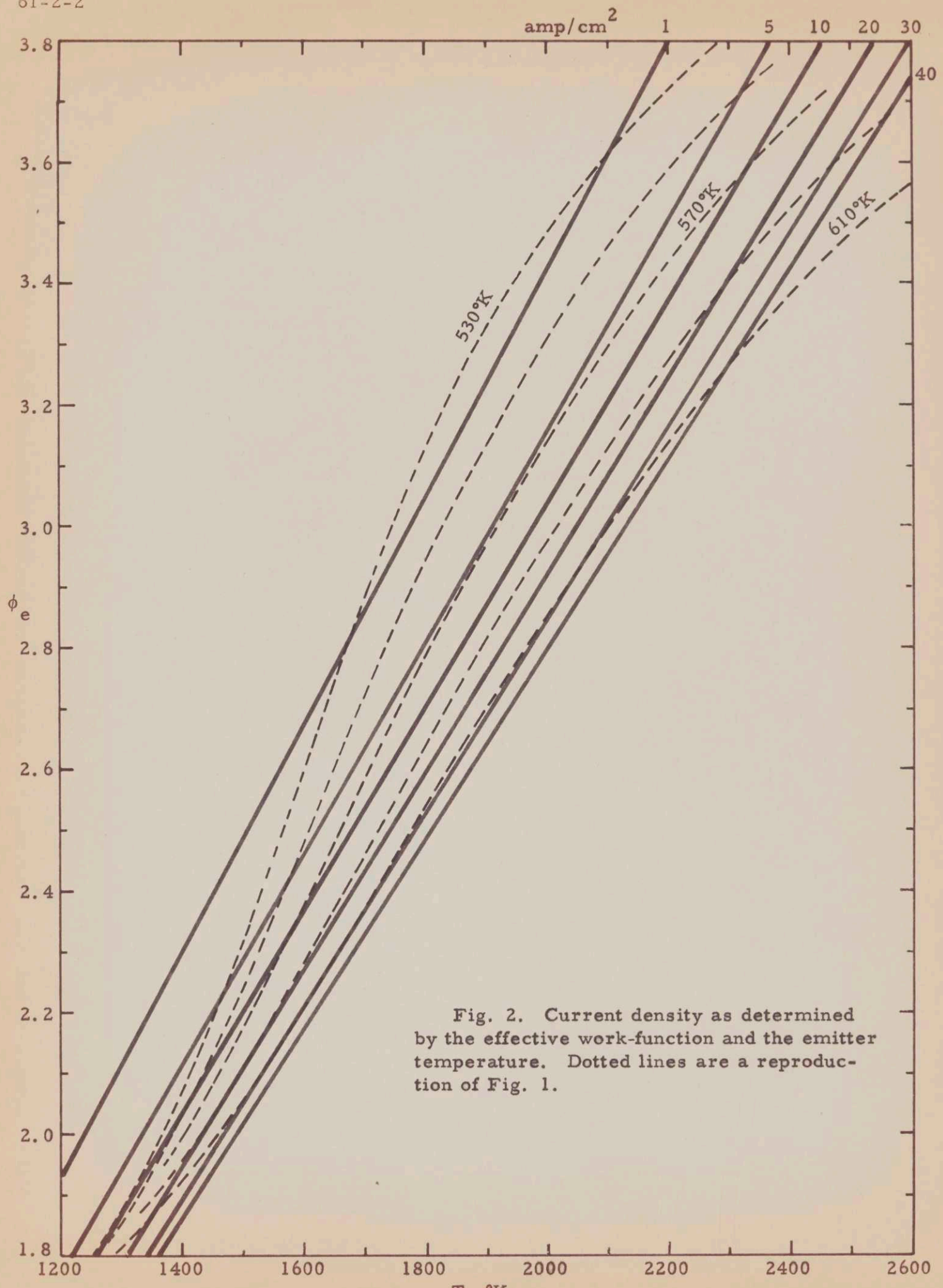

Fig. 2. Current density as determined by the effective work-function and the emitter temperature. Dotted lines are a reproduction of Fig. 1.

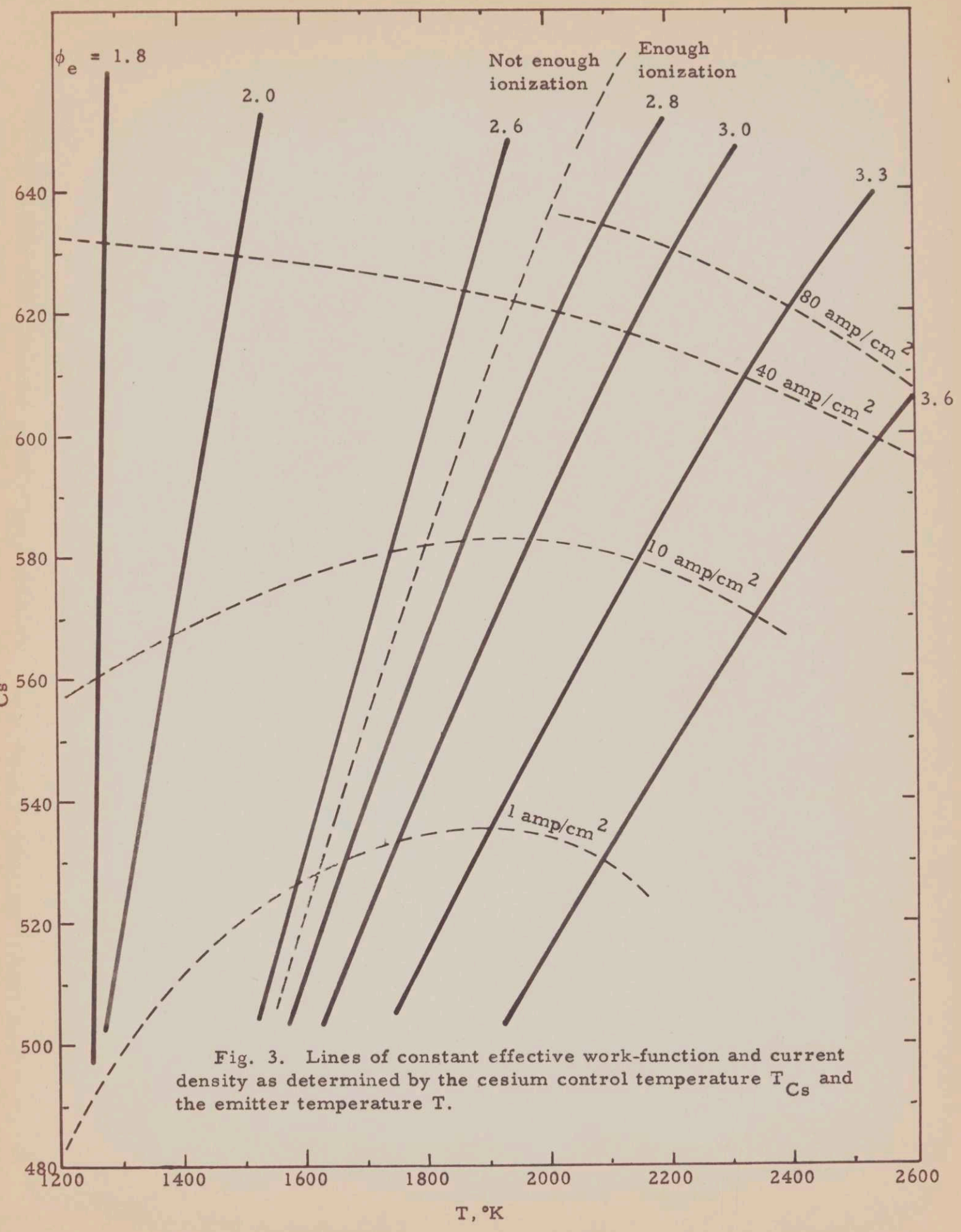

Fig. 3. Lines of constant effective work-function and current density as determined by the cesium control temperature T_{Cs} and the emitter temperature T.

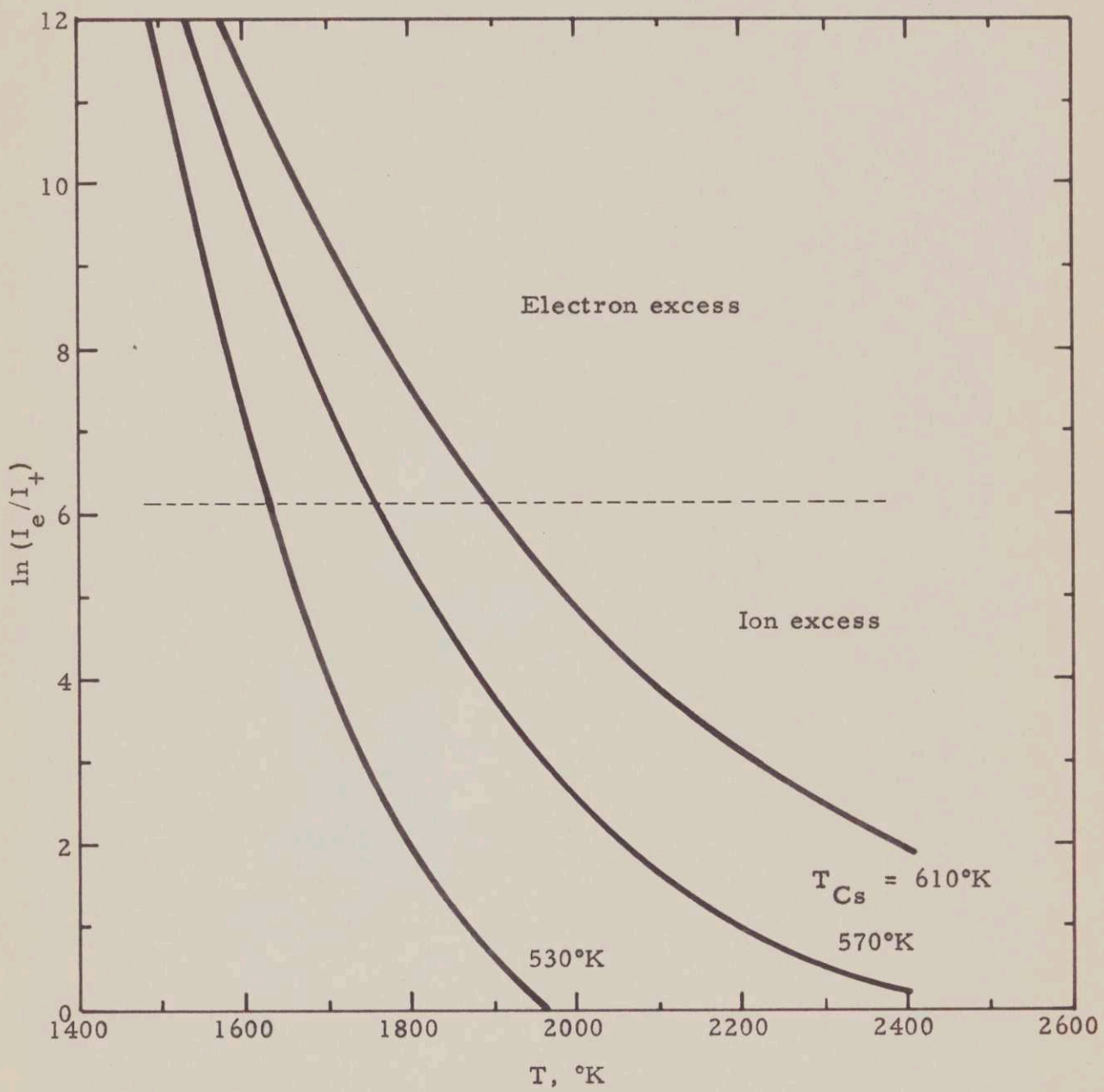

Fig. 4. Ratio of electron current to ion current for selected cesium control temperatures. Dashed line is demarcation between electron excess condition above and ion excess condition below.