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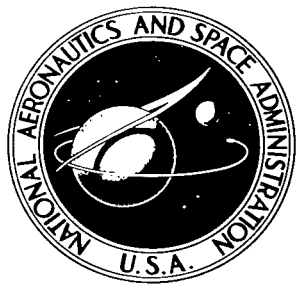

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THEORETICAL BACKGROUND FOR THERMIONIC CONVERSION INCLUDING SPACE-CHARGE THEORY, SCHOTTKY THEORY, AND THE ISOTHERMAL DIODE SHEATH THEORY

by

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CONTENTS

THEORETICAL BACKGROUND FOR THERMIONIC CONVERSION INCLUDING SPACE-CHARGE THEORY, SCHOTTKY THEORY, AND THE ISOTHERMAL DIODE SHEATH THEORY

by Wayne B. Nottingham* and Roland Breitwieser

Lewis Research Center

SUMMARY

A theoretical background to the analysis of thermionic converter performance is presented. The areas of theory treated include (1) space-charge theory for the case where either electrons or ions are the predominant charge carriers, (2) Schottky mirror image theory for ion and electron emission, and (3) Fowler theory applied to a plasma in equilibrium with an emitting surface, treated in terms of the relation of the plasma potential to surface potentials and in terms of the character of the sheath. Included are various graphical and tabulated aids to the analysis of cesium filled thermionic converters. Simplicity of theory and assumption is emphasized so as to yield convenient analytical tools for the first order examination and treatment of thermionic converter data.

I. - INTRODUCTION

Stimulated by the need for an energy conversion system that minimizes the weight per kilowatt, the direct conversion of heat to electricity by thermionics has been intensively investigated in many research centers for the past several years. As a part of this effort many excellent detailed analyses and experimental studies of thermionic processes have been developed. Experience has shown that knowledge of space-charge, Schottky, Fowler (sheath), and isothermal diode theories are required for many phases of this thermionic converter research. A series of lectures by the authors covering these analytical areas has been combined and is the framework of this report.

Space-charge theory is reviewed for the case where the charge carrier is predominantly of one sign. This theory applies directly to the vacuum diode and often can be extended to the analysis of the performance of the plasma diode. The Schottky theory of the transmission of electrons in strongly accelerating fields is reviewed, and simplified relations are developed. A brief review of the theory of the isothermal diode and guides to its application are presented. Reference is made to the Fowler space-charge theory in the isothermal diode analysis. The Fowler theory is used to describe the potential variation of the plasma sheath between the conductor surface and the isothermal plasma.

The primary intent of this report is to translate these well-known theoretical developments into a form amenable to treating experimental data. Review and, on occasions, modified development of theory have been included so that the limitations of theory are thus established. It is felt that the analytical approaches suggested can serve as important aids to the understanding of practical

*Massachusetts Institute of Technology, deceased, 1964.

thermionic converters despite the fact that experimental conditions seldom fit the specific boundary conditions set by theory.

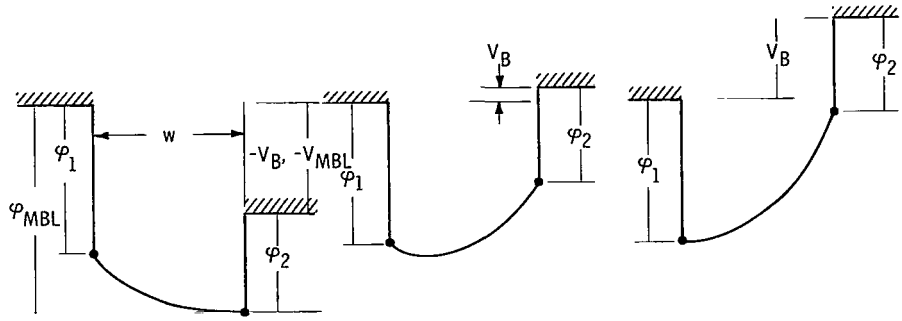
II. - GENERAL DESCRIPTION OF SPACE-CHARGE PROBLEM

The equations to be summarized in this section apply to either electron or ion emission across a diode. The initial formulation relates to the current-voltage curve that describes the delivery of electrons to a collector in absence of any ions. The analysis assumes the emitter and collector work functions are uniform, the surfaces are parallel, infinite planar areas exist, and the temperatures are known. The various ranges of interest are shown in the electron potential diagrams (figs. II:1(a) to (c)) and the corresponding current-voltage curve (fig. II:1(d)). Figure II:1(b) is a typical potential diagram in the space-charge range. Figures II:1(a) and (b) represent the potential distribution at the limits of the space-charge range. The electron potential diagram of special importance in shown in figure II:1(a) in which the interelectrode potential merges with collector potential with zero slope. This is a critical condition of zero field at the collector and serves to separate the "space-charge range" from the "Boltzmann range" and is identified as the Maxwell-Boltzmann limit (MBL). The applied potential at this Maxwell-Boltzmann limit is identified by V_{MBL}. The collector work function φ_2 is defined as the difference between the collector Fermi level and surface potential. Thus, the surface potential φ_{MBL} relative to the emitter Fermi level is equal to absolute sum of the applied potential V_{MBL} and φ_2. Over the range of voltage more negative than this limiting value V_{MBL}, the current observed is a direct measure of the total outflow of electrons from the emitter that have a sufficient energy to overcome the surface barrier at the collector. The straight line portion of the logarithm of the current plotted against voltage is this Boltzmann range (fig. II:1(d)). The equation that relates this current to the applied voltage is the following form of the Richardson-Dushman emission equation:

$$-J_B = 120\times10^4 T^2 \exp\left[\frac{-q(\varphi_2 - V_B)}{kT}\right] \quad \text{amp/sq m} \qquad \text{(II:1)}$$

The equation is written in its general form. The sign convention used is as follows: the work function φ is always treated as a positive quantity. When the Fermi level of the collector is negative with respect to the emitter (displaced downward in fig. II:1(a)), the applied voltage V_B is negative and cancels the negative sign in the parenthesis in equation (II:1). The quantity $(\varphi_2 - V_B)$ represents the surface barrier at the collector that suppresses electron flow from the emitter and is therefore referenced to the emitter Fermi level. It follows that at a given emitter temperature, φ_2 can be determined directly from the current density $-J_B$ and applied voltage V_B. The emitter temperature may also be obtained from the straight line portion of the logarithm of current of a plot such as figure II:1(d). Noting that T appears in the exponent in equation (II:1), it then follows directly that emitter temperature can be established at any arbitrary current ratio

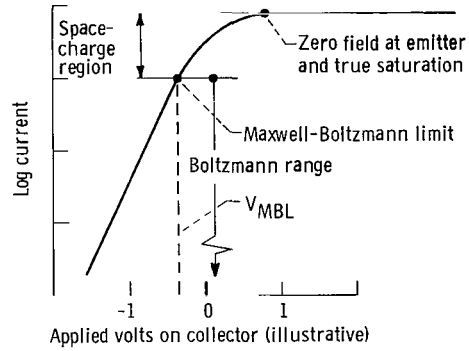
$$T = \frac{(V_{B,2} - V_{B,1})11\,606}{\ln\left(\frac{-J_{B,2}}{-J_{B,1}}\right)} \quad {}^{o}K \qquad \text{(II:2)}$$



(a) Typical potential at Maxwell-Boltzmann limit (start of space-charge region V_B is equal to to V_{MBL}; if voltage is more negative, Boltzmann range is entered).

(b) Example of potential in space-charge region.

(c) Example of potential with zero field at emitter (corresponds to saturation current condition).



(d) Current-voltage curve.

Figure II:1. - Ranges of interest in space-charge analysis of planar diode.

Various current ratios may be used. For example, a convenient current ratio of 3.197 results in

$$T = (V_{B,2} - V_{B,1})10^4 \qquad {}^{o}K \qquad \text{(II:3)}$$

As the applied voltage V_B is changed to make the surface potential less negative, the linear portion of the logarithmic current-voltage curve terminates (fig. II:1(a)). This is the aforementioned critical condition of the limit of the Maxwell-Boltzmann range and the onset of the space-charge condition. At still smaller negative surface potentials, the space-charge minimum moves toward the emitter. A typical potential distribution in the space-charge range is shown in figure II:1(b). Here, although the surface potential of the collector is positive with respect to that of the emitter, the current is determined by the space-charge barrier, which is more negative than the emitter surface potential. The limit of the space-charge range is also shown in the diagram and is associated with the zero slope of the potential at the emitter surface (fig. II:1(c)). The saturation emission capability of the emitter can only be

measured at this condition of zero field at the emitter. The observed current (at zero field) can be used to determine the work function of the emitter by the standard form of the Richardson-Dushman equation

$$-J_0 = 1.2\times10^6 T^2 \exp\left(\frac{-q\varphi_1}{kT}\right) \quad \text{amp/sq m} \qquad \text{(II:4)}$$

Space-charge theory applies specifically to the range of applied voltage for which the surface potential of the collector is varied between that of the Maxwell-Boltzmann limit and that of zero field at the emitter. The theory may be applied to either ions or electrons if proper recognition of charge, particle mass, and potential is made. A surface potential at the Maxwell-Boltzmann limit depends on the spacing, emitter temperature, and to some extent on the emitter work function. If these quantities are known then the applied potential required to establish zero field at the emitter may be computed. The last point is of particular interest since it applies to the evaluation of ion current production at a heated surface in the presence of an easily ionized gas such as cesium. The space-charge relations are also obviously of value in determining the emitter work function from the identification of zero-field emission current.

Diodes of greatest interest to thermionic conversion must necessarily combine the influence of both electrons and ions. The use of the "unicharge", noncollisional space-charge theory limits the quantitative assessment of the properties of the emitter and the collector surface to data obtained at extremely close spacing. As the spacing increases beyond a few microns, plasma conditions develop and current-voltage characteristics are generated that follow the qualitative features associated with the basic space-charge theory, but current-voltage characteristics have to be associated with an "effective spacing" considerably less than the actual interelectrode spacing.

Data obtained near the Maxwell-Boltzmann limit often are less distorted by plasma effects than data obtained near saturation current condition. Thus, the space-charge theory reviewed here is being adapted to determine (1) emission capability of an emitter, (2) information on limiting barriers other than the surface barrier, and (3) effective spacing, by the method of indexing the solution of the space-charge problem to the Maxwell-Boltzmann limit. The results on barriers and spacings apply to both electrons and ions. The evaluation of the barriers and spacing hopefully should lead to a better understanding of the properties of the conducting plasma in the interelectrode space of practical energy converters.

III - LANGMUIR SPACE-CHARGE EQUATION

Langmuir (ref. 1) and others (refs. 2 to 4) have presented and evaluated the basic differential equations relating emitter temperature, charge-to-particle mass ratio, current flow across a diode to the potential as a function of distance. The space-charge formulation involves Poisson's equation, the Maxwell-Boltzmann distribution function, the Boltzmann relation, and conservation equations. The derivation is given in the aforementioned references so it will not be repeated here. The generalized solution makes use of the dimensionless parameters,

$$\psi = \frac{qV}{kT} \qquad \text{(III:1)}$$

$$\chi = \frac{KJ^{1/2}x}{T^{3/4}} \qquad \text{(III:2)}$$

$$K = \frac{q^{1/2}(2\pi m)^{1/4}}{\sqrt{2}\,\epsilon_0^{1/2}k^{3/4}} \qquad {}^{o}K^{3/4}/\text{amp}^{1/2} \qquad \text{(III:3)}$$

where K is 6.5×10^5 for electrons or is 1.442×10^7 for singly charged cesium ions. The value of χ can be obtained conveniently by a nomographic solution presented in figure III:1.

The basic differential equation (ref. 2, for example) is

$$\frac{d^2\psi}{dx^2} = -\left[1 \pm P(\psi^{1/2})\right]e^{\psi} \qquad \text{(III:4)}$$

where P is the well-known "probability integral". The plus sign in equation (III:4) is used in the emitter region (i.e., the region between the space-charge minimum and the emitter), and the negative sign applies to the collector region. The equation can be integrated once to yield a result suitable for numerical integration. The numerical solutions for both regions are given in table III:1 and are essentially equivalent to the values given in references 2, 4, and 5; the small differences reflect the difference in the numerical computing procedures.

Figure III:2 is a graphical representation of table III:1. The shortcoming of the solution in the form shown in figure III:2 is that the dimensionless parameters are referenced to the space-charge minimum and are not obviously related to experimentally observable quantities.

As discussed previously, the Maxwell-Boltzmann limit and the saturation current condition correspond to zero field at the collector (space-charge minimum at collector surface) and zero field (minimum) at emitter, respectively. The two zero-field conditions at the surfaces immediately relate the potential distribution in the interelectrode space to the applied voltage and are therefore the logical starting points for space-charge analysis.

A graphical representation of the space-charge relations is given in figure III:3. The form is similar to figure II:1; however, potential and distance are represented in dimensionless units. The relation between surface potential, work function, and Fermi level is as before, except the potential differences have been divided by kT/q to make them dimensionless. The potential distribution for zero field at the emitter is completely described by curve C-R (fig. III:3), which is the generalized solution of the space-charge conditions in the collector region. The location of the collector surface is established by the values of J, T, and w (i.e., the dimensionless distance X).

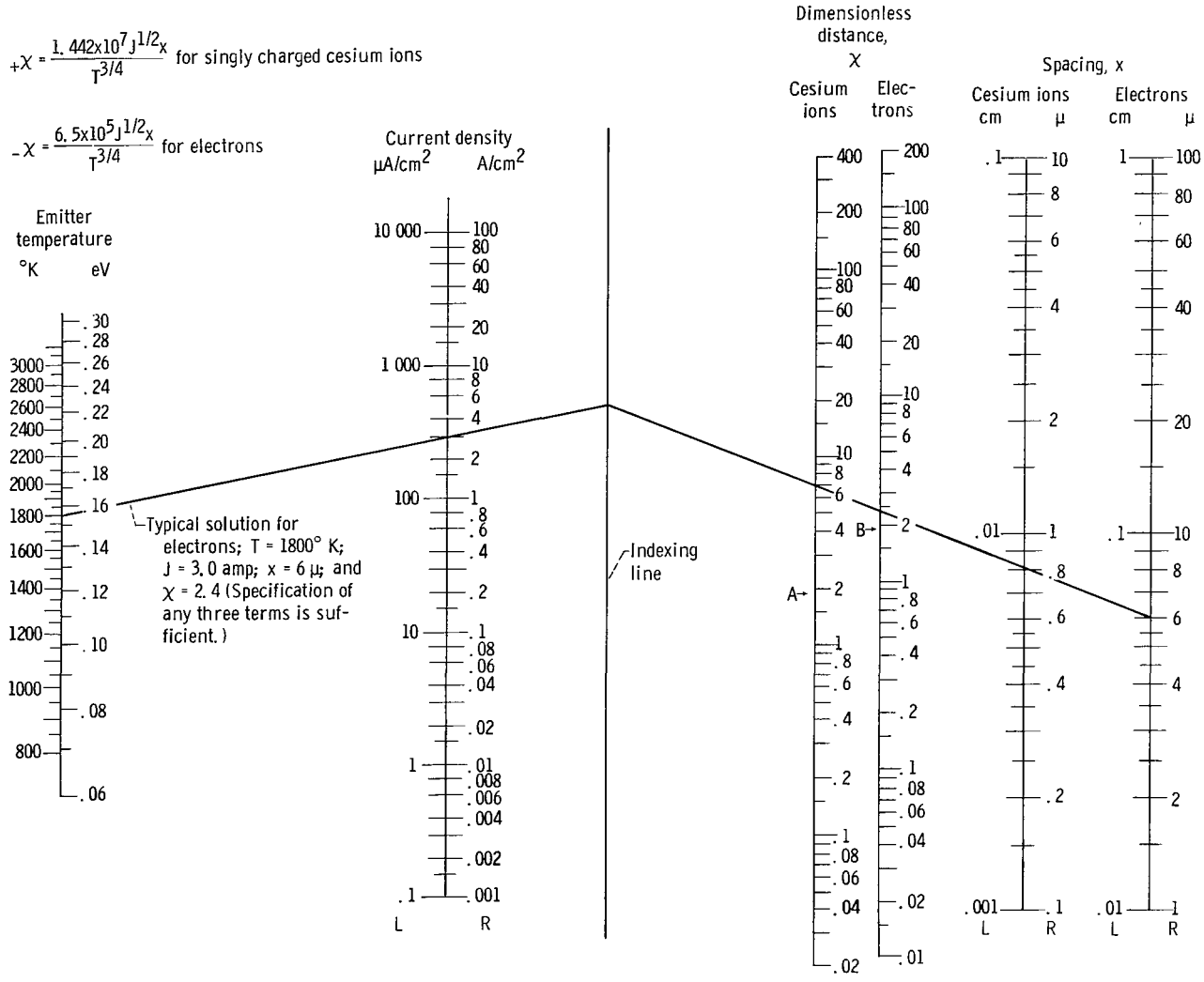


Figure III:1. - Solutions of dimensionless distance parameter for singly charged cesium ions and electrons in ideal planar high vacuum diode. (Relations among current density, temperature, spacing, and zero field at collector surface are established for emitter of unlimited emission capability if nomographic solution is indexed at A or B (χ column) for ions and electrons, respectively.) Use only L or R columns for current density and spacing.

Conditions other than zero field at the emitter can be represented by the generalized space-charge curve (fig. III:2) displaced so that the potential curve corresponding to the emitter region passes through the point corresponding to the surface potential barrier at the surface of the emitter.

Several qualitative observations can be made with regard to figure III:3. Perhaps the most significant is the fact that the space-charge minimum must lie on a single curve (curve E-R) for all possible space-charge conditions. Curve E-R is the numerical solution of the space-charge relation (eq. III:4) in the emitter region and thus provides the means of analytically coupling the space-charge solution to the surface. Visualization of this relation is perhaps best achieved by using a procedure based on the simple graphical analysis of space-charge problems.

TABLE III:1. - NUMERICAL SOLUTION TO LANGMUIR EQUATION FOR SPACE CHARGE

(a) In emitter space (eq. III:3))

Dimensionless potential, ψ_E	Dimensionless distance, X_E	$X_E^2, K^2Jx^2/T^{3/2}$
[a]0.50000 E-02	0.98671 E-01	0.97360 E-02
0.59999 E-02	0.10794 E-00	0.11652 E-01
0.70000 E-02	0.11645 E-00	0.13562 E-01
0.79999 E-02	0.12435 E-00	0.15464 E-01
0.89999 E-02	0.13176 E-00	0.17361 E-01
0.09999 E-01	0.13875 E-00	0.19251 E-01
0.11000 E-01	0.14538 E-00	0.21136 E-01
0.12000 E-01	0.15171 E-00	0.23016 E-01
0.13000 E-01	0.15776 E-00	0.24890 E-01
0.13999 E-01	0.16358 E-00	0.26760 E-01
0.15000 E-01	0.16919 E-00	0.28625 E-01
0.20000 E-01	0.19463 E-00	0.37883 E-01
0.24999 E-01	0.21689 E-00	0.47043 E-01
0.30000 E-01	0.23688 E-00	0.56114 E-01
0.34999 E-01	0.25515 E-00	0.65105 E-01
0.40000 E-01	0.27206 E-00	0.74021 E-01
0.45000 E-01	0.28786 E-00	0.82868 E-01
0.49999 E-01	0.30273 E-00	0.91649 E-01
0.59999 E-01	0.33019 E-00	0.10903 E-00
0.69999 E-01	0.35522 E-00	0.12618 E-00
0.80000 E-01	0.37832 E-00	0.14313 E-00
0.90000 E-01	0.39985 E-00	0.15988 E-00
0.09999 E-00	0.42005 E-00	0.17644 E-00
0.15000 E-00	0.50679 E 00	0.25684 E-00
0.20000 E-00	0.57767 E 00	0.33370 E-00
0.25000 E-00	0.63839 E 00	0.40754 E-00
0.30000 E-00	0.69188 E 00	0.47871 E-00
0.34999 E-00	0.73990 E 00	0.54745 E 00
0.40000 E-00	0.78356 E 00	0.61396 E 00
0.45000 E-00	0.82366 E 00	0.67842 E 00
0.49999 E-00	0.86078 E 00	0.74094 E 00
0.55000 E 00	0.89535 E 00	0.80165 E 00
0.59999 E 00	0.92770 E 00	0.86064 E 00
0.64999 E 00	0.95812 E 00	0.91800 E 00
0.70000 E 00	0.98681 E 00	0.97380 E 00
0.74999 E 00	0.10139 E 01	0.10281 E 01
0.79999 E 00	0.10397 E 01	0.10810 E 01
0.84999 E 00	0.10642 E 01	0.11325 E 01
0.89999 E 00	0.10875 E 01	0.11827 E 01
0.95000 E 00	0.11098 E 01	0.12316 E 01
0.99999 E 00	0.11311 E 01	0.12794 E 01
[b]0.10500 E 01	0.11515 E 01	0.13259 E 01
0.10999 E 01	0.11710 E 01	0.13713 E 01
0.11499 E 01	0.11898 E 01	0.14156 E 01
0.11999 E 01	0.12078 E 01	0.14588 E 01
0.12499 E 01	0.12251 E 01	0.15010 E 01
0.13000 E 01	0.12418 E 01	0.15422 E 01
0.13499 E 01	0.12579 E 01	0.15824 E 01
0.13999 E 01	0.12734 E 01	0.16216 E 01
0.14500 E 01	0.12884 E 01	0.16599 E 01
0.14999 E 01	0.13028 E 01	0.16973 E 01
0.16000 E 01	0.13302 E 01	0.17696 E 01
0.16999 E 01	0.13559 E 01	0.18385 E 01
0.17999 E 01	0.13799 E 01	0.19042 E 01
0.19000 E 01	0.14024 E 01	0.19669 E 01
0.20000 E 01	0.14236 E 01	0.20268 E 01
0.20999 E 01	0.14436 E 01	0.20840 E 01
0.21999 E 01	0.14623 E 01	0.21386 E 01
0.23000 E 01	0.14800 E 01	0.21906 E 01
0.23999 E 01	0.14968 E 01	0.22404 E 01
0.24999 E 01	0.15125 E 01	0.22878 E 01
0.25999 E 01	0.15274 E 01	0.23332 E 01
0.27000 E 01	0.15415 E 01	0.23764 E 01
0.27999 E 01	0.15549 E 01	0.24177 E 01
0.28999 E 01	0.15675 E 01	0.24571 E 01
0.29999 E 01	0.15795 E 01	0.24948 E 01
0.30999 E 01	0.15908 E 01	0.25307 E 01
0.31999 E 01	0.16015 E 01	0.25650 E 01
0.32999 E 01	0.16117 E 01	0.25977 E 01
0.34000 E 01	0.16213 E 01	0.26289 E 01
0.34999 E 01	0.16305 E 01	0.26587 E 01
0.35999 E 01	0.16392 E 01	0.26871 E 01
0.38000 E 01	0.16553 E 01	0.27400 E 01
0.40000 E 01	0.16698 E 01	0.27882 E 01
0.41999 E 01	0.16828 E 01	0.28321 E 01
0.43999 E 01	0.16946 E 01	0.28719 E 01
0.45999 E 01	0.17053 E 01	0.29081 E 01
0.47999 E 01	0.17149 E 01	0.29410 E 01
0.49999 E 01	0.17236 E 01	0.29709 E 01
0.55000 E 01	0.17419 E 01	0.30342 E 01
0.59999 E 01	0.17560 E 01	0.30838 E 01
0.64999 E 01	0.17671 E 01	0.31227 E 01
0.70000 E 01	0.17757 E 01	0.31531 E 01
0.74999 E 01	0.17823 E 01	0.31769 E 01
0.80000 E 01	0.17876 E 01	0.31955 E 01
0.89999 E 01	0.17948 E 01	0.32213 E 01
0.09999 E 02	0.17991 E 01	0.32370 E 01
0.12000 E 02	0.18034 E 01	0.32523 E 01
0.13999 E 02	0.18050 E 01	0.32580 E 01
0.16000 E 02	0.18055 E 01	0.32601 E 01
0.18000 E 02	0.18057 E 01	0.32608 E 01
0.20000 E 02	0.18058 E 01	0.32611 E 01

(b) In collector space (eq. (III:3))

Dimensionless potential, ψ_C	Dimensionless distance, X_C	$X_C^2, K^2Jx^2/T^{3/2}$
[c]0.09999 E-01	0.14406 E-00	0.20756 E-01
0.20000 E-01	0.20527 E-00	0.42138 E-01
0.30000 E-01	0.25284 E-00	0.63929 E-01
0.40000 E-01	0.29334 E-00	0.86052 E-01
0.49999 E-01	0.32933 E-00	0.10846 E-00
0.59999 E-01	0.36211 E-00	0.13112 E-00
0.69999 E-01	0.39246 E-00	0.15402 E-00
0.79999 E-01	0.42088 E-00	0.17714 E-00
0.90000 E-01	0.44773 E-00	0.20046 E-00
0.09999 E-00	0.47325 E-00	0.22397 E-00
0.15000 E-00	0.58660 E 00	0.34410 E-00
0.20000 E-00	0.68409 E 00	0.46798 E-00
0.25000 E-00	0.77142 E 00	0.59509 E 00
0.30000 E-00	0.85153 E 00	0.72511 E 00
0.34999 E-00	0.92616 E 00	0.85777 E 00
0.40000 E-00	0.99644 E 00	0.99289 E 00
0.45000 E-00	0.10631 E 01	0.11303 E 01
0.49999 E-00	0.11268 E 01	0.12699 E 01
0.60000 E 00	0.12470 E 01	0.15551 E 01
0.70000 E 00	0.13593 E 01	0.18479 E 01
0.80000 E 00	0.14655 E 01	0.21477 E 01
0.90000 E 00	0.15665 E 01	0.24540 E 01
[d]0.09999 E 01	0.16632 E 01	0.27665 E 01
0.10999 E 01	0.17563 E 01	0.30849 E 01
0.12000 E 01	0.18463 E 01	0.34088 E 01
0.13999 E 01	0.20180 E 01	0.40726 E 01
0.16000 E 01	0.21808 E 01	0.47562 E 01
0.17999 E 01	0.23363 E 01	0.54584 E 01
0.20000 E 01	0.24856 E 01	0.61782 E 01
0.21999 E 01	0.26295 E 01	0.69146 E 01
0.23999 E 01	0.27689 E 01	0.76669 E 01
0.26000 E 01	0.29042 E 01	0.84345 E 01
0.27999 E 01	0.30359 E 01	0.92167 E 01
0.30000 E 01	0.31643 E 01	0.10012 E 02
0.31999 E 01	0.32898 E 01	0.10822 E 02
0.34000 E 01	0.34126 E 01	0.11646 E 02
0.35999 E 01	0.35329 E 01	0.12481 E 02
0.38000 E 01	0.36510 E 01	0.13330 E 02
0.39999 E 01	0.37670 E 01	0.14190 E 02
0.45000 E 01	0.40488 E 01	0.16393 E 02
0.49999 E 01	0.43203 E 01	0.18665 E 02
0.55000 E 01	0.45829 E 01	0.21003 E 02
0.59999 E 01	0.48378 E 01	0.23404 E 02
0.64999 E 01	0.50859 E 01	0.25866 E 02
0.70000 E 01	0.53279 E 01	0.28386 E 02
0.74999 E 01	0.55643 E 01	0.30962 E 02
0.80000 E 01	0.57958 E 01	0.33592 E 02
0.89999 E 01	0.62455 E 01	0.39007 E 02
0.09999 E 02	0.66798 E 01	0.44620 E 02
0.11000 E 02	0.71007 E 01	0.50420 E 02
0.12000 E 02	0.75099 E 01	0.56399 E 02
0.13000 E 02	0.79087 E 01	0.62548 E 02
0.13999 E 02	0.82982 E 01	0.68860 E 02
0.15000 E 02	0.86790 E 01	0.75326 E 02
0.16000 E 02	0.90515 E 01	0.81930 E 02
0.18000 E 02	0.97683 E 01	0.95420 E 02
0.20000 E 02	0.10378 E 02	0.10772 E 03
0.25000 E 02	0.12052 E 02	0.14526 E 03
0.30000 E 02	0.13630 E 02	0.18580 E 03
0.34999 E 02	0.15134 E 02	0.22906 E 03
0.40000 E 02	0.16578 E 02	0.27484 E 03
0.45000 E 02	0.17971 E 02	0.32298 E 03
0.50000 E 02	0.19322 E 02	0.37334 E 03
0.59999 E 02	0.21915 E 02	0.48027 E 03
0.70000 E 02	0.24390 E 02	0.59488 E 03
0.80000 E 02	0.26769 E 02	0.71661 E 03
0.90000 E 02	0.29068 E 02	0.84498 E 03
0.09999 E 03	0.31298 E 02	0.97961 E 03
0.15000 E 03	0.41674 E 02	0.17367 E 04
0.20000 E 03	0.51145 E 02	0.26158 E 04
0.30000 E 03	0.68397 E 02	0.46781 E 04
0.40000 E 03	0.84171 E 02	0.70848 E 04
0.50000 E 03	0.98937 E 02	0.97886 E 04
0.60000 E 03	0.11295 E 03	0.12757 E 05
0.70000 E 03	0.12636 E 03	0.15968 E 05
0.80000 E 03	0.13929 E 03	0.19403 E 05
0.90000 E 03	0.15181 E 03	0.23048 E 05
0.09999 E 04	0.16398 E 03	0.26889 E 05

[a]Read as 0.5×10^{-2}.
[b]Read as 0.105×10^{1}.
[c]Read as 0.09×10^{-1}.
[d]Read as 0.09×10^{1}.

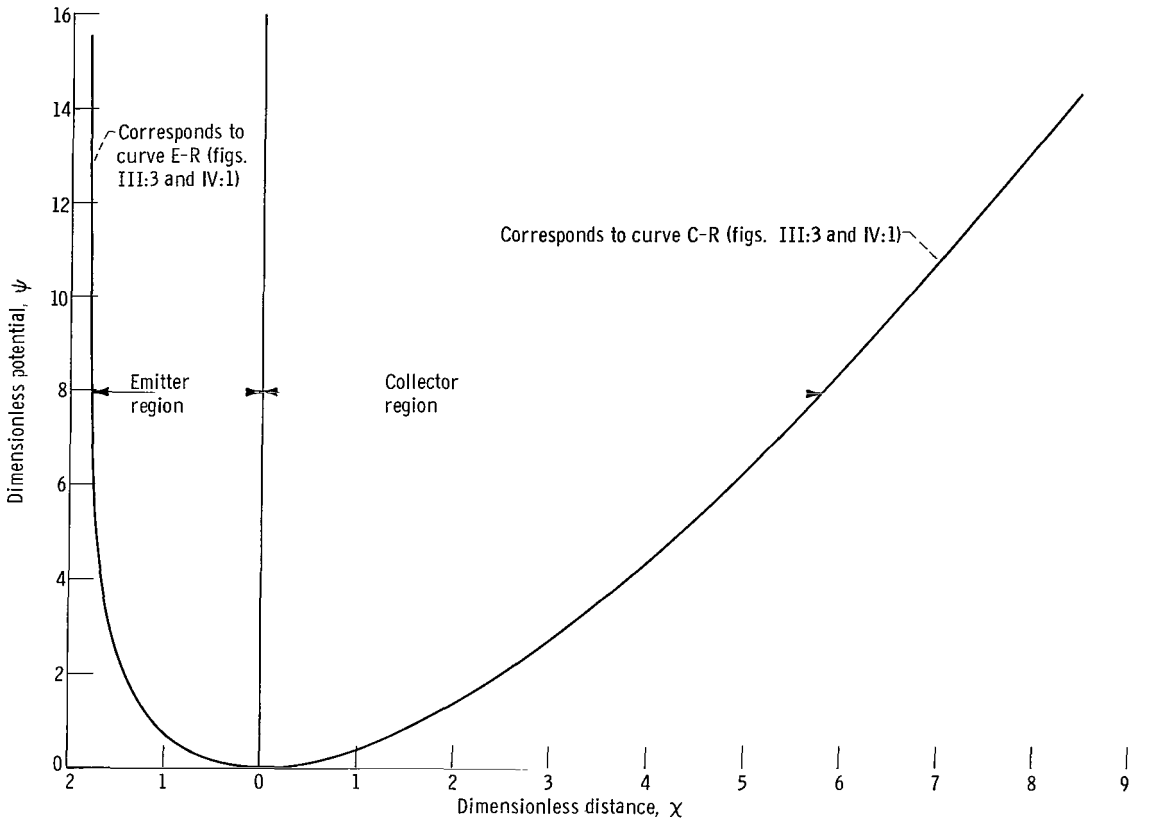


Figure III:2. - Space-charge potential distribution.

A "template" can be made to represent the generalized space-charge solution corresponding to the form given in figure III:2. Starting with zero field at the emitter the space-charge minimum of the template must coincide with the potential at the surface barrier, for example, point 1 in figure III:3. The potential distribution in the interelectrode space can then be drawn and must lie on curve C-R. By noting that the generalized space-charge curve must always cross the surface at point 1, the "space-charge template" then may be shifted to correspond to ever increasing space-charge barriers. (Coordinates must of course be maintained parallel). The magnitude and location of the barrier are described by the position of the minimum. (The reader should note that dimensionless distance χ contains $J^{1/2}$, which decreases as the space-charge barrier becomes larger, therefore distorting the real distance feature of the potential curve.) Examples of the location of the minimum and corresponding potential distributions have been constructed by this procedure and are illustrated in figure III:3 (pt. 2' curve II, pt. 3' curve III, etc.). In the process of shifting the space-charge template from the zero-field condition to curve XIII (for example), the space-charge minimum will trace out curve E-R, which as indicated before is the emitter region branch of the generalized space-charge curve. From the nature of the emitter region space-charge solution, the location of the space-charge minimum cannot exceed a value of $\chi = 1.806$: Thus not only is the location of the minimum completely described but also the limits of $\chi_E = 0$ and 1.806. Curve E-R also represents all possible locations of the

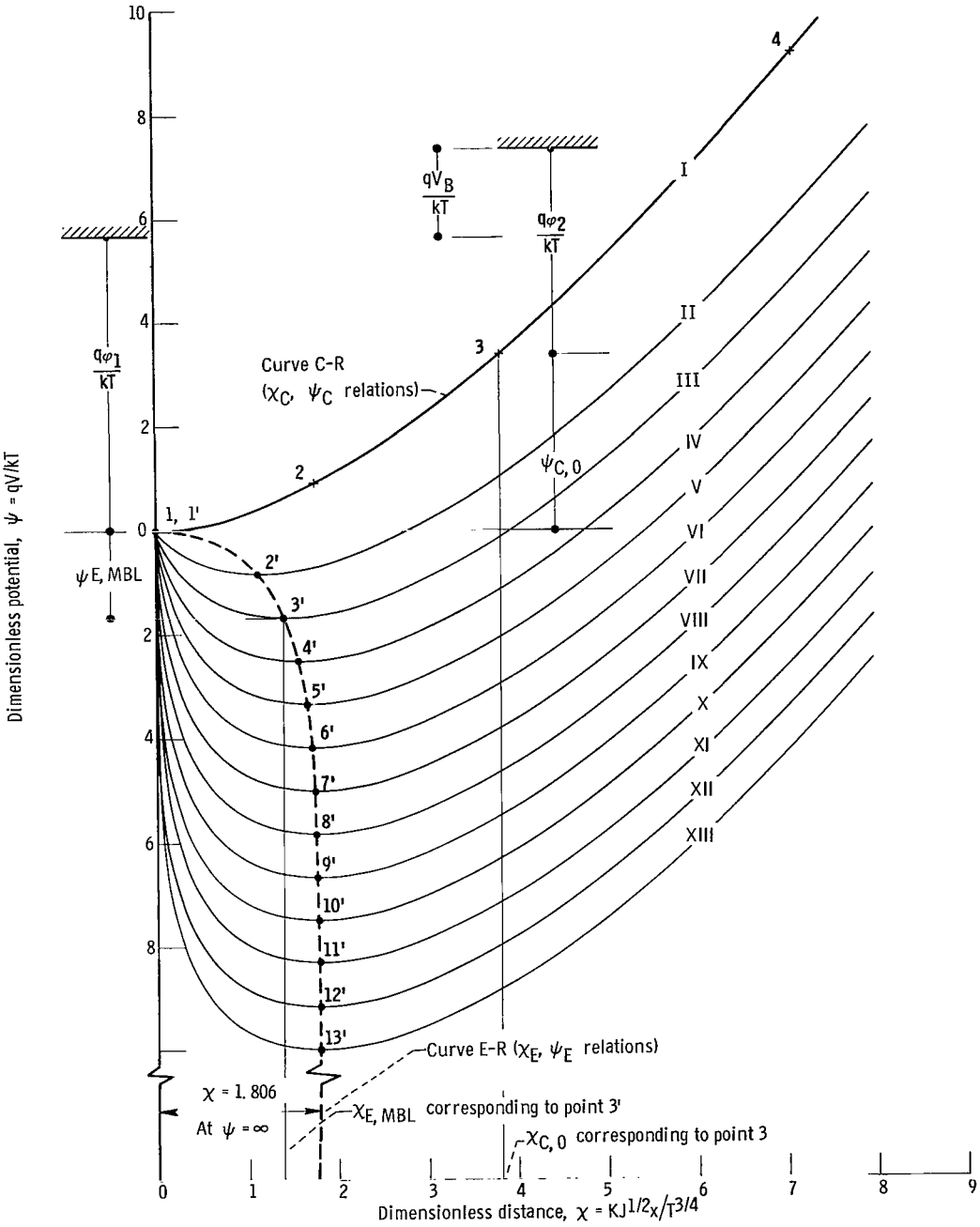


Figure III:3. - Generalized space-charge potential distributions.

collector surface in terms of dimensionless distance at the Maxwell-Boltzmann limit, since by definition zero field at the collector must exist at this limiting condition.

If distance, saturation current, and temperature are held constant ($\chi_{C,O}$ = constant) while applied voltage is varied, then it is possible to uniquely establish the current at the Maxwell-Boltzmann limit and thus $\chi_{E,MBL}$. The related quantities $\psi_{E,MBL}$ and difference in surface potential between saturation current and the current at the MBL condition ($\psi_{C,O} + \psi_{E,MBL}$) follow directly. The general procedure employed is perhaps best illustrated by example. Let the saturation current, distance, and temperature correspond to a value of $\chi_{C,O}$ represented by point 3 on curve C-R figure III:3. At the Maxwell-Boltzmann condition (i.e., zero-field condition at the collector) the current will be inhibited by the space-charge barrier, which is identifiable since the barrier is at the collector surface. The barrier height is $\psi_{E,MBL}$, and the reduction in current is determined from the Boltzmann relation

$$\frac{J_{MBL}}{J_O} = \exp(-\psi_{E,MBL}) \qquad \text{(III:5)}$$

Numerical or graphical iteration quickly determines the value of χ_E (point 3' must lie on the χ_E curve) that satisfies equation (III:5) and the χ_E,ψ_E space-charge relation. Point 3' is thus uniquely established. In a similar sense point 2 corresponds to point 2' or for larger values of $\chi_{C,O}$ point 4 corresponds to point 4', 5 to 5', and so forth.

Further detailed developments of the relation between the two zero-field conditions and the parametric relations involving current, distance, temperature, and mass to charge ratio are given in section IV.

It again should be noted that the key to the numerical solution of the space-charge problem is based on the two zero-field conditions, when the space-charge barrier exists at the emitter and at the collector. Also it is interesting to note that as $\psi_{E,MBL}$ approaches infinity, $\chi_{E,MBL}$ possesses a limiting value of 1.806. For all practical purposes when $\psi_{E,MBL}$ is greater than 10, $\chi_{E,MBL}$ has approached the limiting value. Use will be made of this fact in section VII in the development of a universal unlimited current-voltage curve.

IV - ANALYTICAL DEVELOPMENT OF SPACE-CHARGE RELATIONS

Assume that in a hypothetical case, the emitter temperature, spacing, and current at the Maxwell-Boltzmann limit are known and the objective is to determine the saturation current. The dimensionless distance $\chi_{E,MBL}$ is now defined since

$$\chi_{E,MBL} = \frac{K J_{MBL}^{1/2} w}{T^{3/4}} \qquad \text{(IV:1)}$$

The dimensionless potential $\psi_{E,MBL}$ is also established from the generalized

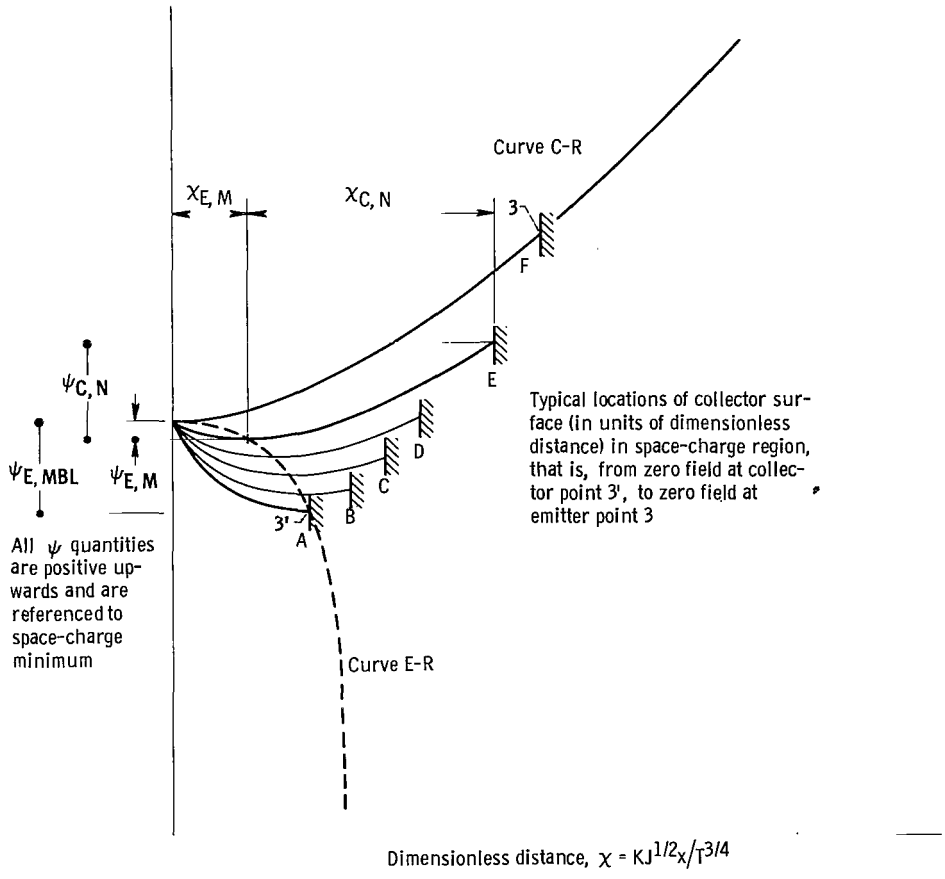


Figure IV:1. - Typical transition potential diagrams in space-charge region.

space-charge relation (table III:1(a) for example). As the applied voltage is made more positive (for electrons), the potential distribution varies as shown in figure IV:1. The collector location in units of χ shifts to the right because of the increase in current. The space-charge barrier shifts from the collector surface (curve A) into the interelectrode space (curves B, C, D, and E) and finally intercepts the emitter surface (curve F). The structure of figure IV:1 is identical to that of figure III:3 (p. 10) except for the increased detail for the transition conditions between points 3' and 3.

As indicated in section III, current will increase up to J_0 between the Maxwell-Boltzmann limit and the saturation condition according to the following relations:

$$J_0 = J_{MBL} \exp(\varphi_{E,MBL}) = J_{MBL} f(\chi_{MBL}) \qquad (IV:2)$$

where J_0 is now the saturation current since zero field exists at the emitter. The numerical evaluation of the ratio of J_0/J_{MBL} for various values of $\chi_{E,MBL}$ is given in figure IV:2. The combination of figure IV:2 and the nomograph in figure III:1 (p. 7) conveniently relates saturation current to J_{MBL},

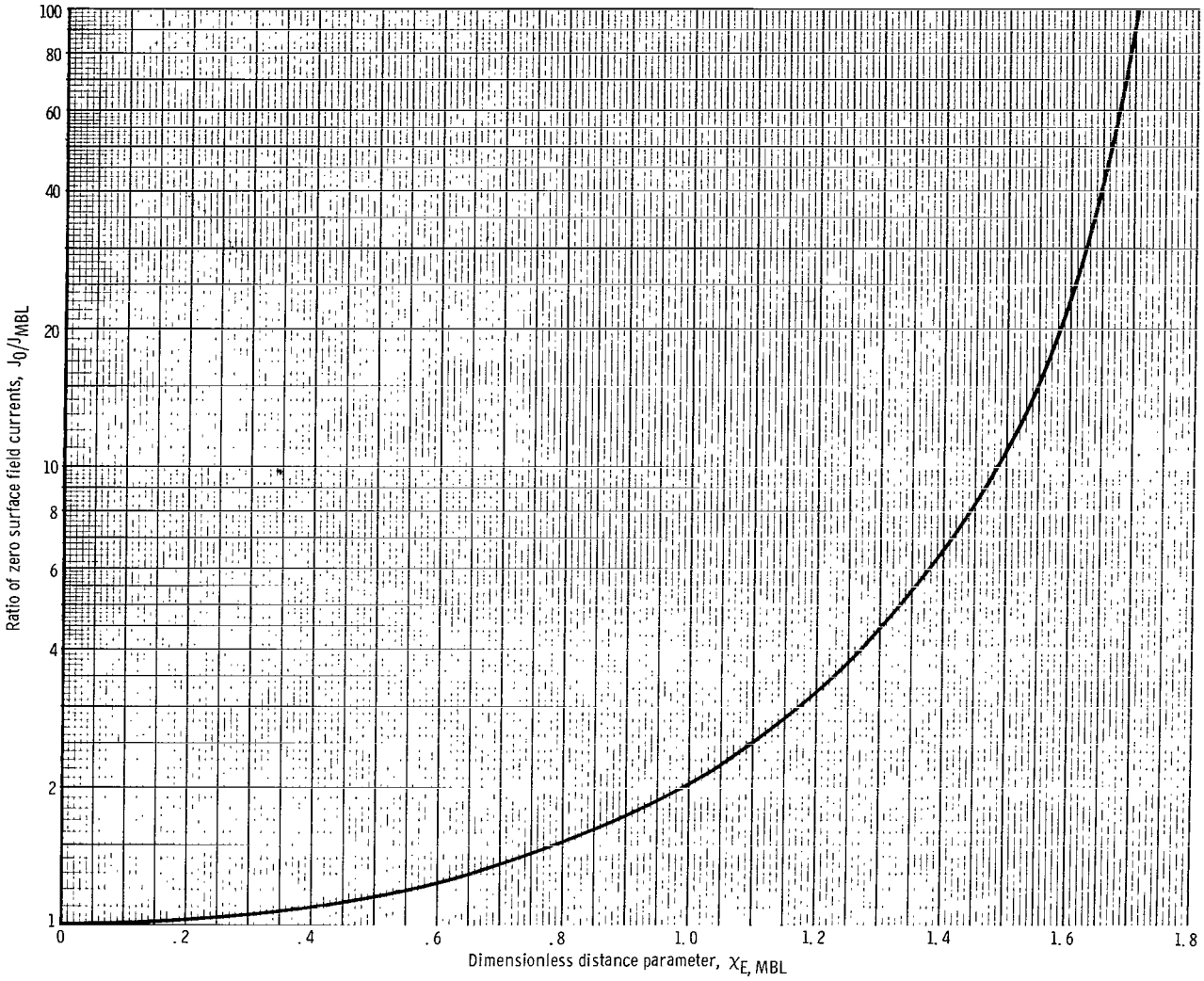


Figure IV:2. - Relation between dimensionless distance evaluated at condition of zero field at collector and ratio of current densities J_0/J_{MBL}.

spacing, and emitter temperature. $\chi_{E,MBL}$ is determined from the nomograph (fig. III:1) for either ions or electrons, and J_0 is subsequently established from figure IV:2.

Additional useful relations can also be determined from an extension of the approach used previously. Since the saturation current is known, the dimensionless distance in the collector region is

$$\chi_{C,0} = \chi_{E,MBL} \exp\left(\frac{\psi_{E,MBL}}{2}\right) \qquad \text{(IV:3)}$$

(All terms in χ are constant except current.) The dimensionless potential $\psi_{C,0}$ is established from $\chi_{C,0}$ (the subscript 0 again refers to zero field at the emitter surface), and therefore the variation in surface potential in

TABLE IV:1. - TABULATIONS OF VARIATION IN APPLIED VOLTAGE (DIFFERENCE IN SURFACE POTENTIAL) THAT EXISTS BETWEEN MAXWELL-BOLTZMANN LIMIT AND SATURATED CURRENT CONDITION FOR IDEAL PLANAR HIGH VACUUM DIODE

[Temperature, distance, and saturation current capability are assumed constant.]

(a) Tabulation for even values of surface potential

Surface potential difference, $\psi_{E,MBL} + \psi_{C,0}$	Dimensionless distance corresponding to -		Current ratio, J_0/J_{MBL}
	Zero field at emitter, $X_{C,0}$	Zero field at collector, $X_{E,MBL}$	
0.09999 E-01	0.10007 E-00	0.99822 E-01	0.10051 E 01
0.20000 E-01	0.14165 E-00	0.14092 E-00	0.10103 E 01
[a]0.30000 E-01	0.17365 E-00	0.17231 E-00	0.10156 E 01
0.40000 E-01	0.20071 E-00	0.19862 E-00	0.10210 E 01
0.49999 E-01	0.22461 E-00	0.22170 E-00	0.10265 E 01
0.59999 E-01	0.24630 E-00	0.24245 E-00	0.10319 E 01
0.69999 E-01	0.26630 E-00	0.26144 E-00	0.10375 E 01
0.79999 E-01	0.28497 E-00	0.27903 E-00	0.10430 E 01
0.90000 E-01	0.30257 E-00	0.29547 E-00	0.10486 E 01
0.09999 E-00	0.31927 E-00	0.31094 E-00	0.10543 E 01
0.15000 E-00	0.39315 E-00	0.37778 E-00	0.10830 E 01
0.20000 E-00	0.45652 E-00	0.43281 E-00	0.11125 E 01
0.25000 E-00	0.51329 E 00	0.48017 E-00	0.11427 E 01
0.30000 E-00	0.56548 E 00	0.52200 E 00	0.11735 E 01
0.34999 E-00	0.61429 E 00	0.55961 E 00	0.12049 E 01
0.40000 E-00	0.66051 E 00	0.59388 E 00	0.12369 E 01
0.45000 E-00	0.70457 E 00	0.62531 E 00	0.12695 E 01
0.49999 E-00	0.74695 E 00	0.65443 E 00	0.13027 E 01
0.60000 E 00	0.82767 E 00	0.70698 E 00	0.13705 E 01
0.70000 E 00	0.90420 E 00	0.75337 E 00	0.14405 E 01
0.80000 E 00	0.97751 E 00	0.79485 E 00	0.15124 E 01
0.90000 E 00	0.10482 E 01	0.83232 E 00	0.15862 E 01
0.09999 E 01	0.11169 E 01	0.86642 E 00	0.16618 E 01
0.10999 E 01	0.11838 E 01	0.89767 E 00	0.17392 E 01
0.12000 E 01	0.12493 E 01	0.92645 E 00	0.18184 E 01
0.13999 E 01	0.13766 E 01	0.97784 E 00	0.19819 E 01
0.16000 E 01	0.14999 E 01	0.10225 E 01	0.21519 E 01
0.17999 E 01	0.16201 E 01	0.10618 E 01	0.23281 E 01
0.20000 E 01	0.17375 E 01	0.10967 E 01	0.25102 E 01
0.21999 E 01	0.18527 E 01	0.11279 E 01	0.26981 E 01
0.23999 E 01	0.19659 E 01	0.11561 E 01	0.28915 E 01
0.26000 E 01	0.20772 E 01	0.11816 E 01	0.30901 E 01
0.27999 E 01	0.21869 E 01	0.12049 E 01	0.32940 E 01
0.30000 E 01	0.22951 E 01	0.12263 E 01	0.35028 E 01
0.31999 E 01	0.24019 E 01	0.12459 E 01	0.37164 E 01
0.34000 E 01	0.25074 E 01	0.12640 E 01	0.39346 E 01
0.35999 E 01	0.26117 E 01	0.12809 E 01	0.41574 E 01
0.38000 E 01	0.27148 E 01	0.12965 E 01	0.43845 E 01
0.39999 E 01	0.28167 E 01	0.13110 E 01	0.46158 E 01
0.45000 E 01	0.30673 E 01	0.13435 E 01	0.52123 E 01
0.49999 E 01	0.33120 E 01	0.13713 E 01	0.58333 E 01
0.55000 E 01	0.35515 E 01	0.13954 E 01	0.64774 E 01
0.59999 E 01	0.37862 E 01	0.14166 E 01	0.71433 E 01
0.64999 E 01	0.40164 E 01	0.14353 E 01	0.78300 E 01
0.70000 E 01	0.42426 E 01	0.14520 E 01	0.85367 E 01
0.74999 E 01	0.44650 E 01	0.14671 E 01	0.92625 E 01
0.80000 E 01	0.46840 E 01	0.14806 E 01	0.10007 E 02
0.89999 E 01	0.51118 E 01	0.15042 E 01	0.11547 E 02
0.09999 E 02	0.55282 E 01	0.15241 E 01	0.13155 E 02
0.11000 E 02	0.59341 E 01	0.15411 E 01	0.14826 E 02
0.12000 E 02	0.63305 E 01	0.15558 E 01	0.16555 E 02
0.13000 E 02	0.67184 E 01	0.15687 E 01	0.18342 E 02
0.13999 E 02	0.70984 E 01	0.15800 E 01	0.20182 E 02
[b]0.15000 E 02	0.74713 E 01	0.15902 E 01	0.22073 E 02
0.16000 E 02	0.78377 E 01	0.15993 E 01	0.24016 E 02
0.18000 E 02	0.85529 E 01	0.16150 E 01	0.28044 E 02
0.20000 E 02	0.92470 E 01	0.16281 E 01	0.32254 E 02
0.25000 E 02	0.10904 E 02	0.16532 E 01	0.43502 E 02
0.30000 E 02	0.12472 E 02	0.16711 E 01	0.55701 E 02
0.34999 E 02	0.13970 E 02	0.16847 E 01	0.68757 E 02
0.40000 E 02	0.15411 E 02	0.16954 E 01	0.82621 E 02
0.45000 E 02	0.16802 E 02	0.17041 E 01	0.97216 E 02
0.50000 E 02	0.18149 E 02	0.17113 E 01	0.11247 E 03
0.59999 E 02	0.20743 E 02	0.17226 E 01	0.14499 E 03
0.70000 E 02	0.23145 E 02	0.17309 E 01	0.17878 E 03
0.80000 E 02	0.25549 E 02	0.17377 E 01	0.21616 E 03
0.90000 E 02	0.27872 E 02	0.17432 E 01	0.25563 E 03
0.09999 E 03	0.30041 E 02	0.17476 E 01	0.29548 E 03
0.15000 E 03	0.40406 E 02	0.17622 E 01	0.52572 E 03
0.20000 E 03	0.49864 E 02	0.17703 E 01	0.79335 E 03
0.30000 E 03	0.67092 E 02	0.17793 E 01	0.14217 E 04
0.40000 E 03	0.82721 E 02	0.17843 E 01	0.21493 E 04
0.50000 E 03	0.97836 E 02	0.17876 E 01	0.29954 E 04
0.60000 E 03	0.10991 E 03	0.17895 E 01	0.37726 E 04
0.70000 E 03	0.12262 E 03	0.17912 E 01	0.46863 E 04
0.80000 E 03	0.13583 E 03	0.17926 E 01	0.57416 E 04
0.90000 E 03	0.14942 E 03	0.17938 E 01	0.69381 E 04
0.09999 E 04	0.16321 E 03	0.17948 E 01	0.82691 E 04

[a]Read as 0.3×10^{-1}.

[b]Read as 0.15×10^{2}.

TABLE IV:1. - Continued. TABULATIONS OF VARIATION IN APPLIED VOLTAGE (DIFFERENCE IN SURFACE POTENTIAL) THAT EXISTS BETWEEN MAXWELL-BOLTZMANN LIMIT AND SATURATED CURRENT CONDITION FOR IDEAL PLANAR HIGH VACUUM DIODE

[Temperature, distance, and saturation current capability are assumed constant.]

(b) Tabulation for even values of $X_{E,MBL}$ (dimensionless distance at zero field at collector)

Surface potential difference, $\psi_{E,MBL} + \psi_{C,O}$	Dimensionless distance corresponding to -		Current ratio, J_O/J_{MBL}
	Zero field at emitter, $X_{C,O}$	Zero field at collector, $X_{E,MBL}$	
[a]0.10034 E-01	0.10025 E-00	0.09999 E-00	0.10051 E 01
0.12150 E-01	0.11034 E-00	0.11000 E-00	0.10062 E 01
0.14471 E-01	0.12044 E-00	0.12000 E-00	0.10074 E 01
0.16998 E-01	0.13057 E-00	0.13000 E-00	0.10081 E 01
0.18339 E-01	0.13563 E-00	0.13500 E-00	0.10095 E 01
0.19733 E-01	0.14071 E-00	0.13999 E-00	0.10102 E 01
0.21178 E-01	0.14579 E-00	0.14500 E-00	0.10110 E 01
0.22671 E-01	0.15088 E-00	0.15000 E-00	0.10117 E 01
0.25827 E-01	0.16107 E-00	0.16000 E-00	0.10134 E 01
0.27482 E-01	0.16617 E-00	0.16500 E-00	0.10143 E 01
0.29191 E-01	0.17129 E-00	0.16999 E-00	0.10152 E 01
0.30956 E-01	0.17641 E-00	0.17500 E-00	0.10162 E 01
0.32772 E-01	0.18153 E-00	0.18000 E-00	0.10171 E 01
0.34640 E-01	0.18667 E-00	0.18499 E-00	0.10181 E 01
0.36558 E-01	0.19181 E-00	0.19000 E-00	0.10192 E 01
0.38529 E-01	0.19696 E-00	0.19499 E-00	0.10202 E 01
0.40551 E-01	0.20212 E-00	0.20000 E-00	0.10213 E 01
0.44777 E-01	0.21246 E-00	0.20999 E-00	0.10236 E 01
0.53879 E-01	0.23326 E-00	0.23000 E-00	0.10286 E 01
0.63871 E-01	0.25422 E-00	0.25000 E-00	0.10341 E 01
0.74770 E-01	0.27536 E-00	0.27000 E-00	0.10401 E 01
0.86584 E-01	0.29670 E-00	0.29000 E-00	0.10467 E 01
0.92848 E-01	0.30744 E-00	0.30000 E-00	0.10502 E 01
0.11311 E-00	0.34003 E-00	0.33000 E-00	0.10617 E 01
0.12783 E-00	0.36207 E-00	0.34999 E-00	0.10701 E 01
0.14358 E-00	0.38438 E-00	0.37000 E-00	0.10792 E 01
0.16113 E-00	0.40714 E-00	0.38999 E-00	0.10898 E 01
0.16915 E-00	0.41842 E-00	0.40000 E-00	0.10942 E 01
0.18760 E-00	0.44152 E-00	0.41999 E-00	0.11051 E 01
0.22776 E-00	0.48879 E-00	0.45999 E-00	0.11291 E 01
0.24972 E-00	0.51305 E 00	0.48000 E-00	0.11424 E 01
0.27297 E-00	0.53776 E 00	0.50000 E 00	0.11424 E 01
0.33673 E-00	0.60162 E 00	0.55000 E 00	0.11567 E 01
0.40937 E-00	0.66894 E 00	0.59999 E 00	0.11965 E 01
0.45770 E-00	0.71126 E 00	0.63000 E 00	0.12430 E 01
0.56611 E 00	0.80092 E 00	0.69000 E 00	0.12746 E 01
0.58576 E 00	0.81656 E 00	0.70000 E 00	0.13473 E 01
0.64802 E 00	0.86495 E 00	0.73000 E 00	0.13607 E 01
0.76290 E 00	0.95067 E 00	0.77999 E 00	0.14039 E 01
0.81304 E 00	0.98692 E 00	0.80000 E 00	0.14855 E 01
0.86598 E 00	0.10244 E 01	0.81999 E 00	0.15218 E 01
0.98045 E 00	0.11036 E 01	0.86000 E 00	0.15608 E 01
0.10425 E 01	0.11455 E 01	0.88000 E 00	0.16469 E 01
0.11077 E 01	0.11889 E 01	0.90000 E 00	0.16946 E 01
0.11768 E 01	0.12343 E 01	0.91999 E 00	0.17452 E 01
0.12879 E 01	0.13058 E 01	0.95000 E 00	0.17999 E 01
0.13271 E 01	0.13307 E 01	0.95999 E 00	0.18895 E 01
0.14090 E 01	0.13822 E 01	0.98000 E 00	0.19216 E 01
0.14956 E 01	0.14361 E 01	0.09999 E 01	0.19895 E 01
0.15411 E 01	0.14640 E 01	0.10100 E 01	0.20623 E 01
0.16361 E 01	0.15219 E 01	0.10299 E 01	0.21012 E 01
0.17371 E 01	0.15826 E 01	0.10500 E 01	0.21832 E 01
0.17900 E 01	0.16142 E 01	0.10599 E 01	0.22720 E 01
0.19012 E 01	0.16799 E 01	0.10800 E 01	0.23692 E 01
0.20196 E 01	0.17491 E 01	0.10999 E 01	0.24195 E 01
0.20822 E 01	0.17852 E 01	0.11099 E 01	0.25283 E 01
0.22135 E 01	0.18605 E 01	0.11300 E 01	0.25867 E 01
0.23543 E 01	0.19403 E 01	0.11499 E 01	0.27110 E 01
0.25057 E 01	0.20251 E 01	0.11699 E 01	0.28469 E 01
0.26688 E 01	0.21153 E 01	0.11900 E 01	0.29959 E 01
0.27549 E 01	0.21625 E 01	0.12000 E 01	0.31598 E 01
0.29383 E 01	0.22620 E 01	0.12199 E 01	0.32475 E 01
0.31368 E 01	0.23685 E 01	0.12400 E 01	0.34379 E 01
0.32425 E 01	0.24246 E 01	0.12499 E 01	0.36485 E 01
0.34678 E 01	0.25430 E 01	0.12700 E 01	0.37624 E 01
0.35882 E 01	0.26057 E 01	0.12799 E 01	0.40097 E 01
0.38453 E 01	0.27382 E 01	0.13000 E 01	0.41442 E 01
0.42807 E 01	0.29586 E 01	0.13299 E 01	0.44365 E 01
0.46088 E 01	0.31213 E 01	0.13500 E 01	0.49479 E 01
0.49731 E 01	0.32993 E 01	0.13699 E 01	0.53457 E 01
0.55599 E 01	0.35990 E 01	0.13999 E 01	0.57997 E 01
0.60945 E 01	0.38256 E 01	0.14200 E 01	0.66088 E 01
0.66322 E 01	0.40768 E 01	0.14399 E 01	0.72582 E 01
0.69338 E 01	0.42131 E 01	0.14500 E 01	0.80154 E 01
0.72566 E 01	0.43574 E 01	0.14600 E 01	0.84425 E 01
0.79742 E 01	0.46727 E 01	0.14799 E 01	0.89074 E 01
0.88041 E 01	0.50290 E 01	0.15000 E 01	0.99684 E 01
0.92723 E 01	0.52263 E 01	0.15099 E 01	0.11240 E 02
0.97788 E 01	0.54370 E 01	0.15200 E 01	0.11979 E 02
0.10329 E 02	0.56631 E 01	0.15300 E 01	0.12794 E 02
0.10931 E 02	0.59063 E 01	0.15399 E 01	0.13700 E 02
0.11589 E 02	0.61686 E 01	0.15499 E 01	0.14709 E 02
0.12312 E 02	0.64524 E 01	0.15600 E 01	0.15838 E 02
0.13110 E 02	0.67606 E 01	0.15700 E 01	0.17108 E 02
0.13994 E 02	0.70963 E 01	0.15799 E 01	0.18542 E 02
0.14978 E 02	0.74632 E 01	0.15899 E 01	0.20172 E 02
0.16072 E 02	0.78643 E 01	0.16000 E 01	0.22032 E 02
0.17313 E 02	0.83100 E 01	0.16100 E 01	0.24159 E 02
0.18711 E 02	0.88023 E 01	0.16199 E 01	0.26641 E 02
0.20303 E 02	0.93508 E 01	0.16300 E 01	0.29523 E 02
0.22128 E 02	0.99655 E 01	0.16400 E 01	0.32909 E 02
0.24238 E 02	0.10658 E 02	0.16499 E 01	0.36924 E 02
0.26702 E 02	0.11448 E 02	0.16599 E 01	0.41731 E 02
0.29616 E 02	0.12356 E 02	0.16700 E 01	0.47563 E 02
0.33086 E 02	0.13466 E 02	0.16800 E 01	0.54745 E 02
0.37300 E 02	0.14641 E 02	0.16899 E 01	0.63681 E 02
0.42452 E 02	0.16100 E 02	0.16999 E 01	0.75058 E 02
0.48966 E 02	0.17877 E 02	0.17100 E 01	0.89699 E 02
0.57308 E 02	0.20061 E 02	0.17200 E 01	0.10930 E 03
0.68179 E 02	0.22780 E 02	0.17299 E 01	0.13404 E 03
0.83487 E 02	0.26418 E 02	0.17399 E 01	0.17340 E 03
0.10512 E 03	0.31263 E 02	0.17500 E 01	0.23051 E 03
0.13865 E 03	0.38273 E 02	0.17599 E 01	0.31916 E 03
[b]0.19547 E 03	0.49194 E 02	0.17693 E 01	0.47288 E 03
0.30768 E 03	0.68566 E 02	0.17800 E 01	0.77249 E 03
0.60563 E 03	0.11269 E 03	0.17900 E 01	0.14838 E 04
0.19450 E 04	0.26639 E 03	0.17999 E 01	0.39636 E 04
0.28478 E 05	0.19599 E 04	0.18049 E 01	0.21903 E 05
			0.11791 E 07

[a]Read as 0.10034×10^{-1}.

[b]Read as 0.19547×10^{3}.

TABLE IV:1. - Concluded. TABULATIONS OF VARIATION IN APPLIED VOLTAGE (DIFFERENCE IN SURFACE POTENTIAL) THAT EXISTS BETWEEN MAXWELL-BOLTZMANN LIMIT AND SATURATED CURRENT CONDITION FOR IDEAL PLANAR HIGH VACUUM DIODE

[Temperature, distance, and saturation current capability are assumed constant.]

(c) Tabulation for even values of $X_{C,O}$ (dimensionless distance at zero field at emitter)

Surface potential difference, $X_{E,MBL} + X_{C,O}$	Dimensionless distance corresponding to -		Current ratio, J_O/J_{MBL}
	Zero field at emitter, $X_{C,O}$	Zero field at collector, $X_{E,MBL}$	
[a] 0.22407 E-01	0.15000 E-00	0.14909 E-00	0.10121 E 01
0.39711 E-01	0.20000 E-00	0.19790 E-00	0.10212 E 01
0.61790 E-01	0.25000 E-00	0.24597 E-00	0.10330 E 01
0.88477 E-01	0.30000 E-00	0.29300 E-00	0.10482 E 01
0.10044 E-00	0.31999 E-00	0.31160 E-00	0.10545 E 01
0.11308 E-00	0.34000 E-00	0.32995 E-00	0.10617 E 01
0.11966 E-00	0.34999 E-00	0.33906 E-00	0.10655 E 01
0.12641 E-00	0.36000 E-00	0.34812 E-00	0.10694 E 01
0.14042 E-00	0.38000 E-00	0.36608 E-00	0.10774 E 01
0.15558 E-00	0.40000 E-00	0.38491 E-00	0.10799 E 01
0.17039 E-00	0.41999 E-00	0.40133 E-00	0.10951 E 01
0.18636 E-00	0.44000 E-00	0.41867 E-00	0.11044 E 01
0.19456 E-00	0.45000 E-00	0.42724 E-00	0.11093 E 01
0.20292 E-00	0.45999 E-00	0.43574 E-00	0.11144 E 01
0.22008 E-00	0.48000 E-00	0.45256 E-00	0.11249 E 01
0.23783 E-00	0.50000 E 00	0.46916 E-00	0.11357 E 01
0.28480 E-00	0.55000 E 00	0.50977 E 00	0.11640 E 01
0.33509 E-00	0.59999 E 00	0.54881 E 00	0.11952 E 01
0.38840 E-00	0.65000 E 00	0.58620 E 00	0.12294 E 01
0.44467 E-00	0.70000 E 00	0.62208 E 00	0.12661 E 01
0.50363 E 00	0.75000 E 00	0.65650 E 00	0.13051 E 01
0.56496 E 00	0.80000 E 00	0.68935 E 00	0.13467 E 01
0.62860 E 00	0.84999 E 00	0.72081 E 00	0.13905 E 01
0.69434 E 00	0.90000 E 00	0.75090 E 00	0.14365 E 01
0.76198 E 00	0.95000 E 00	0.77960 E 00	0.14849 E 01
0.83138 E 00	0.09999 E 01	0.80700 E 00	0.15354 E 01
0.97508 E 00	0.10999 E 01	0.85821 E 00	0.16428 E 01
0.11244 E 01	0.12000 E 01	0.90490 E 00	0.17585 E 01
0.12787 E 01	0.13000 E 01	0.94760 E 00	0.18820 E 01
0.14374 E 01	0.13999 E 01	0.98667 E 00	0.20133 E 01
0.16000 E 01	0.15000 E 01	0.10225 E 01	0.21519 E 01
0.17661 E 01	0.16000 E 01	0.10554 E 01	0.22979 E 01
0.19354 E 01	0.16999 E 01	0.10858 E 01	0.24509 E 01
0.21077 E 01	0.17999 E 01	0.11139 E 01	0.26109 E 01
0.22829 E 01	0.19000 E 01	0.11399 E 01	0.27778 E 01
0.24606 E 01	0.20000 E 01	0.11641 E 01	0.29515 E 01
0.26410 E 01	0.20999 E 01	0.11866 E 01	0.31318 E 01
0.28237 E 01	0.21999 E 01	0.12076 E 01	0.33188 E 01
0.30087 E 01	0.23000 E 01	0.12272 E 01	0.35124 E 01
0.31960 E 01	0.23999 E 01	0.12455 E 01	0.37125 E 01
0.33855 E 01	0.24999 E 01	0.12628 E 01	0.39191 E 01
0.35771 E 01	0.26000 E 01	0.12790 E 01	0.41321 E 01
0.37707 E 01	0.27000 E 01	0.12942 E 01	0.43517 E 01
0.39665 E 01	0.27999 E 01	0.13087 E 01	0.45774 E 01
0.41642 E 01	0.28999 E 01	0.13223 E 01	0.48097 E 01
0.43639 E 01	0.30000 E 01	0.13352 E 01	0.50482 E 01
0.45656 E 01	0.30999 E 01	0.13474 E 01	0.52932 E 01
0.47691 E 01	0.31999 E 01	0.13590 E 01	0.55444 E 01
0.49745 E 01	0.32999 E 01	0.13700 E 01	0.58019 E 01
0.51818 E 01	0.34000 E 01	0.13805 E 01	0.60657 E 01
0.53908 E 01	0.34999 E 01	0.13904 E 01	0.63360 E 01
0.56019 E 01	0.35999 E 01	0.14000 E 01	0.66121 E 01
0.58146 E 01	0.37000 E 01	0.14091 E 01	0.68947 E 01
0.60291 E 01	0.38000 E 01	0.14177 E 01	0.71835 E 01
0.62454 E 01	0.38999 E 01	0.14261 E 01	0.74785 E 01
0.64634 E 01	0.40000 E 01	0.14340 E 01	0.77798 E 01
0.71277 E 01	0.42999 E 01	0.14560 E 01	0.87210 E 01
0.75790 E 01	0.45000 E 01	0.14693 E 01	0.93794 E 01
0.82682 E 01	0.47999 E 01	0.14874 E 01	0.10413 E 02
0.87356 E 01	0.49999 E 01	0.14984 E 01	0.11134 E 02
0.94485 E 01	0.52999 E 01	0.15136 E 01	0.12260 E 02
0.99314 E 01	0.55000 E 01	0.15228 E 01	0.13043 E 02
0.10667 E 02	0.57999 E 01	0.15357 E 01	0.14262 E 02
0.11164 E 02	0.59999 E 01	0.15437 E 01	0.15106 E 02
0.11668 E 02	0.61999 E 01	0.15511 E 01	0.15975 E 02
0.13213 E 02	0.67999 E 01	0.15712 E 01	0.18729 E 02
0.13738 E 02	0.70000 E 01	0.15772 E 01	0.19697 E 02
0.15077 E 02	0.74999 E 01	0.15909 E 01	0.22222 E 02
0.16447 E 02	0.80000 E 01	0.16031 E 01	0.24902 E 02
0.17284 E 02	0.82999 E 01	0.16097 E 01	0.26583 E 02
0.17849 E 02	0.84999 E 01	0.16139 E 01	0.27735 E 02
0.18418 E 02	0.86999 E 01	0.16180 E 01	0.28911 E 02
0.19281 E 02	0.89999 E 01	0.16237 E 01	0.30722 E 02
0.20742 E 02	0.95000 E 01	0.16325 E 01	0.33862 E 02
0.22232 E 02	0.09999 E 02	0.16405 E 01	0.37156 E 02
0.25295 E 02	0.11000 E 02	0.16544 E 01	0.44204 E 02
0.28462 E 02	0.12000 E 02	0.16662 E 01	0.51867 E 02
0.31740 E 02	0.13000 E 02	0.16762 E 01	0.60143 E 02
0.35094 E 02	0.13999 E 02	0.16850 E 01	0.69032 E 02
0.38548 E 02	0.15000 E 02	0.16926 E 01	0.78535 E 02
0.42090 E 02	0.16000 E 02	0.16993 E 01	0.88652 E 02
0.45716 E 02	0.16999 E 02	0.17052 E 01	0.99381 E 02
0.49423 E 02	0.18000 E 02	0.17105 E 01	0.11072 E 03
0.53208 E 02	0.19000 E 02	0.17153 E 01	0.12268 E 03
0.57068 E 02	0.20000 E 02	0.17196 E 01	0.13525 E 03
0.61001 E 02	0.20999 E 02	0.17236 E 01	0.14843 E 03
0.65002 E 02	0.22000 E 02	0.17271 E 01	0.16225 E 03
0.73212 E 02	0.23999 E 02	0.17334 E 01	0.19169 E 03
0.81684 E 02	0.26000 E 02	0.17388 E 01	0.22357 E 03
0.90400 E 02	0.27999 E 02	0.17434 E 01	0.25791 E 03
0.99348 E 02	0.30000 E 02	0.17474 E 01	0.29472 E 03
0.14727 E 03	0.40000 E 02	0.17617 E 01	0.51551 E 03
0.19985 E 03	0.50000 E 02	0.17703 E 01	0.79762 E 03
0.28603 E 03	0.65000 E 02	0.17784 E 01	0.13357 E 04
0.37974 E 03	0.80000 E 02	0.17835 E 01	0.20119 E 04
0.47998 E 03	0.95000 E 02	0.17870 E 01	0.28260 E 04
0.51471 E 03	0.09999 E 03	0.17879 E 01	0.31281 E 04
0.62253 E 03	0.11499 E 03	0.17901 E 01	0.41269 E 04
0.73546 E 03	0.13000 E 03	0.17919 E 01	0.52632 E 04
0.85308 E 03	0.14500 E 03	0.17934 E 01	0.65369 E 04
[b] 0.97506 E 03	0.16000 E 03	0.17946 E 01	0.79484 E 04

[a] Read as 0.22407×10^{-1}.

[b] Read as 0.97506×10^{3}.

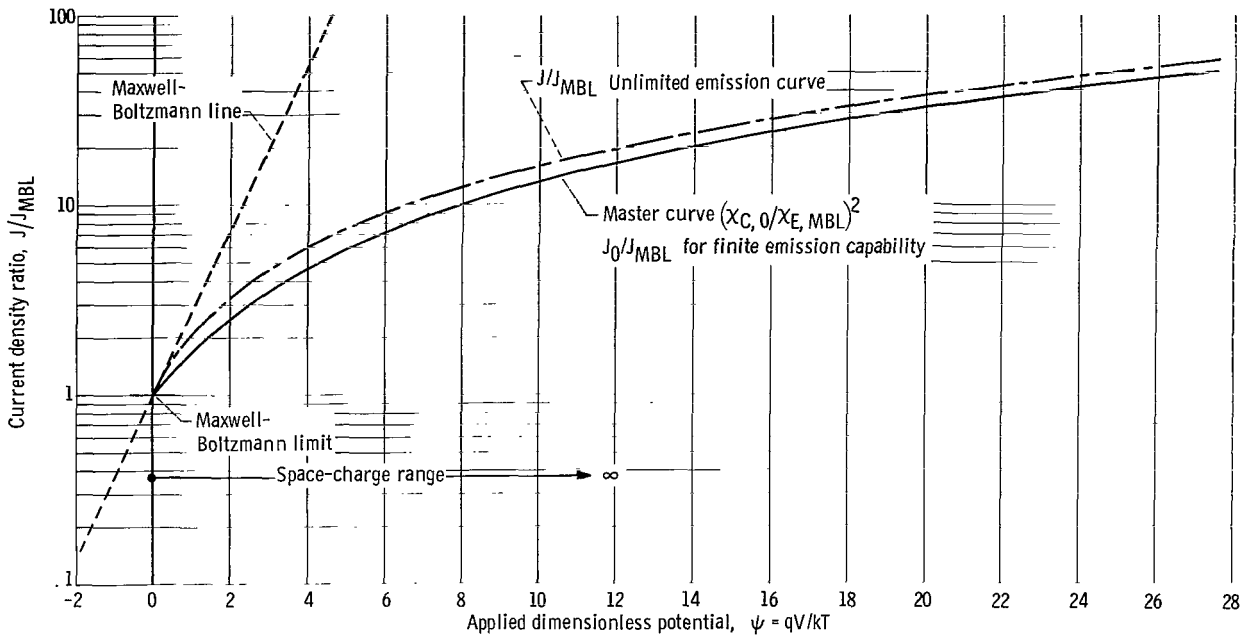


Figure IV:3. - Space-charge curves used in analysis of current-voltage data from planar diodes.

going from the Maxwell-Boltzmann limit to saturation $\psi_{E,MBL} + \psi_{C,0}$ is uniquely determined. These functional relations are useful in treating experimental data and have been compiled in table IV:1. Knowledge of any one of the terms, $\chi_{E,MBL}$, $\chi_{C,0}$, $\chi^2_{C,0}/\chi^2_{E,MBL}$, or $\psi_{E,MBL} + \psi_{C,0}$, uniquely determines all other quantities. It should be noted that $\chi^2_{C,0}/\chi^2_{E,MBL}$ is equivalent to J_0/J_{MBL} and also $\psi_{E,MBL} + \psi_{C,0}$ corresponds to the difference in applied potential (in dimensionless volts) that exists between the Maxwell-Boltzmann limit and the saturation condition. A convenient manner to present the unique relation of the current voltage in the space-charge region is shown in figure IV:3 where the logarithm of J_0/J_{MBL} is plotted as a function of applied potential $\psi_{E,MBL} + \psi_{C,0}$ (solid line). Included in the plot is the straight line (dashed) representation of the Maxwell-Boltzmann line and an unlimited emission curve (dashed line) that will be discussed in section VI. The solid line is the master curve discussed by Nottingham in reference 2. The utility of the master curve is that, with a minimum of experimental information, it permits the quick establishment of the relations between J_{MBL}, J_0, and the applied voltage difference and also provides a starting point for a more detailed treatment of space-charge theory.

V - APPLICATION OF MASTER CURVE

Graphical solutions of space-charge relations are achieved with the "master curve" by plotting the experimental current-voltage data as the logarithm of the current against dimensionless volts on a separate sheet in scales self-consistent with figure IV:3. (The use of dimensionless volts implies knowledge of emitter temperature, which can be determined from the slope of the Maxwell-

Boltzmann line (eq. II:2) or from direct measurement). The master curve then is shifted so that the Maxwell-Boltzmann limits coincide and coordinates of the two sheets are parallel (transparent master graphs or templates are quite useful for this purpose). The current is now normalized in the ratio form in terms of the ordinate of the master curve. The experimental curve must intercept the master curve at the unique condition of zero field at the emitter if space-charge behavior exists. Thus J_0 and related quantities such as work function can be established. The ratio of J_0/J_{MBL} or the dimensionless potential interval $\psi_{E,MBL} + \psi_{C,0}$ can be used to identify $\chi_{E,MBL}$ and $\chi_{C,0}$ through table IV:1.

The effective spacing can be determined from $\chi_{E,MBL}$ or $\chi_{C,0}$ and equation (III:2) since T, J_{MBL}, and J_0 are also known. As stated previously, figure III:1 (p. 7) graphically relates χ, w, and emitter temperature for both ions and electrons and thus is convenient for determining spacing.

Reiterating, two procedures exist by which the saturation current can be determined from the current at the Maxwell-Boltzmann limit. The first requires knowledge of J_{MBL}, T, and w that corresponds to $\chi_{E,MBL}$; this in turn defines the ratio of J_0/J_{MBL} as given in figure III:1. Other relations such as $\chi_{C,0}$ and $\psi_C + \psi_E$ are found directly in table IV:1 by entering at J_0/J_{MBL} or $\chi_{E,MBL}$. An alternate procedure does not require knowledge of spacing but requires that the experimental current-voltage data possess a saturation behavior at a distance equal to the distance that exists when the Maxwell-Boltzmann limit is determined. An intercept technique based on transposing actual data on the theoretical curve provides a solution to the space-charge relations. Once the two end points of the space-charge region are established, transition curves of current-voltages between the end points can be determined. This is the subject of the next section.

VI - TRANSITION CURVES IN SPACE-CHARGE REGION

If it is assumed that the zero field at the collector is established and that the space-charge relations govern the current-voltage behavior up to the saturation condition, it is possible to establish the entire current-voltage characteristic in the space-charge transition region for any given set of starting conditions. The method is merely an extension of the procedure given in section IV and is based upon the effect of the Boltzmann relation on transmitted current.

Returning to figure IV:1 two additional terms of use in the following analysis are the distance from the emitter surface to the space-charge minimum x_M and the corresponding distance to the collector x_N. Then

$$w = x_M + x_N$$

As before, the potential in the emitter space is described by

$$\chi_E = f(\psi_E) \qquad \text{(VI:1)}$$

(e.g., table III:1(a), p. 7) and in the collector space

$$\chi_C = f(\psi_C) \tag{VI:2}$$

(e.g., table III:1(b), p. 7). In the region where the space-charge minimum is in the interelectrode space, the dimensionless distance is

$$\chi_{E,M} + \chi_{C,N} = \frac{KJ^{1/2}x_M}{T^{3/4}} + \frac{KJ^{1/2}x_N}{T^{3/4}} \tag{VI:3}$$

Also

$$\chi_{E,M} + \chi_{C,N} = \frac{KJ_{MBL}^{1/2}(x_M + x_N)}{T^{3/4}} \exp\left(\frac{\psi_{E,MBL} - \psi_{E,M}}{2}\right) \tag{VI:4}$$

(refer to fig. IV:1 for an example of the dimensionless potential distribution). Since $x_M + x_N = w$,

$$\chi_{C,N} = \left[\chi_{E,MBL} \exp\left(\frac{\psi_{E,MBL} - \psi_{E,M}}{2}\right)\right] - \chi_{E,M} \tag{VI:5}$$

or

$$\underbrace{f(\psi_{C,N})}_{\text{eq. (VI:2)}} = \left[\chi_{E,MBL} \exp\left(\frac{\psi_{E,MBL} - \psi_{E,M}}{2}\right)\right] \underbrace{- f(\psi_{E,M})}_{\text{eq. (VI:1)}} \tag{VI:6}$$

Equation (VI:6) is sufficient to solve the entire space-charge transition curve for any initial value of $\chi_{E,MBL}$. The procedure is tedious since it involves (1) starting with a given $\chi_{E,MBL}$ and therefore $\psi_{E,MBL}$, (2) choosing space-charge barrier $\psi_{E,M}$, slightly less than $\psi_{E,MBL}$, (3) establishing the corresponding value of $\chi_{E,M}$, (4) solving for $\chi_{C,N}$, and (5) determining the value of $\psi_{C,N}$ (eq. (VI:2)).

Knowledge of $\psi_{C,N}$ for the assumed initial conditions is sufficient to establish one current-voltage point of the transition curve. The current ratio J/J_{MBL} is known from the starting conditions through the Boltzmann relation

$$\frac{J}{J_{MBL}} = \exp(\psi_{E,MBL} - \psi_{E,M}) \tag{VI:7}$$

The surface potential referred to the Maxwell-Boltzmann limit is

$$\psi_{E,MBL} - \psi_{E,M} + \psi_{C,N} \tag{VI:8}$$

(see fig. IV:1). The remaining points of the transition curve are found by repeating the previous process for additional incremental changes in $\psi_{E,M}$

TABLE VI:1.- LISTING OF COORDINATES FOR CURRENT-VOLTAGE TRANSITION CURVES IN SPACE-CHARGE REGION

Current density ratio, J/J_{MBL}	Dimensionless distance at MBL, $X_{E,MBL}$																	[b]1.806
	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5	1.6	1.7	1.8	
	Surface potential referenced to MBL, $\psi_{E,O} - \psi_{E,M} + \psi_{C,N}$																	
1.1	---	---	---	0.1184	0.1088	0.1048	0.1026	0.1013	0.1005	0.1000	0.09964	0.09942	0.09927	0.09918	0.09913	0.09911	0.09919	0.09920
[a]1.158	---	---	---	.273	------	------	------	------	------	------	------	------	------	------	------	------	------	------
1.2	---	---	---	------	.2554	.2240	.2122	.2060	.2024	.2002	.1987	.1978	.1972	.1968	.1966	.1966	.1967	.1967
[a]1.242	---	---	---	------	.4093	------	------	------	------	------	------	------	------	------	------	------	------	------
1.3	---	---	---	------	------	.3768	.3328	.3155	.3062	.3008	.2973	.2952	.2938	.2930	.2926	.2925	.2927	.2927
[a]1.36	---	---	---	------	------	0.5857	------	------	------	------	------	------	------	------	------	------	------	------
1.4	---	---	---	------	------	------	0.4742	0.4318	0.4127	0.4021	0.3957	0.3918	0.3894	0.3880	0.3873	0.3870	0.3872	0.3873
[a]1.52	---	---	---	------	------	------	.8130	------	------	------	------	------	------	------	------	------	------	------
1.6	---	---	---	------	------	------	------	.7044	.6375	.6084	.5924	.5831	.5776	.5744	.5728	.5722	.5725	.5726
[a]1.74	---	---	---	------	------	------	------	1.1077	------	------	------	------	------	------	------	------	------	------
1.8	---	---	---	------	------	------	------	------	0.8914	0.8224	0.7902	0.7726	0.7625	0.7568	0.7540	0.7529	0.7533	0.7533
2.0	---	---	---	------	------	------	------	------	1.232	1.050	.9904	.9608	.9446	.9357	.9313	.9296	.9300	.9301
[a]2.07	---	---	---	------	------	------	------	------	1.495	------	------	------	------	------	------	------	------	------
2.2	---	---	---	------	------	------	------	------	------	1.301	1.195	1.148	1.124	1.111	1.105	1.103	1.103	1.103
2.4	---	---	---	------	------	------	------	------	------	1.609	1.406	1.336	1.302	1.284	1.276	1.273	1.273	1.273
[a]2.54	---	---	---	------	------	------	------	------	------	2.019	------	------	------	------	------	------	------	------
2.6	---	---	---	------	------	------	------	------	------	------	1.628	1.525	1.478	1.455	1.444	1.440	1.440	1.440
2.8	---	---	---	------	------	------	------	------	------	------	1.867	1.715	1.653	1.623	1.609	1.604	1.604	1.604
3.0	---	---	---	------	------	------	------	------	------	------	2.139	1.908	1.827	1.790	1.772	1.766	1.766	1.766
[a]3.25	---	---	---	------	------	------	------	------	------	------	2.755	------	------	------	------	------	------	------
3.50	---	---	---	------	------	------	------	------	------	------	------	2.410	2.259	2.198	2.170	2.161	2.161	2.161
4.00	---	---	---	------	------	------	------	------	------	------	------	2.976	2.691	2.596	2.557	2.543	2.543	2.543
[a]4.44	---	---	---	------	------	------	------	------	------	------	------	3.845	------	------	------	------	------	------
4.50	---	---	---	------	------	------	------	------	------	------	------	------	3.128	2.988	2.934	2.916	2.915	2.915
5.00	---	---	---	------	------	------	------	------	------	------	------	------	3.575	3.374	3.303	3.278	3.277	3.277
5.5	---	---	---	------	------	------	------	------	------	------	------	------	4.4045	3.756	3.664	3.633	3.631	3.632
6.0	---	---	---	------	------	------	------	------	------	------	------	------	4.561	4.134	4.018	3.981	3.978	3.978
[a]6.61	---	---	---	------	------	------	------	------	------	------	------	------	5.599	------	------	------	------	------
7.0	---	---	---	------	------	------	------	------	------	------	------	------	------	4.887	4.709	4.657	4.652	4.652
8.0	---	---	---	------	------	------	------	------	------	------	------	------	------	5.644	5.381	5.310	5.303	5.304
9.0	---	---	---	------	------	------	------	------	------	------	------	------	------	6.420	6.037	5.944	5.935	5.935
10.0	---	---	---	------	------	------	------	------	------	------	------	------	------	7.249	6.679	6.562	6.550	6.550
11.0	---	---	---	------	------	------	------	------	------	------	------	------	------	8.269	7.311	7.165	7.149	7.150
[a]11.3	---	---	---	------	------	------	------	------	------	------	------	------	------	8.804	------	------	------	------
12	---	---	---	------	------	------	------	------	------	------	------	------	------	------	7.933	7.755	7.736	7.736
14	---	---	---	------	------	------	------	------	------	------	------	------	------	------	9.156	8.900	8.873	8.873
16	---	---	---	------	------	------	------	------	------	------	------	------	------	------	10.36	10.00	9.969	9.970
20	---	---	---	------	------	------	------	------	------	------	------	------	------	------	12.79	12.12	12.06	12.06
[a]24.2	---	---	---	------	------	------	------	------	------	------	------	------	------	------	16.07	------	------	------
25	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	14.62	14.53	14.53
30	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	17.00	16.86	16.87
40	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	21.45	21.24	21.25
50	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	25.72	25.33	25.33
60	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	29.79	29.19	29.19
80	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	37.75	36.41	36.41
[a]89.5	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	42.45	------	------
100	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	43.12	43.13
150	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	58.40	58.41
200	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	72.22	72.23
250	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	85.04	85.04
300	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	97.09	97.10
400	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	119.5	119.5
500	---	---	---	------	------	------	------	------	------	------	------	------	------	------	------	------	140.3	140.3

[a]Denotes intercept with master curve.

[b]Unlimited emission condition as calculated by eq. (VII:1).

until the limit, where $\psi_{E,MBL} - \psi_{E,M} = 0$, and thus saturation conditions are obtained.

Numerical solutions of the transition curves (i.e., typical current-voltage curves in the space-charge region) have been determined and are listed in table VI:1. The intervals are sufficient for the determination of most space charge dominated current-voltage characteristics. The ratio of J/J_{MBL} and the corresponding value of surface potential difference $(\psi_{E,MBL} - \psi_{E,M} + \psi_{C,M})$ are presented for the range of $\chi_{E,MBL}$ (current density, temperature, spacing, and charge to mass ratio) of usual interest in space-charge solutions.

VII - LIMITING SPACE-CHARGE CURVE

A result of interest with regard to the current-voltage transition curves is the similarity of the current ratio J/J_{MBL} and applied potential for those conditions where $\chi_{E,MBL}$ approaches 1.806. If table III:1(a) (p. 7) or figure III:2 (p. 9) are referred to, it can be seen that, at values of $\psi_E > 10$, χ_E is nearly to the limiting value (1.799 compared to 1.806). For all practical purposes over the range of voltages for which $\psi_{E,MBL}$ is greater than 10, the current across the diode is independent of the emission capability of the emitter. Surface barriers are suppressed, space charge dominates, and the emitter acts as if it possesses unlimited emission capability.

When $\psi_{E,MBL}$ is greater than 10, the assumption that $\chi_{E,MBL}$ is nearly equal to 1.806 permits the description of the transition curves by the following approximation of equation (VI:6):

$$f(\psi_{C,N}) \approx 1.806 \left[\exp\left(\frac{\psi_{E,MBL} - \psi_{E,M}}{2}\right)\right] - 1.806 \qquad \text{(VII:1)}$$

This approximation is based upon the following:

(1) When $\psi_{E,MBL} > 10$, $\chi_{E,MBL} \approx 1.806$.

(2) Also, $\chi_{E,M} \approx 1.806$ at $\psi_{E,M}$ near 10.

(3) At the lower values of $\psi_{E,M}$, $\left[\exp\left(\frac{\psi_{E,MBL} - \psi_{E,M}}{2}\right)\right] \gg \chi_{E,M}$.

Then

$$\exp\left(\psi_{E,MBL} - \psi_{E,M}\right) = \frac{J}{J_{MBL}} \qquad \text{(VII:2)}$$

The ratio of J/J_{MBL} as a function of change in applied potential from the MBL limit $(\psi_{E,MBL} - \psi_{E,M} + \psi_{C,M})$ may be determined directly. This result is tabulated in the last column in table VI:1 and corresponds to the curve labeled unlimited emission in figure IV:3 (p. 15). The unlimited emission curve provides an adequate representation of the current-voltage regions for space-charge

limited current conditions over a wide range of applied potentials and accurately reflects the current-voltage trends during the initial application of accelerating potential for almost all cases where space-charge effects are of significance.

VIII - REMARKS CONCERNING APPLICATION OF SPACE-CHARGE THEORY

It is generally impossible to separate the electron current from the ion current so that the Maxwell-Boltzmann limit for the ion current is quantitatively established. Only in extreme cases of high ion current density and a minimum of collision phenomena is the match between theory and experiment satisfactory. A more applicable space-charge treatment of ion current deals with the determination of the applied voltage needed to reach ion saturation at the condition before the onset of the Schottky effect. The procedure requires a reasonable estimate of the saturated ion current J_0. In general, this is calculated by knowing the arrival rate of cesium atoms, cesium ionization potential, and the estimated or measured emitter work function. The Langmuir-Saha equation or some modification of it may be used to calculate the anticipated zero-field ion current density. The value of the constant K (eq. (III:2)) is 1.442×10^7 for the case of cesium ions. If this value is used along with the other data in equation (III:2) or figure III:1 (p. 6), the value of $\chi_{c,0}$ may be computed. Reference to table III:1(b) (p. 7) establishes the corresponding value of $\psi_{c,0}$. This quantity when multiplied by kT/q then gives the potential difference between the surface of the emitter and the surface of the ion collector, which must be established in order to obtain the zero-field ion emission. This information coupled with the Schottky treatment of current-voltage information (to be discussed in sections IX and X) provides a useful step in analyzing current-voltage information.

The use of the generalized space-charge relations also involves the presentation of the experimental data in a form similar to the master and unlimited emission curves shown in figure IV:3 (p. 15). The procedure previously outlined required transposing the curves so that the Maxwell-Boltzmann limits coincided. The crossover of the experimental curve with the master curve gives zero-field emission and permits the direct determination of spacing w. Experiment has shown this value is in excellent agreement for the vacuum diode (ref. 2). The transition curves are also accurately described by the unlimited emission curve at the initial values of applied potentials. The plasma diode at extremely close spacing exhibits space-charge behavior in close agreement with the analytical predictions. If, however, as is true in many cases, the spacing is greater than a single mean free path for an ion or an electron, the development of plasma conditions tends to make the effective spacing considerably less than the true one. Semiquantitative information on the nature of the barrier in terms of height and location can be obtained by the use of the space-charge relations. The unlimited emission curve can also be used as a useful "barometer" of the applicability of the space-charge relations. The experimental data that clearly exceed the condition of "unlimited" data indicate the single-charge space-charge relations cannot be applied in a direct fashion and suitable adjustments must be made. The conditions in which this occurs in the case of electron transmission are often those of large ion currents. In the cases where the large ion current

predominates, application of the space charge to the ion often yields useful information enabling a sorting of electron and ion currents.

IX - GENERAL DISCUSSION OF SCHOTTKY MIRROR-IMAGE THEORY

Schottky (ref. 6) was one of the first to call attention to the mirror-image concept. The force acting on an electron as it progresses from the surface of a uniform conductor out to a point well outside of the conductor is dominated by the attraction between the electron and the induced surface charge of the opposite sign distributed over the conducting surface. This statement implies that the outside space is electrostatically field-free except for the field produced by the electron or ion and its induced surface charge.

Figure IX:1 has been prepared to give an accurate scale drawing of the mirror-image potential function. Two curves are shown. The upper curve is the potential function for an electron, and the lower curve is the potential function for a positive ion. In both cases the mirror-image force is one which attracts the electron or ion to the surface. Thus, electron energy levels lie in this potential-function plane below the electron potential function line; ion energy levels lie above the potential function.

Figure IX:1. - Mirror-image potential function for electrons and singly charged ions.

Some ambiguity exists in the point of termination of the mirror-image potential function. Figure IX:1 indicates intersection at the Fermi level for the electron image function. The ion image function is considered to be symmetrical with respect to the electron image function. The axis of symmetry is the zero potential line.

Figure IX:1 displayed the electron and ion functions in the absence of any external electrostatic field produced by surface and/or space charges. The superposition of electrostatic forces and the mirror-image forces permits the display of potential functions in the presence of combined forces. Figure IX:2 illustrates the superposition and has been prepared to show two important facts. The first relates to the potential functions with zero external field. The ordinate scale has been expanded a factor of 10 to show that at a distance of 1.4×10^{-8} meter, the potential function differs from that at infinity by only 0.026 electron volt. This energy is the electron

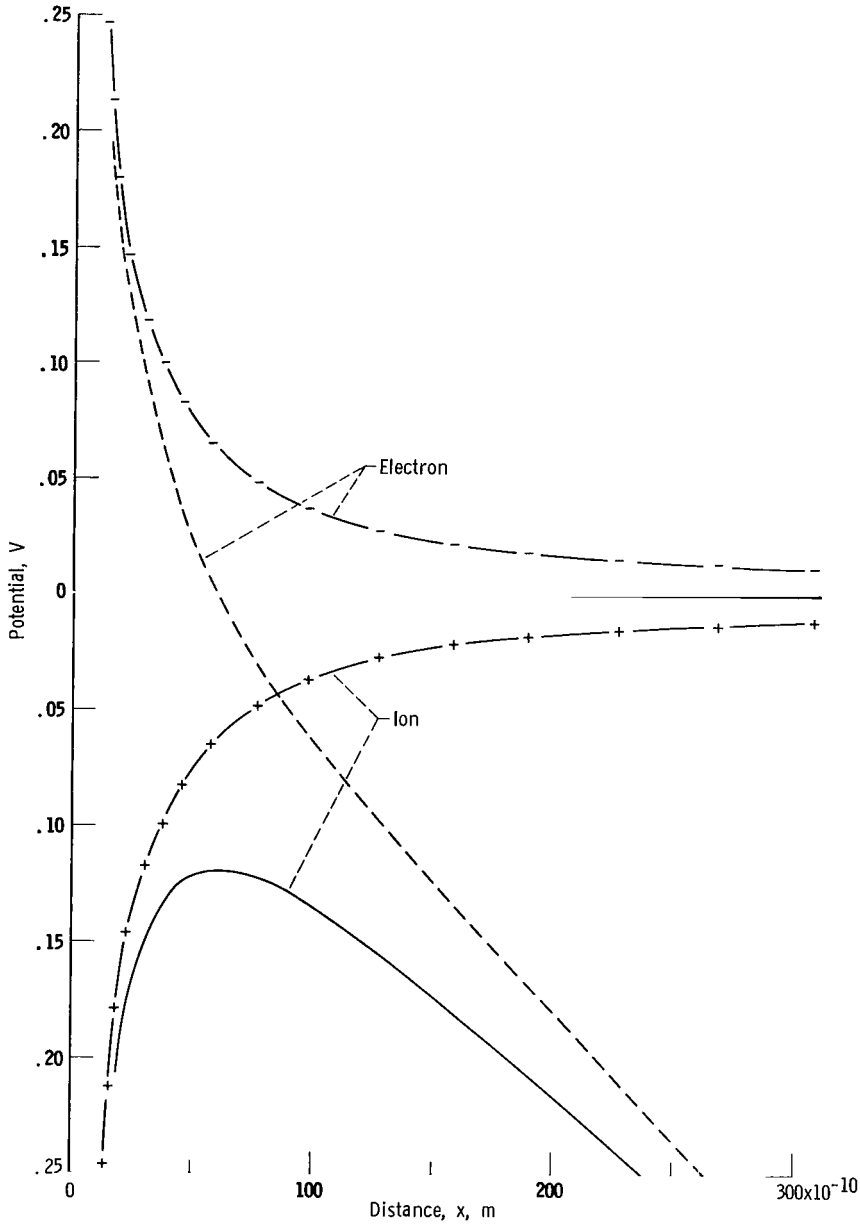


Figure IX:2. - Mirror-image potential functions in presence of ion accelerating field of 10^7 volts per meter.

volt equivalent of room temperature. Thus, for all practical purposes, the mirror-image force is of little or no consequence at a distance from the conducting surface of 10^{-8} meter (approximately 40 to 100 atomic radii).

The second fact relates to the potential functions associated with an ion accelerating field of 10^7 volts per meter. Again, all ion energy levels lie above the ion potential line, shown here as a solid line. Similarly, the electron energy levels all lie below the electron potential line shown as the dashed line. Ion removal from the surface is enhanced by the accelerating field. The

critical distance for ion escape has been brought to approximately 0.6×10^{-8} meter, and the necessary initial kinetic energy for escape has been lowered by 0.12 electron volt. (The effects are identical for electrons in the presence of an electron accelerating field). The atomic scale of the dimensions involved in the location of the critical distance and point of the termination of the mirror-image function permits the simple superposition of the Schottky effect on the thermionic emission, the space charge, and the sheath relations treated in this report. The relations that follow are limited to accelerating fields of 10^7 volts per meter or less. Field strengths greater than this introduce a probability of electron tunneling and are also more dependent on the nature of the force function near the emitter surface. Morris (ref. 7) has analyzed Schottky (and penetration) effects on electron emission for a mirror-image function terminating on the conductor surface at the Fermi level. The comparison (ref. 7) of the terminated image function to the more usual simple nonterminated form indicates that, at field strengths less than 10^7 volts per meter, the current densities of the two cases deviate by only 1 percent. Field strengths greater than 10^7 volts per meter are unlikely in a thermionic converter; therefore, the simple formalism of the Schottky effect based upon the nonterminated image potential is used in the development of the equations in this section.

As a consequence of the experimental fact that both electrons and ions leave a heated surface with a Maxwell-Boltzmann energy distribution, it is possible to write the equation for the variation of current density produced by a variation in the surface field applicable to both particles. This result expressed in logarithmic form is

$$\ln J = \ln J_0 + \frac{(3.8\times10^{-5}E^{1/2})11\ 606}{T} \qquad \text{(IX:8)}$$

As a first approximation it is practical to assume that the electrostatic field E is directly proportional to the difference in the surface potentials of the emitter and the collector.

The surface potential difference is determined from the applied potential by correcting for the contact potential difference (φ considered positive only)

$$\pm V_C = \pm(\varphi_1 - \varphi_2) \qquad \text{(IX:9)}$$

The plus sign applies for an ion accelerating field, the minus sign for an electron accelerating field. The assumption that E is proportional to the applied voltage corrected for contact potential can be expressed in terms of geometrical factor identified as the "effective spacing". This proportionality factor then appears as

$$E = \frac{V_B - (\pm V_C)}{w_{eff}} \qquad \text{(IX:10)}$$

where V_B (the applied potential) is treated as a positive quantity if it produces an accelerating field for the particle in question. After this substitution is made in equation (IX:8), it may be written in either of the following forms:

$$\ln J = \ln J_0 + 3.8\times10^{-5}\left[\frac{V_B - (\pm V_C)}{w_{eff}}\right]^{1/2}\frac{11\ 606}{T} \qquad \text{(IX:11)}$$

or

$$\log_{10} J = \log_{10} J_0 + 1.65\times10^{-5}\left[\frac{V_B - (\pm V_C)}{w_{eff}}\right]^{1/2}\frac{11\ 606}{T} \qquad \text{(IX:12)}$$

These equations suggest that the logarithm of the current density should be plotted as a function of the square root of the applied voltage (corrected for contact potential difference) divided by the electron volt equivalence of temperature. If a straight line results, it is then justified to assume that the linear relation expressed by equation (IX:10) is applicable. Field distortion which results from geometrical factors only does not interfere with the linearity of the plot but simply gives an unrealistic value of w_{eff}. Space-charge effects are the most serious and the most difficult to include in the analysis since then E will be a nonlinear function of V. If the space charge is due to the ions or electrons being measured, the field itself will always be weaker than that computed from geometrical considerations. If the space-charge present is of the opposite sign, then the field will be stronger than would be computed by equation (IX:10). Both of these effects become less important at higher values of applied voltage. This can be seen in figure IX:3, which is a typical "Schottky plot" of cesium ion emission observed in a thermionic converter operating at voltages corresponding to a strong ion accelerating field. It is legitimate to apply equation (IX:12) to data of this type by drawing a straight line

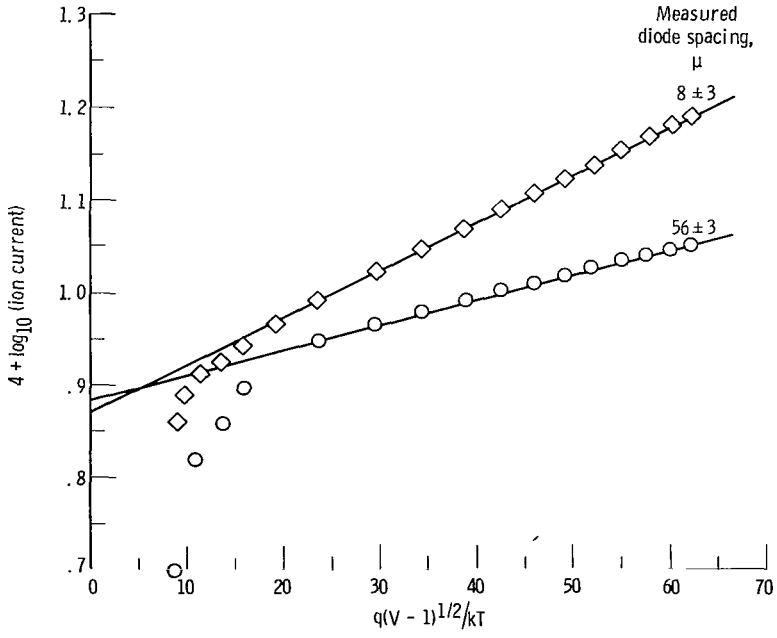


Figure IX:3. - Typical Schottky plot of cesium ion emission from tungsten emitter in planar thermionic converter. Emitter temperature, 1472° K; cesium reservoir temperature, 470° K; $\varphi_1 - \varphi_2 \approx 1$.

through the higher voltage data and extrapolating the line to zero voltage (based on surface potential difference). The value of $\log_{10} J$ is thus established. The slope of the line gives the value of spacing. This may be expressed explicitly as

$$w_{eff} = \frac{2.72 \times 10^{-10}}{S^2} \text{ m} \qquad \text{(IX:13)}$$

In this equation, S is the slope of the straight line drawn when $\log_{10} J$ is used; that is,

$$S = \frac{T}{11\,606} \frac{\log_{10} J_1 - \log_{10} J_2}{\sqrt{V_1 - (\pm V_C)} - \sqrt{V_2 - (\pm V_C)}} \qquad \text{(IX:14)}$$

X - CONCLUDING REMARKS CONCERNING USE OF SCHOTTKY THEORY

Although the theory reviewed in the previous section of this report has generally been applied to electrons, it is equally valid as it applies to ions. The theory is most likely to be of value in the treatment of ion currents in the analysis of voltage-current curves taken in a plasma diode. When the ratio of the emitter temperature to the cesium bath temperature is less than 2.9, the sheath condition at the emitter is generally electron rich. Ion current data taken in a very closely spaced diode and with applied potentials approximately 2 volts more negative than the open-circuit voltage in this electron-rich region follow the Schottky theory quite well. The slopes are very consistent with the actual spacing. The extrapolation of the line to establish the zero-field condition yields information by which a comparison can be made with the Langmuir-Saha theory of ionization. This method of analysis applied to spacings that are large compared with the mean free path of the ions often results in a nearly straight line display of the data, and yet the slope of the line is far in excess of that anticipated from geometrical considerations. Thus an abnormally small value of w_{eff} in comparison with the actual value is interpreted as a direct indication that a "plasma" or "collisional" condition has developed in the interelectrode space. The field is no longer directly proportional to the applied voltage but is greatly distorted by the presence of space-charge and collisional effects. The observed current falls very much more rapidly with a change in voltage and therefore corresponds to a much steeper slope of the Schottky line than can possibly be justified on the Schottky theory basis. Such an analysis still has value in that the experimental results cast in this form clearly illustrate that the flow of ions is inhibited by the presence of the atoms in spite of the fact that an ion accelerating field is presumed to exist across the entire interelectrode space.

The Maxwell-Boltzmann portion of the log - current-voltage curve is usually linear over several orders of magnitude of current flow in a well-controlled vacuum diode experiment. Subsequent interpretation of the space-charge region leading to the determination of emitter and collector work function is quite direct by the techniques described in the earlier sections of this report. The presence of ion currents even though small distorts the Boltzmann line and in-

terferes with the "single-charge" interpretation of the net current results. A first step in the reduction of the net current data (where $_{+}J \ll {}_{-}J$) is the use of the Schottky analysis to determine the zero-field ion current. If this value and other terms in χ indicate the ion space-charge effect is minor, then the net current can be corrected directly for the ion current contribution. As the accelerating potential is reduced and the simple corrections become more inaccurate, the large electron current will usually dominate and mask the uncertainties in reflection and space-charge effects on ion currents.

XI - REVIEW OF SHEATH AND PLASMA THEORY OF ISOTHERMAL DIODE

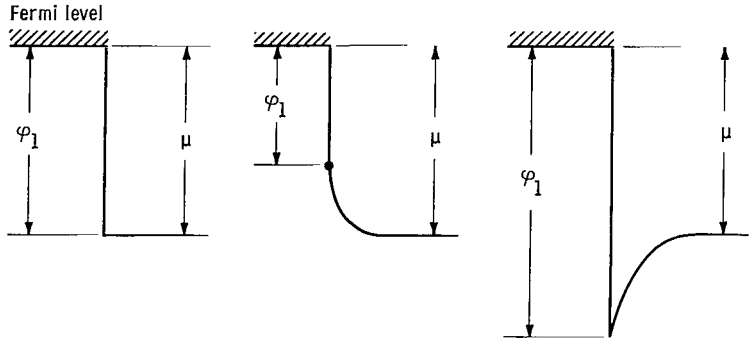
Voltage-current curves of a cesium plasma diode operated at extremely close spacing are quite readily interpreted in terms of conventional formulations based on the Richardson-Dushman emission equation, Langmuir-Saha (ref. 8) ion production probability equation, conventional space-charge theory, Schottky (ref. 6) theory, and extrapolation of Langmuir-Taylor (ref. 9) cesium coverage data. It is particularly interesting to observe both the ion and electron currents at various spacings when the emitter temperature T and the cesium temperature T_{Cs} are related in terms of their ratio by $2.9 < (T/T_{Cs}) < 3.4$. Within this range, conditions near the emitter go from electron rich to ion rich. It is assumed that under the latter condition, there is no difficulty collecting the full value of electron emission current available at the emitter. Experiment shows that over a limited range in spacing, this full current is observed, but as the spacing is increased to become comparable with the electron mean free path an electron space-charge barrier develops to inhibit the flow in spite of the ion-rich condition near the surface (ref. 10). The reverse of this picture applies if the emitter sheath is electron rich. The ion production observed at larger spacings often falls below that observed at close spacings. In both cases, it is believed that a plasma condition has formed close to the emitter and that variations in applied collector potential modify the collector sheath more noticeably than they do the electron- or ion-limiting barriers. In recognition of this observation the theory of the isothermal diode was analyzed in detail (ref. 11) so that information on the potentials associated with the plasma could be established. A brief review of the results of the isothermal analysis is included to show how the numerical results were established. Inasmuch as the equations and their derivations are readily found in the literature, the emphasis of the following sections will be placed upon presenting the equations in a form that permits quick application to experimental data. The relations involving numerical values of cesium vapor pressure differ from those in reference 11 since more recent vapor pressure data are used.

The first step in the development of the theory of an isothermal diode comes from an application of the Saha (refs. 8 and 12) equation, which relates the concentration of ions or electrons (since these are equal) to the temperature, concentration of atoms, and the ionization potential. This equation is

$$ {}_{+}n_p = {}_{-}n_p = \left[\frac{2(2\pi mkT)^{3/2}}{h^3} \frac{n}{2} \exp\left(\frac{qV_i}{kT}\right) \right]^{1/2} (1 - f)^{1/2} \qquad \text{no./m}^3 \qquad \text{(XI:1)} $$

The random current for cesium ions is directly expressible by

$$ \ln {}_{+}J_p = -17.51 + \frac{5}{4} \ln T - \frac{qV_i}{2kT} + \frac{1}{2} \ln n \qquad \text{amp/sq m} \qquad \text{(XI:2)} $$



(a) Work function equals plasma potential to give no sheath.

(b) Work function less than plasma potential to give electron rich sheath.

(c) Work function greater than plasma potential to give ion rich sheath.

Figure XI:1. - Examples of potential diagrams for three different work functions.

The random current of electrons is given by

$$\ln {}_{-}J_p = -11.31 + \frac{5}{4} \ln T - \frac{qV_i}{2kT} + \frac{1}{2} \ln n \qquad \text{amp/sq m} \qquad \text{(XI:3)}$$

These two current densities are related by the square root of mass ratio (492) for cesium.

An isothermal plasma is generally bounded by a material substance in which it is possible to identify the Fermi level. As a result of the definition of chemical potential (e.g., ref. 13) and the use of equation (XI:2), the plasma potential, relative to the Fermi level of the surrounding material, is given by

$$\mu = \frac{kT}{q} \left(25.31 + \frac{3}{4} \ln T + \frac{qV_i}{2kT} - \frac{1}{2} \ln n \right) \qquad \text{V} \qquad \text{(XI:4)}$$

The diagrams of figure XI:1 illustrate three examples. The first is the potential diagram associated with the absence of any plasma sheath found when the work function is equal to the plasma potential. In figure XI:1(b), the work function is lower while figure XI:1(c) applies to a high work-function surface. In each case, the electron emission from the surface is equal to the electron current impinging on the surface from the plasma. The net electron current at the boundary and any position in the sheath is always zero. The net ion current at the boundary and in the sheath is also always zero.

Since diodes for the thermionic conversion of heat to electricity are never isothermal, the application of the aforementioned results is somewhat qualitative; thus there is seldom any need to determine the isothermal plasma potential to an accuracy better than about 1 percent. Figure XI:2 serves to relate the plasma potential to the isothermal temperature and the cesium atom density expressible in terms of the corresponding cesium condensation temperature. For more accurate results, a very simple formula may be used with the help of the correlation chart given as figure XI:3. Both approaches are based on noncollisional transport in the interelectrode space. The equation to be used

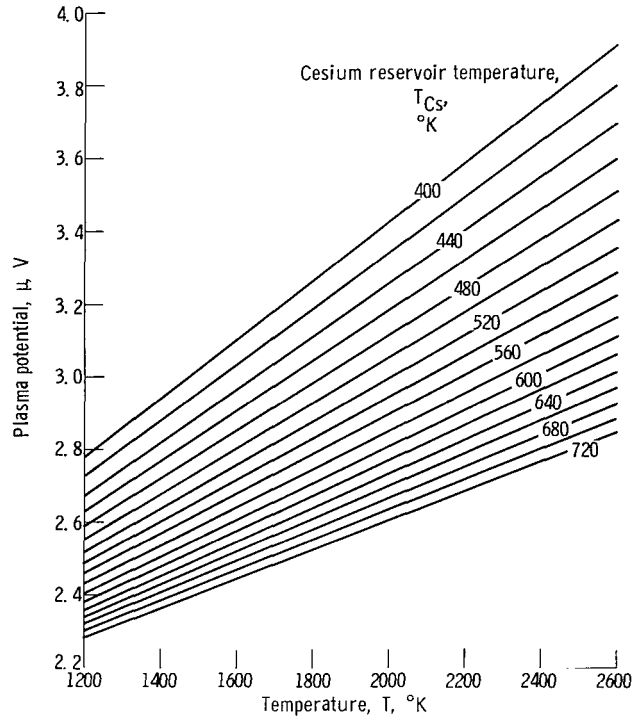


Figure XI:2. - Plasma potential as function of surface temperature and cesium reservoir temperature.

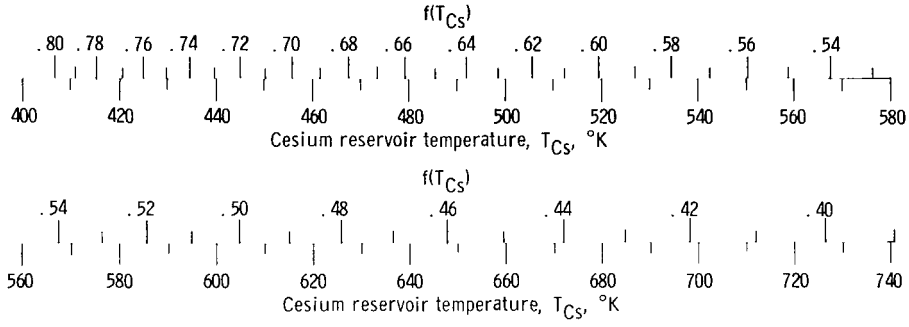


Figure XI:3. - Correlation chart for $f(T_{Cs})$ as function of cesium reservoir temperature used in equation (XI:6) ($\mu = 1.799 + f(T_{Cs})Tx10^{-3}$, V) for computation of isothermal plasma potential referenced to Fermi level.

with this chart is

$$\mu = 1.799 + f(T_{Cs}) \frac{T}{1000} \quad V \qquad \text{(XI:6)}$$

XII - FOWLER POTENTIAL FUNCTION IN SHEATH

The Fowler (ref. 14) solution of the space-charge equation is used to give a determination of the distribution in potential in the transition region between the surface of the surrounding conductor and the plasma potential μ. Figure XII:1 defines certain essential points. The mathematical solution allows

the potential to approach a value of ∞ by assuming a "fictitious" surface which lies inside the true surface a distance x_0. The detailed development of the equations in this section is given in reference 11. The Fowler solution is simplified by the introduction of a distance parameter similar to the "Debye distance"; the Fowler distance differs only by a factor. This parameter is given by

$$x_1 = \frac{1}{2} \frac{(\epsilon_0 k)^{1/2}}{q} \frac{T^{1/2}}{n_p^{1/2}} = 34.5 \frac{T^{1/2}}{n_p^{1/2}} \quad \text{m or } 5\times10^{-3} \text{ Debye lengths} \qquad \text{(XII:1)}$$

The exact equation for the distance from the fictitious surface to the real surface is given by

$$x_0 = x_1 \sqrt{2} \ln \left(\tanh \left| \frac{\varphi_1 - \mu}{\frac{4kT}{q}} \right| \right)^{-1} = x_1 \sqrt{2} \ln \left(1 + \frac{2}{\exp \left| \frac{\varphi_1 - \mu}{\frac{2kT}{q}} \right| - 1} \right) \quad \text{m} \qquad \text{(XII:2)}$$

The insertion of realistic values into equation (XII:2) shows that x_0 seldom deviates from x_1 as much as a factor of 2. A specific numerical illustration may be of interest as it applies to the temperature ratio T_1/T_{Cs} of 2200° K/660° K, which yields a value of x_1 of 1.42×10^{-7} meter. The corresponding values of φ_1 and μ are 3.18 and 2.83 volts, respectively. With these values substituted in equation (XII:2), the value of x_0 is 1.68×10^{-7} meter, which is only 20 percent larger than x_1.

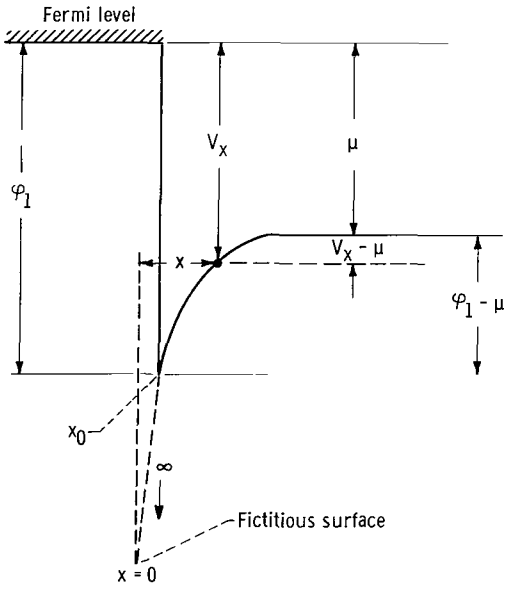


Figure XII:1. - Potential diagram for positive ion sheath.

The Fowler space-charge equation expressed in terms of the potential function V_x relative to the isothermal plasma potential is given by

$$V_x - \mu = \frac{4kT}{q} \tanh^{-1} \left[\exp \left(- \frac{x}{\sqrt{2}\, x_1} \right) \right] \quad \text{V} \qquad \text{(XII:3)}$$

This equation may be solved to give the distance x from the fictitious surface to a specific value of the potential relative to the plasma potential. The equation is

$$x = x_1 \sqrt{2} \ln \left(\tanh \frac{V_x - \mu}{\frac{4kT}{q}} \right)^{-1} \quad m \qquad \text{(XII:4)}$$

The distance to a given value of the potential relative to the real surface requires the subtraction of x_0 (eq. (XII:2)).

It is often desirable to know the sheath thickness so that it can be compared with the actual interelectrode spacing. Inspection of equation (XII:4) shows that as V_x approaches μ, the distance x approaches infinity. This means that there is no absolutely sharp boundary to the space-charge sheath; thus some criterion should be chosen to establish a finite distance. One such practical criterion would be that $|V_x - \mu| = kT/q$ since this quantity is a good measure of thermal energy of the charged particles involved. This particular value of the distance defines the symbol $x_{\overline{V}}$ and is given by

$$x_{\overline{V}} = 1.99\, x_1 \quad m \qquad \text{(XII:5)}$$

The distance from the actual surface depends on the value of x_0 given by equation (XII:2) and may be computed by

$$x_{\overline{V}} - x_0 = x_1 \sqrt{2} \left\{ 1.407 - \ln \left[1 + \frac{2}{\exp \left(\frac{\varphi_1 - \mu}{\frac{2kT}{q}} \right) - 1} \right] \right\} \quad m \qquad \text{(XII:6)}$$

If the difference in potential across the sheath $(\varphi_1 - \mu)$ is $3kT/q$ or more, the approximate form of equation (XII:6) is given by

$$x_{\overline{V}} - x_0 \approx x_1 \sqrt{2} \left(1.407 - 2\exp - \left| \frac{\varphi_1 - \mu}{\frac{2kT}{q}} \right| \right) \quad m \qquad \text{(XII:7)}$$

Equation (XII:2) expanded in series form is

$$x_0 = x_1 \sqrt{2} \frac{2}{\exp \frac{\psi_1}{2}} \left(1 + \frac{1}{3\exp \psi_1} + \frac{1}{5\exp 2\psi_1} + \ldots \right) \quad m \qquad \text{(XII:8)}$$

where

$$\psi_1 = \frac{\varphi_1 - \mu}{\frac{kT}{q}}$$

The error in the use of only the first term of this formula is less than 1 percent for $(\varphi_1 - \mu)q/kT = 3.5$; if two terms are used, the 1 percent error is at $\psi_1 = 1.5$.

The Fowler solution of the sheath analysis also establishes the field at the surface

$$\frac{d\psi_1}{d\left(\frac{x}{x_1}\right)} = \sqrt{2} \sinh \frac{\psi_1}{2} \qquad \text{(XII:9)}$$

In dimensional form, the field at the surface becomes

$$\frac{dV_x}{dx} = \left(\frac{2kTn_p}{\epsilon_o}\right)^{1/2} 2 \sinh \frac{\varphi - \mu}{\frac{2kT}{q}} \qquad V/m \qquad \text{(XII:10)}$$

An approximate logarithmic form valid for $\psi_1 > 4$ is

$$\ln\left(\frac{dV_x}{dx}\right) \approx -13.247 + \frac{1}{2} \ln n_p + \frac{1}{2} \ln T + \frac{\varphi - \mu}{\frac{2kT}{q}} \qquad \text{(XII:11)}$$

XIII- RELATION OF ISOTHERMAL DIODE THEORY TO SCHOTTKY REDUCTION IN WORK FUNCTION

Under some conditions of operation of practical thermionic diodes, strong ion accelerating sheaths may form which in turn increase electron emission. The increased emission may result in part from a reduction in work function in accordance with the Schottky mirror-image theory. The relations given below are based on equations in sections IX and XII and are given in a form that permit a direct calculation of "sheath" enhanced electron emission current.

A logarithmic form of equation (IX:8) is

$$\ln \ln\left(\frac{I_F}{I_O}\right) = -10.179 + \ln\left(\frac{q}{kT}\right) + \frac{1}{2} \ln \left(\frac{dV_x}{dx}\right)_{x=x_O} \qquad \text{(XIII:1)}$$

In these equations, I_F is the emission current in the presence of the electron accelerating field of strength calculated by equation (XII:10) or (XII:11). The symbol I_O is the current density from the emitter when the field is zero. This equation may be combined with equation (XII:10) to give a useful logarithmic expression as

$$\ln\left(\ln \frac{I_F}{I_O}\right) = -14.117 + \frac{1}{4} \ln n_p + \frac{3}{4} \ln \frac{q}{kT} + \frac{1}{2} \ln \sinh\left(\frac{\varphi_1 - \mu}{\frac{2kT}{q}}\right) \qquad \text{(XIII:2)}$$

A second form of this equation depends on the use of equation (XII:11) in equation (XIII:1). This result, good when $(\varphi_1 - \mu)/(kT/q) > 4$, is

$$\ln\left(\ln \frac{I_F}{I_0}\right) = - 14.463 + \frac{1}{4} \ln n_p + \frac{3}{4} \ln \left(\frac{q}{kT}\right) + \frac{\varphi_1 - \mu}{\frac{4kT}{q}} \qquad \text{(XIII:3)}$$

To make direct calculations from the atom density and temperature without first determining n_p, the exact and the approximate formulas are, respectively

$$\ln \ln\left(\frac{I_F}{I_0}\right) = - 6.216 + \frac{9}{16} \ln\left(\frac{q}{kT}\right) - \frac{qV_i}{8kT} + \frac{1}{8} \ln n + \frac{1}{2} \ln \sinh\left(\frac{\varphi_1 - \mu}{\frac{2kT}{q}}\right) \qquad \text{(XIII:4)}$$

For $(\varphi_1 - \mu)/(kT/q) > 4$,

$$\ln \ln\left(\frac{I_F}{I_0}\right) \approx - 6.562 + \frac{9}{16} \ln\left(\frac{q}{kT}\right) - \frac{qV_i}{8kT} + \frac{1}{8} \ln n + \frac{\varphi_1 - \mu}{\frac{4kT}{q}} \qquad \text{(XIII:5)}$$

XIV - CONCLUDING REMARKS CONCERNING ISOTHERMAL DIODE THEORY

The isothermal diode theory suffers from the limitations involved in all equilibrium approaches. Its application to a thermionic converter represents a major perturbation to the basic assumptions; however, since a semiquantitative insight into the properties of a diode can be achieved from such a simple utilitarian approach, its judicious use is of value.

The exact description of the sheath region and the equations of sheath thickness and surface field have been formulated by the isothermal diode theory. The relations would be expected to give a first-order approximation of the sheath and plasma at the condition where the random current is considerably larger than the directed current. Such a condition could occur when the cesium pressure is quite high and the T_1/T_{Cs} is in the region where electron emission is modest. A similar condition can be encountered when the diode is operated with applied potential sufficiently retarded to inhibit the transmission of the electron current. Houston (ref. 15) has indicated reasonable agreement of his experimental data with isothermal theory at these conditions.

Lastly, a great deal of utility is derived from the isothermal theory in establishing some of the properties of the plasma conditions. Its use in conjunction with the space-charge theory helps to define the conditions where transitions between space-charge and plasma effects may appear in experimental results.

XV - ADDITIONAL AIDS TO ANALYSIS OF THERMIONIC CONVERTER PERFORMANCE

Continual use of the Richardson-Dushman emission equation is made in the analysis of thermionic converter data. Excellent charts exist that provide graphical solutions for these relations (see Luke (ref. 16), for example); however, the charts that are available often do not cover the range of interest in the detail desired. Presentation of comprehensive detailed charts to cover each situation involves the obvious problem of generating excess information. Therefore, a compromise has been made. Solutions to the Richardson-Dushman equation which is

$$J_0 = 1.2\times10^6\ T^2 \exp\left(-\frac{q\varphi}{kT}\right) \quad \text{amp/sq m} \qquad \text{(XV:1)}$$

in terms of the work function have been tabulated (table XV:1) for a range of current densities of 10^{-3} to 10^{-6} amperes per square meter and temperatures from 500° to 3200° K.

The exponential relation between the work function and current density permits the linear display of the tabulated results on semilog graphs in the form shown in figure XV:1. The tabulated solution provides a convenient compilation of the intercepts of each constant temperature line. Thus the user can select the range and scales of interest and quickly tailor the charts to his own use.

Cesium vapor pressure and related properties are also of primary interest in thermionic conversion. Several adequate references (refs. 17 and 18) exist and are presently in use; however, recent vapor pressure data in the 700° to 1300° K range indicate some small corrections should be made, particularly if thermodynamic consistancy is to be attained for cesium vapor in equilibrium with the liquid or solid phase. Heimel (ref. 19), in his review of the thermodynamic properties of cesium, recommends that the following equation be used for the vapor pressure of cesium:

$$\log_{10} p\ (\text{N/sq m}) = \frac{-4053.30}{T} - 0.915282 \log_{10} T + 12.05025 \qquad \text{(XV:2)}$$

Equation (XV:2) was selected since it represents a reasonable compromise among the known thermodynamic properties of cesium.

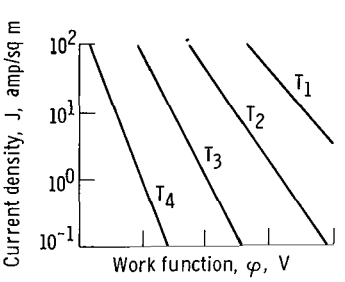


Figure XV:1. - Typical presentation of Richardson-Dushman equations.

An alternate expression (ref. 19) for cesium vapor pressure based only on the various vapor pressure data (including recent work) is as follows:

$$\log_{10} p\,(\text{N/sq m}) = \frac{-3920.38}{T} - 0.519781 \log_{10} T + 10.71914 \qquad \text{(XV:3)}$$

Equation (XV:3), although in excellent agreement with experimental vapor pressure data (least-squares fit to the three-term expression), leads to incon-

TABLE XV:1. - COMPILATION OF INTERCEPTS OF RICHARDSON-DUSHMAN EQUATION FOR USE IN PREPARING GRAPHICAL SOLUTIONS

Temperature, °K	Current density, amp/sq m			
	10^{-3}	10^{0}	10^{3}	10^{6}
	Work function, eV			
500	1.436	1.139	0.841	0.543
510	1.467	1.163	0.860	0.556
520	1.497	1.188	0.878	0.569
530	1.528	1.212	0.897	0.581
540	1.558	1.237	0.915	0.594
550	1.589	1.261	0.934	0.607
560	1.619	1.286	0.953	0.619
570	1.650	1.311	0.972	0.632
580	1.681	1.336	0.990	0.645
590	1.711	1.360	1.009	0.658
600	1.742	1.385	1.028	0.671
610	1.773	1.410	1.047	0.684
620	1.804	1.435	1.066	0.697
630	1.835	1.460	1.085	0.710
640	1.865	1.485	1.104	0.723
650	1.896	1.509	1.123	0.736
660	1.927	1.534	1.142	0.749
670	1.958	1.559	1.161	0.762
680	1.989	1.584	1.180	0.775
690	2.020	1.609	1.199	0.788
700	2.051	1.635	1.218	0.801
710	2.082	1.660	1.237	0.814
720	2.113	1.685	1.256	0.828
730	2.144	1.710	1.275	0.841
740	2.175	1.735	1.295	0.854
750	2.207	1.760	1.314	0.867
760	2.238	1.785	1.333	0.881
770	2.269	1.811	1.352	0.894
780	2.300	1.836	1.372	0.907
790	2.331	1.861	1.391	0.921
800	2.363	1.886	1.410	0.934
810	2.394	1.912	1.430	0.948
820	2.425	1.937	1.449	0.961
830	2.456	1.962	1.468	0.974
840	2.488	1.988	1.488	0.988
850	2.519	2.013	1.507	1.001
860	2.551	2.039	1.527	1.015
870	2.582	2.064	1.546	1.028
880	2.613	2.090	1.566	1.042
890	2.645	2.115	1.585	1.056
900	2.676	2.141	1.605	1.069
910	2.708	2.166	1.624	1.083
920	2.739	2.192	1.644	1.096
930	2.771	2.217	1.664	1.110
940	2.802	2.243	1.683	1.124
950	2.834	2.268	1.703	1.137
960	2.865	2.294	1.723	1.151
970	2.897	2.320	1.742	1.165
980	2.928	2.345	1.762	1.179
990	2.960	2.371	1.782	1.192
1000	2.992	2.397	1.801	1.206
1010	3.023	2.422	1.821	1.220
1020	3.055	2.448	1.841	1.234
1030	3.087	2.474	1.861	1.248
1040	3.118	2.499	1.880	1.261
1050	3.150	2.525	1.900	1.275
1060	3.182	2.551	1.920	1.289
1070	3.214	2.577	1.940	1.303
1080	3.245	2.603	1.960	1.317
1090	3.277	2.628	1.980	1.331
1100	3.309	2.654	2.000	1.345
1110	3.341	2.680	2.019	1.359
1120	3.373	2.706	2.039	1.373
1130	3.404	2.732	2.059	1.387
1140	3.436	2.758	2.079	1.401
1150	3.468	2.784	2.099	1.415
1160	3.500	2.810	2.119	1.429
1170	3.532	2.836	2.139	1.443
1180	3.564	2.862	2.159	1.457
1190	3.596	2.888	2.179	1.471
1200	3.628	2.914	2.199	1.485
1210	3.660	2.940	2.219	1.499
1220	3.692	2.966	2.239	1.513
1230	3.724	2.992	2.260	1.527
1240	3.756	3.018	2.280	1.542
1250	3.788	3.044	2.300	1.556
1260	3.820	3.070	2.320	1.570
1270	3.852	3.096	2.340	1.584
1280	3.884	3.122	2.360	1.598
1290	3.916	3.148	2.380	1.613
1300	3.948	3.174	2.401	1.627
1310	3.980	3.200	2.421	1.641
1320	4.012	3.227	2.441	1.655
1330	4.044	3.253	2.461	1.670
1340	4.076	3.279	2.481	1.684
1350	4.109	3.305	2.502	1.698
1360	4.141	3.331	2.522	1.712
1370	4.173	3.358	2.542	1.727
1380	4.205	3.384	2.562	1.741
1390	4.237	3.410	2.583	1.755
1400	4.270	3.436	2.603	1.770
1410	4.302	3.463	2.623	1.784
1420	4.334	3.489	2.644	1.799
1430	4.366	3.515	2.664	1.813
1440	4.399	3.541	2.684	1.827
1450	4.431	3.568	2.705	1.842
1460	4.463	3.594	2.725	1.856
1470	4.495	3.620	2.746	1.871
1480	4.528	3.647	2.766	1.885
1490	4.560	3.673	2.786	1.900
1500	4.592	3.700	2.807	1.914
1510	4.625	3.726	2.827	1.929
1520	4.657	3.752	2.848	1.943
1530	4.689	3.779	2.868	1.958
1540	4.722	3.805	2.889	1.972
1550	4.754	3.832	2.909	1.987
1560	4.787	3.858	2.930	2.001
1570	4.819	3.885	2.950	2.016
1580	4.851	3.911	2.971	2.030
1590	4.884	3.938	2.991	2.045
1600	4.916	3.964	3.012	2.059
1610	4.949	3.991	3.032	2.074
1620	4.981	4.017	3.053	2.089
1630	5.014	4.044	3.073	2.103
1640	5.046	4.070	3.094	2.118
1650	5.079	4.097	3.115	2.133
1660	5.111	4.123	3.135	2.147
1670	5.144	4.150	3.156	2.162
1680	5.176	4.176	3.176	2.177
1690	5.209	4.203	3.197	2.191
1700	5.241	4.230	3.218	2.206
1710	5.274	4.256	3.238	2.221
1720	5.307	4.283	3.259	2.235
1730	5.339	4.309	3.280	2.250
1740	5.372	4.336	3.300	2.265
1750	5.404	4.363	3.321	2.280
1760	5.437	4.389	3.342	2.294
1770	5.470	4.416	3.363	2.309
1780	5.502	4.443	3.383	2.324
1790	5.535	4.469	3.404	2.339
1800	5.567	4.496	3.425	2.353
1810	5.600	4.523	3.445	2.368
1820	5.633	4.550	3.466	2.383
1830	5.665	4.576	3.487	2.398
1840	5.698	4.603	3.508	2.413
1850	5.731	4.630	3.529	2.428
1860	5.764	4.656	3.549	2.442
1870	5.796	4.683	3.570	2.457
1880	5.829	4.710	3.591	2.472
1890	5.862	4.737	3.612	2.487
1900	5.894	4.764	3.633	2.502
1910	5.927	4.790	3.654	2.517
1920	5.960	4.817	3.674	2.532
1930	5.993	4.844	3.695	2.547
1940	6.025	4.871	3.716	2.561
1950	6.058	4.898	3.737	2.576
1960	6.091	4.924	3.758	2.591
1970	6.124	4.951	3.779	2.606
1980	6.157	4.978	3.800	2.621
1990	6.190	5.005	3.821	2.636
2000	6.222	5.032	3.842	2.651
2010	6.255	5.059	3.863	2.666
2020	6.288	5.086	3.883	2.681
2030	6.321	5.113	3.904	2.696
2040	6.354	5.140	3.925	2.711
2050	6.387	5.166	3.946	2.726
2060	6.420	5.193	3.967	2.741
2070	6.452	5.220	3.988	2.756
2080	6.485	5.247	4.009	2.771
2090	6.518	5.274	4.030	2.786
2100	6.551	5.301	4.051	2.801
2110	6.584	5.328	4.072	2.816
2120	6.617	5.355	4.093	2.832
2130	6.650	5.382	4.114	2.847
2140	6.683	5.409	4.135	2.862
2150	6.716	5.436	4.156	2.877
2160	6.749	5.463	4.178	2.892
2170	6.782	5.490	4.199	2.907
2180	6.815	5.517	4.220	2.922
2190	6.848	5.544	4.241	2.937
2200	6.881	5.571	4.262	2.952
2210	6.914	5.598	4.283	2.968
2220	6.947	5.625	4.304	2.983
2230	6.980	5.652	4.325	2.998
2240	7.013	5.680	4.346	3.013
2250	7.046	5.707	4.367	3.028
2260	7.079	5.734	4.389	3.043
2270	7.112	5.761	4.410	3.059
2280	7.145	5.788	4.431	3.074
2290	7.178	5.815	4.452	3.089
2300	5.842	4.473	3.104	
2310	5.869	4.494	3.120	
2320	5.896	4.516	3.135	
2330	5.924	4.537	3.150	
2340	5.951	4.558	3.165	
2350	5.978	4.579	3.180	
2360	6.005	4.600	3.196	
2370	6.032	4.622	3.211	
2380	6.059	4.643	3.226	
2390	6.087	4.664	3.242	
2400	6.114	4.685	3.257	
2410	6.141	4.707	3.272	
2420	6.168	4.728	3.287	
2430	6.195	4.749	3.303	
2440	6.223	4.770	3.318	
2450	6.250	4.792	3.333	
2460	6.277	4.813	3.349	
2470	6.304	4.834	3.364	
2480	6.332	4.855	3.379	
2490	6.359	4.877	3.395	
2500	6.386	4.898	3.410	
2510	6.413	4.919	3.426	
2520	6.441	4.941	3.441	
2530	6.468	4.962	3.456	
2540	6.495	4.983	3.472	
2550	6.523	5.005	3.487	
2560	6.550	5.026	3.502	
2570	6.577	5.047	3.518	
2580	6.604	5.069	3.533	
2590	6.632	5.090	3.549	
2600	6.659	5.112	3.564	
2610	6.686	5.133	3.580	
2620	6.714	5.154	3.595	
2630	6.741	5.176	3.610	
2640	6.768	5.197	3.626	
2650	6.796	5.219	3.641	
2660	6.823	5.240	3.657	
2670	6.851	5.261	3.672	
2680	6.878	5.283	3.688	
2690	6.905	5.304	3.703	
2700	6.933	5.326	3.719	
2710	6.960	5.347	3.734	
2720	6.988	5.369	3.750	
2730	7.015	5.390	3.765	
2740	7.042	5.412	3.781	
2750	7.070	5.433	3.796	
2760	7.097	5.455	3.812	
2770	7.125	5.476	3.827	
2780	7.152	5.498	3.843	
2790	7.180	5.519	3.858	
2800	7.207	5.541	3.874	
2810	7.235	5.562	3.890	
2820	7.262	5.584	3.905	
2830	7.290	5.605	3.921	
2840	7.317	5.627	3.936	
2850	7.344	5.648	3.952	
2860	7.372	5.670	3.968	
2870	7.399	5.691	3.983	
2880	7.427	5.713	3.999	
2890	7.455	5.734	4.014	
2900	7.482	5.756	4.030	
2910	7.510	5.778	4.046	
2920	7.537	5.799	4.061	
2930	7.565	5.821	4.077	
2940	7.592	5.842	4.092	
2950	7.620	5.864	4.108	
2960	7.647	5.886	4.124	
2970	7.675	5.907	4.139	
2980	7.702	5.929	4.155	
2990	7.730	5.950	4.171	
3000	7.758	5.972	4.186	
3010	7.785	5.994	4.202	
3020	7.813	6.015	4.218	
3030	7.840	6.037	4.233	
3040	7.868	6.059	4.249	
3050	7.896	6.080	4.265	
3060	7.923	6.102	4.281	
3070	7.951	6.124	4.296	
3080	7.978	6.145	4.312	
3090	8.006	6.167	4.328	
3100	8.034	6.189	4.343	
3110	8.061	6.210	4.359	
3120	8.089	6.232	4.375	
3130	8.117	6.254	4.391	
3140	8.144	6.275	4.406	
3150	8.172	6.297	4.422	
3160	8.200	6.319	4.438	
3170	8.227	6.341	4.454	
3180	8.255	6.362	4.470	
3190	8.283	6.384	4.485	

TABLE XV [illegible] - RECOMM[illegible] CESI[illegible] VAPOR PRE[illegible] - RE[illegible]

Temperature, °K	Cesi[illegible] vap[illegible] pre[illegible], N/sq m	Torr	Vapor density, atoms/[illegible]	Mean free path, m	Evapor[illegible] rate, atoms/(sq m)(sec)	Atom arrival rate (eq[illegible] current), amp/sq m
250	[a].43884 -6	.32912 -8	.12714 15	.19874 4	.63454 16	.10166 -2
251	50731	38051	14641	17259	73214	11729
252	58584	43941	16842	15005	84379	13518
253	67574	50684	19341	1306[illegible]	97135	15562
254	778[illegible]	58395	2223[illegible]	1138[illegible]	11165 17	17894
255	.8959[illegible] -6	.6727[illegible] -8	.25452 15	.99276 3	.12829 17	.20551 -2
256	10[illegible] -5	7725[illegible]	29145	86699	14719	2358[illegible]
257	115[illegible]	38713	3333[illegible]	75797	16869	27025
258	13[illegible]	10176 -7	3805[illegible]	66336	19312	30939
259	1554[illegible]	116[illegible]	43478	58118	22086	35383
260	.17796 -5	.1[illegible]46 -7	.49576 15	.5097[illegible] 3	.25231 17	.40422 -2
261	2014[illegible]	1526[illegible]	56466	44749	28794	46130
262	232[illegible]	1743[illegible]	64252	39327	32827	5259[illegible]
263	26[illegible]	19889	73036	34597	37386	59895
264	3022[illegible]	22672	82939	30466	42536	68145
265	.34422 -5	.258[illegible]8 -7	.940[illegible]2 15	.26855 3	.48347 17	.77455 -2
266	39163	2937[illegible]	10664 16	23695	54898	87950
267	445[illegible]6	33392	12075	20927	62276	9977[illegible]
268	505[illegible]	379[illegible]	1365[illegible]	1850	70578	11307 -1
269	57322	42954	15436	1637	79910	12802
270	.6496 -5	.48724 -7	.17428 16	.14499 3	.90392 17	.1448[illegible] -1
271	[illegible]355[illegible]	55.66	1966[illegible]	12853	10215 18	16366
272	83[illegible]	6240	22154	11405	11574	18478
273	94022	7052[illegible]	24948	10129	[illegible]	20844
274	1061[illegible] -4	79624	2806[illegible]	900[illegible] 2	14664	23492
275	.11976 -4	.89826 -7	.3154[illegible] 16	.801[illegible] 2	.16512 18	.26453 -1
276	13478	10.24 -6	35425	71127	18577	29761
277	152	1[illegible]4[illegible]	[illegible]	[illegible]	2088[illegible]	33454
278	171[illegible]	12828	4454[illegible]	567[illegible]	23454	37572
279	19224	1442	499[illegible]	[illegible]	26313	42152
280	[illegible] -4	.16[illegible] -6	.5586 16	.452[illegible] 2	.29607 18	.47272 -1
281	2421	181[illegible]	6247[illegible]	40446	33056	52958
282	[illegible]	21183	698[illegible]	3619[illegible]	3707[illegible]	59279
283	[illegible]	228[illegible]	77[illegible]	3242[illegible]	4[illegible]384	663
284	[illegible]	255[illegible]	[illegible]	20[illegible]	46248	74093
285	.38[illegible] -4	.29[illegible] -6	[illegible]	.2807[illegible] 2	.51643 18	.82736 -1
286	[illegible]	[illegible]	[illegible]	[illegible]	57622	92314
287	[illegible]	[illegible]	[illegible]	[illegible]	64263	1029[illegible] 0
288	[illegible]	[illegible]	[illegible]	[illegible]	71569	11466
289	[illegible]	444	[illegible]	[illegible]	7967[illegible]	12764
290	[illegible]	[illegible]	[illegible]	[illegible] 2	.8861[illegible] 18	.14198 0
291	[illegible]	[illegible]	[illegible]	138[illegible]	[illegible]	157[illegible]
292	[illegible]	[illegible]	[illegible]	1244[illegible]	10941 19	17528
293	[illegible]	68[illegible]	224[illegible]	11243	12143	1[illegible]451
294	[illegible]	[illegible]	24[illegible]	[illegible]	13467	21575
295	[illegible] -3	[illegible] -6	.2753[illegible] 17	.917[illegible] 1	.14926 19	.239[illegible] 0
296	2439	[illegible]	30438	870[illegible]	1654[illegible]	2648
297	13788	137[illegible] -5	336[illegible]	[illegible]	18253	29302
298	[illegible]	1[illegible]467	37[illegible]	68[illegible]	2023	32412
299	[illegible]	[illegible]	40[illegible]	6168	2235[illegible]	3592[illegible]
300	.187[illegible] -3	[illegible] -6	.45[illegible]	[illegible] 1	.24694 19	.39561 0
301	[illegible]	55[illegible]	4976	[illegible]	272[illegible]	43663
302	2[illegible]84	17[illegible]6	[illegible]	[illegible]	300[illegible]	48158
303	25224	1[illegible]	[illegible]	[illegible]	33132	5308
304	2783	[illegible]	663[illegible]	[illegible]	36495	58466
305	[illegible] -3	[illegible] -6	.728[illegible]	.446[illegible]	.40[illegible]2 19	.64358 0
306	[illegible]	251[illegible]	[illegible]	[illegible]	44192	70798
307	[illegible]	[illegible]	[illegible]	[illegible]	4856[illegible]	778[illegible]
308	[illegible]	[illegible]	4634[illegible]	[illegible]	[illegible]	855[illegible]
309	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
310	[illegible]	[illegible] -6	[illegible]	[illegible]	[illegible]	[illegible]
311	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]24	1[illegible]29[illegible]
312	[illegible]	[illegible]	[illegible]	[illegible]	772[illegible]	238[illegible]
313	[illegible]	[illegible]	[illegible]	[illegible]	846[illegible]	13563
314	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]2674	14867
315	[illegible]	[illegible]	[illegible]	[illegible] 1	.10[illegible]39	.16243 1
316	[illegible]	[illegible]	[illegible]	1279	11084	17760
317	[illegible]	[illegible]	2154[illegible]	11723	12114	1947[illegible]
318	[illegible] -2	[illegible]	23[illegible]	[illegible]	13230	2119[illegible]
319	11[illegible]	84[illegible]	2561[illegible]	28449 0	1444[illegible]	23134
320	[illegible]	[illegible]	[illegible]	[illegible]	.15253 20	.25237 1
321	[illegible]	[illegible]	[illegible]	83[illegible]	17175	27516
322	[illegible]	[illegible]	[illegible]	[illegible]	19716	29984
323	[illegible]	12[illegible]	[illegible]	[illegible]	2018[illegible]	32654
324	1744[illegible]	13[illegible]	39[illegible]	[illegible]	22187	35845
325	[illegible] -2	[illegible] -4	.6247 18	[illegible]	.24138 20	.3867[illegible] 1
326	[illegible]	[illegible]446	[illegible]	[illegible]	26746	42048
327	[illegible]	[illegible]	[illegible]	[illegible]	29524	45697
328	2444[illegible]	184[illegible]	54[illegible]	[illegible]	[illegible]	49637
329	250[illegible]	20[illegible]	[illegible]	[illegible]	37637	53888
330	[illegible]	[illegible] -4	.6[illegible] 18	[illegible]	.36495 20	.58474 1
331	[illegible]	[illegible]	68[illegible]	3665	39584	63418
332	[illegible]	[illegible]	[illegible]	[illegible]	4291[illegible]	68745
333	[illegible]	[illegible]	[illegible]	[illegible]	45492	74483
334	[illegible]	[illegible]	[illegible]	[illegible]	50347	80659
335	[illegible] -2	[illegible] -4	[illegible]	[illegible]	.5444[illegible] 20	.87356 1
336	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	94454
337	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.10[illegible]14 2
338	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11[illegible]
339	[illegible]	[illegible]	[illegible]	[illegible]	7444[illegible]	1192[illegible]
340	[illegible]	[illegible] -4	[illegible]	[illegible]	[illegible] 20	.128[illegible] 2
341	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
342	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
343	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
344	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
345	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
346	[illegible]	[illegible]	[illegible]	[illegible]	12623	[illegible]
347	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
348	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
349	28[illegible]	[illegible]	[illegible]	[illegible]	15724	2519
350	.1383	[illegible] -3	[illegible]	[illegible]	[illegible] 2	[illegible] 2
351	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
352	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
353	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3356
354	[illegible]	[illegible]	[illegible]	[illegible]	2748[illegible]	[illegible]
355	[illegible]	.1[illegible] -3	.4[illegible] 19	.67[illegible]	.24[illegible] 21	.3866 2
356	2[illegible]	[illegible]	[illegible]	[illegible]	25[illegible]	[illegible]
357	229[illegible]	17185	4649[illegible]	54352	27726	444[illegible]
358	24585	[illegible]	[illegible]	50746	29709	47595
359	26[illegible]	[illegible]	5320[illegible]	47[illegible]	31421	50979
360	.2827[illegible] -2	.2[illegible] -3	.56888 19	.446[illegible] -1	.3426[illegible] 21	.5458 2
361	[illegible]	22726	6079[illegible]	415[illegible]	36462	58415
362	[illegible]	24347	6445[illegible]	395[illegible]	390[illegible]	62494
363	347[illegible]	26[illegible]	6976[illegible]	364[illegible]	417[illegible]	66833
364	372[illegible]	279[illegible]	7405[illegible]	34121	44596	71446
365	.37[illegible] -1	.2[illegible] -3	.79028 19	.31[illegible] -1	.47656 21	.76348 2
366	425[illegible]	315[illegible]	8435[illegible]	29973	509[illegible]	81556
367	45[illegible]	3416[illegible]	898[illegible]	28[illegible]	5436[illegible]	87088
368	48684	365[illegible]	[illegible]	2636[illegible]	58[illegible]	9296[illegible]
369	52[illegible]	39[illegible]	10217 20	24[illegible]	61916	99172
370	.55[illegible] -1	.41673 -3	.10877 20	.2329 -1	.66042 21	.1058 3
371	5932	444[illegible]	[illegible]1583	21816	70419	11282
372	633[illegible]	4745[illegible]	12329	20494	7506[illegible]	12025
373	67[illegible]	5057[illegible]	13120	1926	79978	12813
374	72[illegible]	[illegible]	13956	18104	85188	13648
375	.76824 -1	.57622 -3	.1484[illegible] 20	.17727 -1	.90726 21	.14532 3
376	8188[illegible]	61415	15776	167[illegible]	95549	15468
377	8724[illegible]	65435	16767	15[illegible]74	10273 22	16459
378	92921	6979[illegible]	1782[illegible]	14[illegible]	10928	17507
379	98936	7420[illegible]	1890[illegible]	13363	11620	18615
380	.10531 0	.78984 -3	.20[illegible]74 20	.12588 -1	.1235[illegible] 22	.19788 3
381	11205	8604[illegible]	2130[illegible]	11847	13124	2102[illegible]
382	11518	89392	2265[illegible]	1118[illegible]	13942	22337
383	12673	95053	2372[illegible]	10542	14806	2372[illegible]
384	13471	10[illegible] -2	25412	9943[illegible] -2	15718	2518[illegible]
385	.14315 0	.10737 -2	.26933 20	.918[illegible]9 -2	.1668 22	.26723 3
386	15206	11406	2853[illegible]	88547	1769[illegible]	2835
387	16148	12112	30226	83508	18765	3006[illegible]
388	17143	12856	32006	78949	19895	318[illegible]
389	18194	1364[illegible]	3388[illegible]	7468[illegible]	210[illegible]2	33[illegible]
390	.1935[illegible] 0	.14478 -2	.35853 20	.7047[illegible] -2	.22345 22	.3580[illegible] 3
391	20473	15356	37930	66619	23673	379[illegible]
392	21708	16282	40114	6299[illegible]	25069	40162
393	23010	17259	42412	59578	26533	42517
394	24383	18288	44828	56367	28086	44996
395	.25830 0	.19374 -2	.47368 20	.53344 -2	.29715 22	.47606 3
396	27355	20517	50038	50499	31430	50352
397	28961	21722	52842	47818	33233	53242
398	30652	22991	55790	45293	35130	56281
399	32433	24327	58882	42914	37125	59476
400	.34368 0	.25732 -2	.62129 20	.40671 -2	.39221 22	.62834 3

Temperature, °K	Cesium vap[illegible] pre[illegible], N/sq m	Torr	Vapor density, atoms/[illegible]	Mean free path, m	Evap[illegible] rate, atoms/(sq m)(sec)	Atom arrival rate (eq[illegible] current), amp/sq m
400	.34368 0	.25732 -2	.62129 20	.40671 -2	.39221 22	.62834 3
401	3628[illegible]	27212	65537	38556	41424	66364
402	38354	28768	69113	36561	43739	70072
403	40537	30425	72864	34679	46170	73967
404	42832	32126	76795	32901	48723	78057
405	.45243 0	.33975 -2	.8092[illegible] 20	.31226 -2	.51403 22	.82350 3
406	47778	35836	85244	29642	54215	86856
407	5044[illegible]	37833	89773	28147	57166	91583
408	53237	39933	94518	26734	60261	96542
409	56177	42133	99487	25399	6350[illegible]	10174 4
410	.59255 0	.44445 -2	.10469 21	.24136 -2	.6691[illegible] 22	.10719 4
411	62490	4687[illegible]	11014	22943	70478	11291
412	65885	49417	11584	21814	74215	11890
413	69445	52087	12180	20745	78131	12517
414	73179	54888	12804	19735	82233	13174
415	.77094 0	.57824 -2	.13457 21	.18778 -2	.86527 22	.13862 4
416	81197	60902	14139	17872	91023	14582
417	85497	64127	14852	17014	95729	15336
418	90003	67506	15597	1620[illegible]	10065 23	16125
419	94721	71046	16376	15431	10580	16950
420	.99663 0	.74752 -2	.17189 21	.14700 -2	.11119 23	.17813 4
421	10486 1	78632	18038	14008	11682	18716
422	11025	82694	18925	13352	1227[illegible]	19659
423	11592	86944	1985[illegible]	12729	12887	20645
424	12185	9139[illegible]	20818	12139	13530	21675
425	.128[illegible] 1	.960[illegible] -2	.21824 21	.11578 -2	.142[illegible] 23	.22751 4
426	13453	1009[illegible] -1	22876	11046	1490[illegible]	23875
427	14131	10599	23972	10541	15636	25049
428	14847	1113[illegible]	25115	1006[illegible]	1640[illegible]	26274
429	1558[illegible]	11666	2630[illegible]	9605[illegible] -3	17199	27553
430	.16356 1	.122[illegible] -1	.27549 21	.9[illegible]721 -3	.18032 23	.28888 4
431	17162	128[illegible]2	28844	87605	189[illegible]	3028[illegible]
432	180[illegible]	135[illegible]	30192	836[illegible]	198[illegible]	31733
433	1888[illegible]	14166	31596	79973	20753	33247
434	19[illegible]	1485[illegible]	3305[illegible]	76435	21738	34826
435	[illegible] 1	[illegible] -1	.3458[illegible] 21	.730[illegible] -3	.22766 23	.36472 4
436	2[illegible]768	[illegible]	3616[illegible]	6986[illegible]	23836	38187
437	224[illegible]	[illegible]	378[illegible]	6682	2495[illegible]	39975
438	235[illegible]	17[illegible]	3954[illegible]	639[illegible]	261[illegible]	41837
439	252[illegible]	187[illegible]	4131[illegible]	6115[illegible]	27[illegible]	43776
440	.262[illegible] 1	.196[illegible]	.43[illegible] 21	.585[illegible] -3	.288[illegible] 23	.45795 4
441	2746[illegible]	20596	45[illegible]	56[illegible]22	29898	47898
442	2874[illegible]	2[illegible]562	4711[illegible]	53635	31263	50085
443	[illegible]0[illegible]88	2256[illegible]	4919[illegible]	[illegible]	32685	52363
444	31485	23615	51367	49192	34164	54733
445	.3294[illegible] 1	.247[illegible]	.5362[illegible] 2[illegible]	.47125 -3	.357[illegible] 23	.57198 4
446	34455	25843	5596[illegible]	45154	37[illegible]	59762
447	36[illegible]33	27[illegible]	58392	432[illegible]	38967	62428
448	37[illegible]5	28[illegible]	609[illegible]	414[illegible]	40697	652
449	39383	2[illegible]	63537	39769	42496	68081
450	.41[illegible] 1	.308[illegible] -1	.66258 2[illegible]	.38136 -3	.44765 23	.71075 4
451	[illegible]	3226[illegible]	69082	3657[illegible]	46[illegible]	74187
452	44934	33[illegible]	72012	35[illegible]	48325	77419
453	46935	35[illegible]	75[illegible]	33648	5042[illegible]	80777
454	490[illegible]	36[illegible]	78[illegible]	[illegible]	525[illegible]	84264
455	.511[illegible] 1	.38[illegible]	.8[illegible]476 21	.3[illegible] -3	.548[illegible] 23	.87884 4
456	5342[illegible]	40[illegible]	84867	29774	572[illegible]3	91642
457	55[illegible]	[illegible]	88383	28[illegible]	5963[illegible]	95543
458	58[illegible]	[illegible]	[illegible]	[illegible]	62165	9959[illegible]
459	6[illegible]	[illegible]	[illegible]	26375	64786	[illegible] 5
460	.6[illegible]23	.474[illegible] -1	.9[illegible] 21	.25345 -3	.675[illegible] 23	.10815 5
461	56[illegible]	47[illegible]	[illegible]377 22	2435	70127	11267
462	688[illegible]	[illegible]	[illegible]	234[illegible]	73252	11735
463	[illegible]	[illegible]	[illegible]	22497	762[illegible]	12221
464	[illegible]	[illegible]	[illegible]	2[illegible]63	7943[illegible]	12725
465	.77986 1	.68[illegible] -1	.12149 22	.20799 -3	.82689 23	.13247 5
466	81258	60947	1263[illegible]	200[illegible]	86066	13788
467	84652	63493	1313[illegible]	19244	89565	14349
468	88173	66134	13647	18515	931[illegible]	14930
469	91823	68872	14182	17817	96945	15531
470	.956[illegible] 1	.71[illegible] -1	.14735 22	.1714[illegible] -3	.10083 24	.16154 5
471	99531	7465[illegible]	1530[illegible]	165[illegible]	10486	16799
472	[illegible]367 2	7777[illegible]	15[illegible]	1589[illegible]	10903	17467
473	[illegible]78[illegible]	80[illegible]	16511	15394	11334	18158
474	11[illegible]	84138	17[illegible]	1474	1178[illegible]	18873
475	[illegible] 2	.8753[illegible] -1	.1779[illegible] 22	.1419[illegible] -3	.12243 24	.19614 5
476	[illegible]238	91[illegible]	18472	[illegible]	1272[illegible]	20379
477	12623	94687	1917[illegible]	[illegible]	13215	21172
478	13126	9844[illegible]	[illegible]	127[illegible]	1372[illegible]	2199[illegible]
479	13646	10235 0	2[illegible]	1224[illegible]	14256	22838
480	.14184 2	.10639 0	.21405 22	.11805 -3	.148[illegible] 24	.23714 5
481	14741	11056	22199	11382	15368	24620
482	15317	11489	23[illegible]	[illegible]	15952	25556
483	15914	11936	23866	10588	16556	26523
484	16530	12399	24740	10214	17180	27523
485	.17168 2	.12877 0	.25642 22	.98543 -4	.17824 24	.28556 5
486	17828	13372	26573	95092	18490	29623
487	18510	13884	27533	91776	19178	30725
488	19216	14413	28523	88584	19889	31863
489	19947	14959	29545	85526	20622	33038
490	.20698 2	.15525 0	.3[illegible] 22	.82581 -4	.21[illegible] 24	.34251 5
491	21477	16109	31685	79749	2216	355[illegible]
492	2228[illegible]	16712	329[illegible]	770[illegible]	2296[illegible]	36795
493	23112	1[illegible]335	[illegible]	74428	238[illegible]	38129
494	2397[illegible]	179[illegible]	35149	71889	24655	395[illegible]
495	.24857 2	.1864[illegible] 0	.36376 22	.69473 -4	.25545 24	.4092[illegible] 5
496	257[illegible]	1933	3763[illegible]	67133	2645[illegible]	42389
497	2[illegible]718	20[illegible]	38967	64889	2747[illegible]	43899
498	27694	20772	4028[illegible]	62729	28374	45467
499	287[illegible]	21527	416[illegible]	60[illegible]	29376	47067
500	.2974 2	.2[illegible] 0	.43[illegible]96 22	.5864[illegible] -4	.30[illegible] 24	.48718 5
501	3[illegible]81[illegible]	23111	44551	56718	31475	50425
502	31919	[illegible]	4605[illegible]	548[illegible]	325[illegible]	5218[illegible]
503	33[illegible]	247[illegible]	47[illegible]	[illegible]	33[illegible]	53996
504	34[illegible]	2568	492[illegible]	51349	3487	55864
505	.35453 2	.26[illegible] 0	.[illegible]854 22	.49489 -4	.36[illegible] 24	.57788 5
506	367[illegible]	[illegible]	52546	48088	373[illegible]	597[illegible]
507	37996	28445	54287	46548	38581	61812
508	3932[illegible]	2949[illegible]	56078	4509[illegible]	39895	63914
509	40695	3052[illegible]	5792[illegible]	43636	41247	66075
510	.42114 2	.3158[illegible] 0	.598[illegible] 22	.4227[illegible] -4	.42638 24	.683[illegible] 5
511	43571	32680	61765	409[illegible]1	440[illegible]	7060[illegible]
512	45073	338[illegible]	63768	39625	45544	72965
513	46620	34967	65824	38385	47062	75396
514	48213	36162	67947	37189	48623	77897
515	.49855 2	.37394 0	.70123 22	.36034 -4	.50230 24	.80471 5
516	51547	3866	72361	3492	51882	83119
517	53286	39967	74667	33845	53583	85847
518	55078	41311	77022	32807	55331	88644
519	56923	42695	79449	31806	57130	91526
520	.58824 2	.44121 0	.81941 22	.30837 -4	.58976 24	.94488 5
521	60777	45586	845[illegible]	2990[illegible]	6088	97535
522	62789	47095	87132	2900[illegible]	62835	10067 6
523	64859	48647	89832	28129	64845	10389
524	66989	50245	92605	27286	66910	10719
525	.69179 2	.5188[illegible] 0	.9545[illegible] 22	.26473 -4	.69033 24	.11059 6
526	71433	53578	98373	25686	71213	11409
527	73750	55316	10137 23	24926	73454	11768
528	76134	57104	10445	24192	75756	12137
529	78585	58942	10761	23482	78121	12515
530	.81124 2	.6083[illegible] 0	.11085 23	.22795 -4	.8055[illegible] 24	.12905 6
531	83694	62775	11417	22132	83044	13304
532	86357	64772	11758	2149	85605	13714
533	89[illegible]93	668[illegible]	1210[illegible]	2086[illegible]	88235	14136
534	919[illegible]	68934	24[illegible]	20268	90934	14568
535	.947[illegible]	[illegible]	.[illegible]28[illegible] 23	.1968[illegible] -4	.937[illegible] 24	.15012 6
536	[illegible]	[illegible]	[illegible]	19[illegible]	96[illegible]	15468
537	[illegible]	756[illegible]	[illegible]595	1858[illegible]	99469	15936
538	1[illegible]	[illegible]	13[illegible]	18055	10247 25	164[illegible]
539	1[illegible]26	[illegible]	[illegible]	17545	10554	[illegible]
540	.11[illegible] 3	.828[illegible] 0	.148[illegible] 23	.17[illegible]2 -4	[illegible] 25	.17[illegible] 6
541	[illegible]386	854[illegible]	15266	16574	11193	[illegible]
542	[illegible]1735	88[illegible]	15683	16[illegible]	[illegible]1525	18463
543	12[illegible]	9[illegible]	[illegible]613	15[illegible]	11[illegible]	1[illegible]
544	12459	93452	1655[illegible]	15231	12214	19567
545	.12836 3	.962[illegible] 0	.[illegible]706 23	.148[illegible] -4	.12572 25	.20141 6
546	13223	99176	17543	14404	12939	20729
547	1362	10216 1	18036	140[illegible]	13315	21331
548	14027	1052[illegible]	18542	13628	13701	21949
549	14440	10834	19060	13258	14096	22582
550	.14874 3	.11156 1	.19589 23	.12899 -4	.14501 25	.23231 5

[a]Read as 0.43[illegible]

TABLE XV 2. - [illegible] SODIUM VAPOR [illegible] RELATIONS

Temperature, °K	Sodium vapor pressure, N/sq m	Sodium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Condensation rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m	Temperature, °K	Sodium vapor pressure, N/sq m	Sodium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Condensation rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m
550	.14874 3	.11156 1	.9589 23	.12899 -4	.14501 25	.23231 6	700	.45265 4	.33951 2	.46841 24	.53945 -6	.39118 26	.62669 7
551	15313	11486	20132	12551	14916	23896	701	46074	34558	47611	53073	39788	63743
552	15764	11824	20687	12214	15341	24578	702	46895	35174	48390	52218	40469	64833
553	16227	12171	21256	11888	15777	25276	703	47728	35799	49179	51138	41158	65938
554	16701	12527	21837	11571	16224	25991	704	48576	36433	49979	50558	41857	67058
555	.17188 3	.12892 1	.22433 23	.11264 -4	.16681 25	.26724 6	705	.49431 4	.37076 2	.50790 24	.49751 -6	.42566 26	.68194 7
556	17686	13266	23042	10966	17150	27475	706	50302	37729	51611	48959	43285	69345
557	18197	13649	23666	10677	17629	28243	707	51185	38391	52443	48183	44014	70513
558	18721	14042	24303	10397	18121	29031	708	52081	39063	53285	47421	44752	71696
559	19258	14445	24956	10125	18624	29837	709	52989	39745	54139	46674	45501	72896
560	.19809 3	.14858 1	.25623 23	.98615 -5	.19139 25	.30662 6	710	.53911 4	.40436 2	.55003 24	.45940 -6	.46260 26	.74112 7
561	20373	15281	26306	96057	19666	31507	711	54847	41138	55879	45222	47030	75345
562	20951	15714	27004	93573	20206	32372	712	55796	41849	56765	44514	47810	76594
563	21543	16158	27718	91163	20759	33257	713	56758	42571	57663	43821	48600	77861
564	22149	16613	28448	88824	21325	34163	714	57734	43303	58573	43141	49401	79144
565	.22771 3	.17079 1	.29194 23	.86554 -5	.21903 25	.35090 6	715	.58724 4	.44046 2	.59494 24	.42472 -6	.50213 26	.80445 7
566	23407	17557	29957	84349	22496	36039	716	59728	44799	60426	41817	51036	81763
567	24059	18045	30737	82209	23102	37010	717	60746	45562	61371	41173	51870	83099
568	24727	18546	31534	80131	23722	38004	718	61778	46337	62327	40542	52715	84452
569	25410	19059	32349	78113	24356	39020	719	62825	47122	63295	39922	53571	85824
570	.26110 3	.19584 1	.33181 23	.76153 -5	.25005 25	.40059 6	720	.63887 4	.47918 2	.64275 24	.39313 -6	.54438 26	.87213 7
571	26826	20121	34032	74249	25669	41123	721	64963	48726	65267	38715	55317	88621
572	27560	20671	34901	72399	26347	42210	722	66055	49544	66272	38128	56207	90047
573	28311	21234	35790	70602	27041	43322	723	67161	50374	67289	37552	57109	91492
574	29079	21811	36697	68857	27751	44459	724	68283	51216	68318	36986	58023	92956
575	.29865 3	.22401 1	.37624 23	.67160 -5	.28477 25	.45622 6	725	.69420 4	.52069 2	.69360 24	.36431 -6	.58949 26	.94439 7
576	30670	23004	38571	65512	29219	46810	726	70573	52933	70415	35885	59886	95942
577	31494	23622	39538	63910	29977	48025	727	71742	53810	71483	35349	60836	97463
578	32336	24254	40525	62353	30753	49267	728	72926	54698	72563	34823	61798	99004
579	33198	24900	41533	60839	31545	50537	729	74127	55599	73656	34306	62772	10057 8
580	.34080 3	.25561 1	.42563 23	.59367 -5	.32355 25	.51834 6	730	.75344 4	.56511 2	.74763 24	.33798 -6	.63759 26	.10215 8
581	34982	26238	43614	57936	33182	53160	731	76577	57437	75883	33299	64759	10375
582	35904	26930	44687	56545	34028	54515	732	77827	58374	77016	32809	65771	10537
583	36847	27637	45783	55192	34892	559	733	79094	59324	78163	32328	66795	10701
584	37812	28361	46901	53876	35775	57314	734	80377	60287	79323	31855	67833	10567
585	.38798 3	.29101 1	.48042 23	.52596 -5	.36677 25	.58759 6	735	.81678 4	.61263 2	.80497 24	.31390 -6	.68884 26	.11036 8
586	39807	29857	49207	51351	37598	60235	736	82996	62251	81685	30934	69948	11206
587	40838	30631	50395	50140	38539	61742	737	84332	63253	82887	30485	71025	11379
588	41892	31421	51608	48962	39500	63282	738	85685	64268	84103	30045	72116	11553
589	42969	32229	52845	47816	40482	64854	739	87056	65296	85333	29612	73220	11730
590	.44071 3	.33055 1	.54108 23	.46700 -5	.41484 25	.66460 6	740	.88445 4	.66338 2	.86577 24	.29186 -6	.74338 26	.11909 8
591	45196	33899	55396	45614	42507	68099	741	89852	67393	87836	28768	75470	12091
592	46346	34762	56709	44558	43552	69773	742	91277	68462	89109	28357	76616	12274
593	47521	35643	58049	43529	44619	71482	743	92721	69546	90397	27953	77775	12460
594	48722	36544	59416	42528	45708	73227	744	94184	70643	91700	27556	78949	12648
595	.49949 3	.37464 1	.60810 23	.41553 -5	.46819 25	.75007 6	745	.95666 4	.71754 2	.93017 24	.27165 -6	.80137 26	.12838 8
596	51202	38404	62231	40604	47954	76825	746	97166	72883	94350	26782	81340	13031
597	52482	39364	63680	39680	49112	78680	747	98686	74020	95697	26404	82557	13226
598	53790	40345	65157	38781	50293	80573	748	.10023 5	75174	97060	26034	83789	13423
599	55126	41347	66664	37906	51499	82504	749	10178	76344	98438	25669	85035	13623
600	.56490 3	.42370 1	.68199 23	.37051 -5	.52729 25	.84475 6	750	.10336 5	.77528 2	.99832 24	.25311 -6	.86217 26	.13825 8
601	57882	43415	69765	[illegible]	53986	86486	751	10496	78727	.10124 25	24959	87513	14030
602	59305	44481	71360	35410	55265	88537	752	10658	79942	10267	24612	88865	14237
603	60757	45571	72986	34621	56571	90630	753	10822	81171	10411	24271	90172	14446
604	62239	46683	74644	33852	57903	92765	754	10988	82417	10556	23937	91495	14658
605	.63753 3	.47819 1	.76332 23	.33103 -5	.59262 25	.94942 6	755	.11156 5	.83677 2	.10704 25	.23607 -6	.92833 26	.14872 8
606	65298	48977	78053	32373	60649	97163	756	11326	84954	10853	23283	94187	15089
607	66875	50159	79806	31662	62062	99427	757	11499	86246	11003	22964	95556	15309
608	68484	51367	81593	30969	63503	.10174 7	758	11673	87555	11155	22651	96942	15531
609	70127	52599	83413	30293	64973	10409	759	11850	88879	11309	22343	98344	15757
610	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	760	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
611	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	761	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
612	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11163	762	[illegible]	[illegible]	[illegible]	21449	[illegible]	[illegible]
613	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	11398	763	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
614	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	764	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
615	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	765	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
616	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	766	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
617	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	767	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
618	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	768	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
619	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	769	[illegible]	[illegible]	[illegible]	[illegible]	11128	[illegible]
620	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	770	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
621	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	3615	771	4145	[illegible]	4269	[illegible]	[illegible]	8660
622	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	13917	772	4351	[illegible]	3466	18765	11810	18920
623	[illegible]	[illegible]	[illegible]	22627	[illegible]	4224	773	4560	13721	[illegible]	18519	11974	19183
624	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	4536	774	4772	[illegible]	3826	8278	[illegible]	3449
625	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	.14854 7	775	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
626	[illegible]	[illegible]	[illegible]	[illegible]	4745	15179	776	[illegible]	[illegible]	[illegible]	[illegible]	12433	9990
627	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5509	777	5621	1566	[illegible]	[illegible]	12649	[illegible]
628	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	5845	778	[illegible]	[illegible]	[illegible]	[illegible]	12822	[illegible]
629	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	779	[illegible]	[illegible]	[illegible]	[illegible]	12998	[illegible]
630	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	780	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
631	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	781	[illegible]	1243	[illegible]	6691	13356	21326
632	[illegible]	[illegible]	[illegible]	8619	[illegible]	17252	782	6554	12417	[illegible]	[illegible]	13535	[illegible]
633	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	783	[illegible]	[illegible]	5532	[illegible]	13718	[illegible]
634	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	784	[illegible]	[illegible]	[illegible]	6062	[illegible]	[illegible]
635	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	785	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
636	[illegible]	[illegible]	[illegible]	[illegible]	1712	[illegible]	786	[illegible]	13133	[illegible]	[illegible]	14279	[illegible]
637	[illegible]	[illegible]	[illegible]	6834	[illegible]	[illegible]	787	[illegible]	[illegible]	6342	15467	[illegible]	[illegible]
638	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	788	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
639	[illegible]	336	[illegible]	[illegible]	2464	[illegible]	789	18254	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
640	[illegible]	[illegible]	[illegible]	[illegible]	.12723 26	[illegible]	790	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
641	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	791	18765	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
642	[illegible]	[illegible]	[illegible]	[illegible]	3256	[illegible]	792	[illegible]	[illegible]	[illegible]	14522	[illegible]	24762
643	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	21675	793	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
644	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	794	9552	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
645	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	795	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
646	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	796	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
647	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	797	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
648	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	798	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
649	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	799	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
650	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	800	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
651	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	801	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
652	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	802	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
653	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	803	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
654	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	804	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
655	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	805	.22672 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
656	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	806	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
657	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	807	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
658	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	23207	808	23588	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
659	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	809	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
660	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	810	.24216 5	[illegible]	[illegible]	[illegible]	[illegible]	.31167 8
661	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	811	24535	[illegible]	[illegible]	[illegible]	[illegible]	31558
662	[illegible]	[illegible]	4248	[illegible]	[illegible]	[illegible]	812	24857	[illegible]	22135	[illegible]	9945	31959
663	[illegible]	6955	[illegible]	[illegible]	[illegible]	32158	813	25182	18888	22437	[illegible]	[illegible]	32351
664	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	814	25511	9135	[illegible]	[illegible]	[illegible]	[illegible]
665	[illegible]3518 4	[illegible]	.25617 24	[illegible]	.21852 26	.33406 7	815	.25844 5	.19384 3	[illegible]	[illegible]	[illegible]	.33160 8
666	23986	[illegible]	[illegible]	[illegible]	21251	34045	816	26180	[illegible]	[illegible]	[illegible]	20954	33570
667	24461	18347	[illegible]	[illegible]	21656	34694	817	26519	19891	23512	[illegible]	21213	33985
668	24945	18710	[illegible]	93414	22067	35353	818	[illegible]	[illegible]	[illegible]	[illegible]	21474	34403
669	25436	[illegible]	[illegible]	91746	22485	36023	819	[illegible]	[illegible]	[illegible]	[illegible]	21738	34825
670	.25936 4	.19453 2	.28041 24	.90113 -6	.22910 26	.36703 7	820	.27558 5	.20670 3	.24364 25	.10380 -6	.22006 27	.35252 8
671	26444	19834	28567	88514	23341	37396	821	27912	20935	24627	10261	22273	35682
672	26960	20222	29061	86968	23779	38096	822	28269	21203	24912	10143	22544	36117
673	27485	20615	29583	85415	24224	38808	823	28630	21474	25199	10028	22818	36556
674	28018	21015	30112	83914	24676	39532	824	28994	21747	25489	.99136 -7	23094	36998
675	.28560 4	.21422 2	.30649 24	.82444 -6	.25134 26	.40267 7	825	.29362 5	.22023 3	.25781 25	.98031 -7	.23373 27	.37446 8
676	29111	21835	31194	81004	25600	41013	826	29734	22302	26076	96903	23655	37897
677	29670	22254	31747	79594	26073	41770	827	30110	22584	26374	95810	23940	38353
678	30239	22681	32307	78212	26553	42539	828	30489	22869	26674	94732	24227	38812
679	30817	23114	32876	76859	27040	43320	829	30873	23156	26976	93665	24516	39277
680	.31404 4	.23554 2	.33453 24	.75534 -6	.27535 26	.44113 7	830	.31260 5	.23446 3	.27282 25	.92620 -7	.24809 27	.39745 8
681	32000	24002	34038	74236	28037	44917	831	31651	23740	27590	91586	25104	40218
682	32606	24456	34632	72963	28547	45734	832	32046	24036	27900	90567	25402	40695
683	33221	24917	35233	71717	29064	46563	833	32444	24335	28214	89561	25702	41177
684	33846	25386	35844	70496	29589	47404	834	32847	24637	28530	88569	26006	41663
685	.34481 4	.25862 2	.36463 24	.69299 -6	.30122 26	.48258 7	835	.33254 5	.24942 3	.28849 25	.87591 -7	.26312 27	.42154 8
686	35126	26346	37090	68126	30663	49124	836	33665	25250	29170	86626	26621	42649
687	35780	26837	37727	66977	31212	50004	837	34079	25561	29494	85674	26933	43148
688	36445	27336	38372	65851	31769	50896	838	34498	25875	29820	84735	27248	43652
689	37121	27842	39027	64747	32334	51801	839	34921	26192	30150	83809	27565	44161
690	.37806 4	.28357 2	.39690 24	.63665 -6	.32908 26	.52720 7	840	.35348 5	.26513 3	.30482 25	.82895 -7	.27886 27	.44674 8
691	38503	28879	40362	62604	33490	53652	841	35779	26836	30817	81994	28209	45192
692	39210	29409	41044	61564	34080	54598	842	36214	27162	31155	81105	28535	45715
693	39927	29947	41735	60545	34679	55557	843	36654	27492	31496	80228	28864	46242
694	40656	30494	42435	59545	35286	56530	844	37097	27825	31839	79362	29196	46774
695	.41396 4	.31049 2	.43145 24	.58566 -6	.35902 26	.57518 7	845	.37545 5	.28161 3	.32186 25	.78508 -7	.29531 27	.47311 8
696	42147	31612	43865	57605	36527	58519	846	37998	28500	32535	77666	29870	47853
697	42909	32184	44594	56663	37161	59535	847	38454	28843	32887	76834	30211	48399
698	43683	32764	45333	55739	37804	60565	848	38915	29188	33242	76014	30555	48950
699	44468	33353	46082	54833	38456	61609	849	39380	29537	33600	75204	30902	49506
700	.45265 4	.33951 2	.46841 24	.53945 -6	.39118 26	.62669 7	850	.39850 5	.29889 3	.33960 25	.74406 -7	.31252 27	.50067 8

TABLE XV - CESIUM VAPOR PRESSURE RELATIONS (BASED ON "BEST FIT" OF VAPOR PRESSURE DATA)

Temperature, °K	Cesium vapor pressure, N/sq m	Cesium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Evaporation rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m
250	[a].61827 -6	.46368 -8	.17912 15	.14107 4	.89396 16	.14322 -2
251	71237	53431	20559	12291	10281 17	16470
252	81995	61500	23569	10721	11810	18920
253	94272	70709	26991	93616 3	13551	21710
254	10827 -5	81206	30877	81077	15532	24884
255	.12421 -5	.93162 -8	.35283 15	.71617 3	.17784 17	.28491 -2
256	14234	10676 -7	40275	6274	20340	32586
257	16294	12221	45925	55021	23239	37230
258	18632	13975	52313	48302	26523	42491
259	21285	15965	59529	42447	30239	48445
260	.24289 -5	.18218 -7	.67671 15	.37340 3	.34442 17	.55178 -2
261	27690	20769	76857	3288	39188	62782
262	31535	23652	87186	28982	44544	71363
263	35877	26910	98817	25571	50587	81036
264	40778	30586	11189 16	22563	57383	91931
265	.46303 -5	.34730 -7	.12657 16	.19964 3	.65035 17	.10419 -1
266	52527	39398	14304	17665	73637	11797
267	59529	44650	16150	15646	83298	13345
268	67402	50555	18218	1387	94138	15082
269	76246	57188	20532	12307	10629 18	17028
270	.86170 -5	.64632 -7	.23118 16	.10930 3	.11990 18	.19209 -1
271	97297	72978	26007	97155 2	13514	21650
272	10976 -4	82327	29231	86443	15217	24378
273	12371	92792	32826	76976	17120	27427
274	13932	10450 -6	36832	68605	19244	30830
275	.15675 -4	.11757 -6	.41290 16	.61197 2	.21612 18	.34625 -1
276	17622	13217	46249	54636	24252	38853
277	19793	14846	51760	48819	27191	43562
278	22213	16661	57880	43657	30461	488
279	24908	18682	64670	39073	34095	54623
280	.27707 -4	.20932 -6	.72198 16	.34999 2	.38133 18	.61091 -1
281	31242	23433	80537	31375	42613	68269
282	34947	26212	89769	28148	47582	76230
283	39060	29297	99980	25273	53089	85051
284	43623	32720	11127 17	2271	59186	94819
285	.48681 -4	.36513 -6	.12373 17	.20422 2	.65932 18	.10563 0
286	54283	40715	13749	18379	73391	11758
287	60484	45366	15266	16552	81632	13078
288	67342	50510	16938	14918	90729	14535
289	74922	56195	18779	13454	10077 19	16143
290	.83292 -4	.62473 -6	.20805 17	.12145 2	.11183 19	.17916 0
291	92540	69407	23033	1097	12402	19869
292	10272 -3	77043	25482	99163 1	13744	22019
293	11395	85465	28170	89698	15220	24384
294	12631	94739	31121	81194	16843	26984
295	.13992 -3	.10495 -5	.34357 17	.73546 1	.18626 19	.29840 0
296	15488	11617	37913	66665	20583	32976
297	17133	12851	41788	60469	22731	36417
298	18940	14206	46039	54885	25086	40189
299	20923	15693	50689	4985	27666	44322
300	.23098 -3	.17325 -5	.55772 17	.45307 1	.30491 19	.48848 0
301	25482	19113	61324	41205	33582	53801
302	28094	21072	67396	37498	36963	59217
303	30954	23217	74000	34146	40658	65137
304	34082	25563	81212	31114	44694	71603
305	.37503 -3	.28129 -5	.89071 17	.28369 1	.49100 19	.78660 0
306	41242	30933	97629	25882	53906	86360
307	45324	33996	10694 18	23628	59145	94755
308	49781	37338	11708	21583	64855	10390 1
309	54641	40984	12809	19727	71072	11386
310	.59940 -3	.44958 -5	.14006 18	.18041 1	.77839 19	.12470 1
311	65714	49288	15304	16509	85195	13649
312	72000	54004	16716	15116	93200	14931
313	78842	59135	18244	13848	10189 20	16324
314	86293	64727	19968	12695	11133	17836
315	.94372 -3	.70784 -5	.21702 18	.11643 1	.12158 20	.19477 1
316	10316 -2	77376	23648	10685	13269	21257
317	11270	84533	25754	98115 0	14473	23187
318	12306	92301	28032	90141	15778	25278
319	13429	10073 -4	30495	82861	17192	27542
320	.14647 -2	.10986 -4	.33156 18	.7621	.18721 20	.29993 1
321	15967	11976	36031	7013	20376	32644
322	17396	13048	39134	6457	22165	35510
323	18942	14208	42481	59481	24099	38607
324	20616	15463	46091	54823	26187	41953
325	.22425 -2	.16820 -4	.49982 18	.50555 0	.28441 20	.45565 1
326	24381	18287	54174	46643	30874	49462
327	26493	19871	58687	43056	33497	53665
328	28773	21581	63545	39765	36325	58196
329	31234	23427	68770	36743	39372	63077
330	.33889 -2	.25418 -4	.74389 18	.33968 0	.42654 20	.68334 1
331	36751	27565	80427	31418	46186	73992
332	39834	29878	86913	29073	49986	80080
333	43156	32369	93877	26916	54072	86627
334	46732	35051	10135 19	24931	58465	93665
335	.50580 -2	.37937 -4	.10937 19	.23104 0	.63185 20	.10123 2
336	54718	41041	11797	2142	68253	10935
337	59168	44379	12718	19868	73693	11806
338	63949	47965	13705	18437	79530	12741
339	69085	51817	14762	17117	85790	13744
340	.74598 -2	.55953 -4	.15893 19	.15899 0	.92501 20	.14819 2
341	80510	60391	17104	14774	99692	15971
342	86863	65152	18398	13734	10739 21	17205
343	93669	70257	19782	12774	11564	18526
344	10096 -1	75728	21260	11985	12446	19940
345	.10878 -1	.81589 -4	.22840 19	.11077 0	.13390 21	.21452 2
346	11715	87865	24526	10317	14420	23069
347	12611	94586	26325	95986 -1	15478	24797
348	13569	10177 -3	28240	89457	1663	26644
349	14594	10946	3029	83418	17862	28614
350	.15697 -1	.11769 -3	.32473 19	.77813 -1	.19176 21	.30721 2
351	16862	12647	34798	72614	20578	32963
352	18113	13584	37274	6779	22074	35367
353	19445	14584	3991	63317	23668	37918
354	20875	15658	42716	59154	25368	40641
355	.22397 -1	.16799 -3	.45711 19	.55241 -1	.27179 21	.43549 2
356	24020	18016	48876	5170	29108	46633
357	25751	19314	52250	48361	31161	49922
358	27595	20698	55836	45255	33347	53423
359	29560	22172	59646	42364	35671	57148
360	.31653 -1	.23741 -3	.63691 19	.39674 -1	.38144 21	.61108 2
361	33881	25412	67985	37168	40772	65319
362	36252	27191	72541	34833	43565	69793
363	38774	29082	77375	32657	46531	74546
364	41456	31094	82500	30628	49682	79593
365	.44308 -1	.33233 -3	.87933 19	.28736 -1	.53026 21	.84951 2
366	47338	35506	93690	2697	56575	90637
367	50557	37920	99788	25322	60340	96668
368	53975	40484	10625 20	23783	64332	10306
369	57604	43206	11308	22345	68564	10984
370	.61455 -1	.46094 -3	.12031 20	.21002 -1	.73048 21	.11703 3
371	65540	49158	12797	19746	77799	12464
372	69872	52408	13606	18577	82830	13270
373	74465	55852	14461	17473	88157	14123
374	79332	59503	15365	16445	93793	15026
375	.84489 -1	.63371 -3	.16320 20	.15483 -1	.99757 21	.15982 3
376	89950	67467	17329	14581	10606 22	16992
377	95733	71804	18394	13737	11273	18060
378	10185 0	76395	19518	12946	11978	19189
379	10833	81257	20705	12204	12723	20383
380	.11518 0	.86389 -3	.21956 20	.11509 -1	.13509 22	.21643 3
381	12242	91821	23275	10856	14340	22973
382	13008	97564	24666	10244	15217	24378
383	13817	10363 -2	26132	96696	16142	25861
384	14671	11004	27676	91301	17118	27425
385	.15574 0	.11681 -2	.29303 20	.86233 -2	.18148 22	.29074 3
386	16527	12396	31015	81471	19234	30813
387	17533	13151	32818	76996	20378	32647
388	18594	13947	34715	72788	21584	34578
389	19714	14787	36711	68831	22854	36613
390	.20895 0	.15672 -2	.38809 20	.65109 -2	.24192 22	.38756 3
391	22140	16606	41016	61606	25600	41013
392	23452	17590	43336	58308	27082	43388
393	24834	18627	45774	55203	28642	45886
394	26290	19719	48334	52278	30283	48515
395	.27823 0	.20869 -2	.51024 20	.49523 -2	.32009 22	.51280 3
396	29437	22080	53848	46926	33823	54186
397	31136	23354	56812	44477	35730	57241
398	32924	24695	59923	42168	37734	60451
399	34804	26105	63186	3999	39839	63824
400	.36782 0	.27588 -2	.66509 20	.37935 -2	.42049 22	.67366 3

Temperature, °K	Cesium vapor pressure, N/sq m	Cesium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Evaporation rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m
400	.36782 0	.27588 -2	.66609 20	.37935 -2	.42049 22	.67366 3
401	38861	29147	70199	35996	44371	71094
402	41046	30786	73961	34164	46807	74988
403	43342	32508	77905	32435	49364	79084
404	45754	34317	82036	30801	52047	83382
405	.48287 0	.36217 -2	.86364 20	.29255 -2	.54860 22	.87889 3
406	50946	38212	90897	27799	57811	92616
407	53738	40306	95643	2642	60904	97571
408	56668	42504	10061 21	25115	64145	10276 4
409	59742	44809	10581	23881	67542	10821
410	.62966 0	.47225 -2	.11124 21	.22716 -2	.71100 22	.11391 4
411	66347	49764	11693	21609	74827	11988
412	69892	52422	12288	20563	78729	12613
413	73607	55209	12910	19573	82813	13267
414	77500	58129	13560	18634	87088	13952
415	.81578 0	.61188 -2	.14237 21	.17746 -2	.91560 22	.14669 4
416	85850	64392	14949	16903	96239	15418
417	90323	67746	15690	16105	10113 23	16202
418	95005	71259	16464	15348	10625	17021
419	99906	74935	17272	1463	11159	17879
420	.10503 1	.78781 -2	.18115 21	.13949 -2	.11718 23	.18773 4
421	11040	82806	18995	13302	12302	19709
422	11601	87014	19914	12689	12912	20686
423	12188	91415	20871	12107	13549	21707
424	12801	96016	21870	11554	14214	22772
425	.13442 1	.10082 -1	.22911 21	.11029 -2	.14909 23	.23884 4
426	14112	10585	23997	1053	15633	25046
427	14812	11110	25128	10056	16389	26257
428	15543	11658	26307	96053 -3	17175	27521
429	16307	12231	27534	9177	18001	28839
430	.17104 1	.12829 -1	.28813 21	.87697 -3	.18859 23	.30213 4
431	17936	13453	30145	83923	19754	31646
432	18804	14104	31531	80138	20686	33147
433	19710	14784	32974	76631	21658	34697
434	20656	15493	34476	73294	22670	36318
435	.21641 1	.16232 -1	.36038 21	.70117 -3	.23724 23	.38008 4
436	22669	17003	37663	67091	24823	39767
437	23741	17807	39353	6421	25966	416
438	24858	18644	41110	61464	27157	43507
439	26022	19517	42937	5885	28396	45492
440	.27234 1	.20427 -1	.44836 21	.56357 -3	.29686 23	.47558 4
441	28498	21375	46805	53982	31027	49708
442	29813	22361	48867	51716	32423	51944
443	31183	23389	50990	49556	33875	54269
444	32609	24459	53207	47494	35384	56688
445	.34094 1	.25572 -1	.55499 21	.45553 -3	.36957 23	.59202 4
446	35639	26731	57883	43654	38585	61815
447	37246	27937	60359	41864	40287	64531
448	38918	29191	62928	40151	42041	67351
449	40658	30495	65593	38523	43871	70284
450	.42466 1	.31852 -1	.68351 21	.36966 -3	.45771 23	.73329 4
451	44346	33262	71227	35476	47745	76490
452	46301	34728	74202	34054	49794	79777
453	48332	36252	77283	32694	51922	83181
454	50443	37835	80484	31395	54125	86715
455	.52636 1	.39481 -1	.83771 21	.30154 -3	.56421 23	.90383 4
456	54914	41188	87234	28966	58798	94197
457	5728	42957	90791	2783	61264	98149
458	59737	44804	94487	26745	63821	10225 5
459	62287	46718	98299	25706	66473	10649
460	.64934 1	.48706 -1	.10225 22	.24721 -3	.69223 23	.11090 5
461	67682	50764	10634	23776	72074	11547
462	70537	52903	11058	22861	75028	12020
463	73490	5512	11498	21977	78096	12510
464	76558	57422	11953	21147	81266	13019
465	.79740 1	.59808 -1	.12422 22	.20347 -3	.84549 23	.13546 5
466	83039	62283	12908	19576	87952	14091
467	86457	64845	13411	18847	91477	14655
468	90015	67518	13931	18138	95126	15240
469	93680	70265	14469	17464	98905	15846
470	.97488 1	.73121 -1	.15025 22	.16818 -3	.10281 24	.16471 5
471	10143 2	76080	15600	16198	10686	17121
472	10552	79145	16194	15603	11105	17791
473	10975	82321	16808	15033	11538	18485
474	11414	85609	17443	14487	11987	19203
475	.11868 2	.89013 -1	.18098 22	.13962 -3	.12450 24	.19946 5
476	12338	92538	18775	13458	12930	20714
477	12824	96186	19475	12975	13425	21508
478	13327	99962	20197	12511	13936	22329
479	13848	10387 0	20942	12066	14467	23177
480	.14387 2	.10791 0	.21711 22	.11636 -3	.15015 24	.24054 5
481	14945	11209	22504	11227	15580	24960
482	15521	11642	23326	10833	16164	25896
483	16118	12089	24172	10454	16768	26863
484	16734	12551	25048	10089	17392	27862
485	.17371 2	.13029 0	.25946 22	.97371 -4	.18035 24	.28894 5
486	18030	13524	26874	94024	18700	29958
487	18711	14034	27832	9079	19386	31058
488	19415	14562	28819	87679	20094	32192
489	20142	15108	29837	84688	20826	33365
490	.20891 2	.15671 0	.30887 22	.81810 -4	.21581 24	.34573 5
491	21669	16253	31968	79042	22359	35821
492	22470	16854	33081	76379	23162	37107
493	23298	17474	34231	73814	2399	38435
494	24152	18115	35411	71349	24845	39804
495	.25034 2	.18777 0	.36634 22	.68975 -4	.25727 24	.41216 5
496	25944	1946	378	66689	26635	42671
497	26884	20164	39183	64488	27572	44172
498	27853	20891	40514	62369	28538	45719
499	28853	21642	41885	60325	29533	47313
500	.29885 2	.22415 0	[illegible]	[illegible]	[illegible]	[illegible]
501	30951	23214	4474	[illegible]	[illegible]	[illegible]
502	32048	24037	46244	5464	32704	52394
503	33180	24886	47783	5288	33822	54191
504	34347	25762	49365	51186	34981	56041
505	.3555 2	.26665 0	.50996 22	.49551 -4	.36171 24	.57948 5
506	3679	27576	52662	47974	37376	599
507	38069	28554	54352	46456	38657	61931
508	39387	29542	56163	44951	39956	64011
509	40745	30561	57985	43577	41292	66153
510	.42143 2	.31610 0	.59858 22	.42214 -4	.42668 24	.68357 5
511	43584	32690	61784	40898	44084	70624
512	45069	33804	63763	39629	45540	72958
513	46597	34950	65797	38404	47039	75357
514	48171	36131	67887	3722	48580	77826
515	.49792 2	.37346 0	.70035 22	.36080 -4	.50166 24	.80370 5
516	5146	38598	72242	34978	51797	82982
517	53178	39886	74509	33917	53474	85669
518	54946	41212	76837	32886	55199	88432
519	56765	42577	79228	31897	56971	91272
520	.58637 2	.43981 0	.81686 22	.30936 -4	.58794 24	.94191 5
521	60564	45426	84208	30004	60667	97192
522	62545	46912	86794	29117	62592	10028 6
523	64584	48441	89451	28264	64570	10344
524	66680	50013	92178	27419	66602	10670
525	.68836 2	.51631 0	.94978 22	.26605 -4	.68690 24	.11005 6
526	71053	53293	97857	25824	70835	11348
527	73333	55003	10080 23	25068	73038	11701
528	75676	56761	10382	24338	75301	12064
529	78085	58569	10692	23632	77624	12436
530	.80561 2	.60425 0	.11011 23	.22949 -4	.80010 24	.12818 6
531	83105	62333	11337	22288	82459	13210
532	85720	64294	11672	21649	84974	13613
533	88407	66309	12015	21031	87555	14027
534	91167	68379	12367	20432	90203	14451
535	.94002 2	.70506 0	.12728 23	.19853 -4	.92921 24	.14887 6
536	96914	72690	13097	19293	95711	15333
537	99905	74933	13476	1875	98573	15792
538	10298 3	77237	13865	18225	10151 25	16262
539	10613	79602	14263	17716	10452	16745
540	.10937 3	.82031 0	.14671 23	.17224 -4	.10761 25	.17240 6
541	11269	84524	15089	16746	11078	17747
542	11610	87083	15517	16284	11402	18267
543	11960	89709	15955	15837	11734	18801
544	12320	92404	16405	15403	12077	19348
545	.12689 3	.95170 0	.16865 23	.14983 -4	.12427 25	.19909 6
546	13067	98008	17336	14576	12786	20484
547	13455	10092 1	17818	14181	13154	21073
548	13853	10391	18312	13799	13531	21677
549	14262	10697	18818	13428	13917	22296
550	.14681 3	.11011 1	.19335 23	.13069 -4	.14313 25	.22930 6

[a]Read as 0.61827×10^{-6}.

TABLE XV:3. - Concluded. CESIUM VAPOR PRESSURE RELATIONS (BASED ON "BEST FIT" OF VAPOR PRESSURE DATA)

Temperature, °K	Cesium vapor pressure, N/sq m	Cesium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Impingement rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m
550	.14681 3	.11011 1	.19335 23	.13069 -4	.14311 25	.22930 6
551	15110	11333	19865	12721	14718	23579
552	15551	11664	20407	12382	15133	24245
553	16002	12003	20962	12055	15559	24926
554	16465	12350	21529	11737	15995	25625
555	.16940 3	.12706 1	.22110 23	.11429 -4	.16441 25	.26339 6
556	17427	13071	22704	11129	16898	27072
557	17925	13445	23312	10839	17366	27821
558	18436	13828	23934	10558	17845	28589
559	18960	14221	24569	10285	18336	29375
560	.19497 3	.14624 1	.25220 23	.10019 -4	.18838 25	.30179 6
561	20047	15036	25884	97620 -5	19352	31002
562	20610	15458	26564	95122	19877	31845
563	21187	15891	27259	92696	20416	32707
564	21777	16334	27970	90341	20966	33589
565	.22383 3	.16788 1	.28696 23	.88055 -5	.21530 25	.34492 6
566	23002	17253	29439	85834	22106	35416
567	23637	17729	30197	83678	22696	36361
568	24286	18216	30973	81583	23299	37327
569	24951	18715	31765	79548	23916	38316
570	.25632 3	.19225 1	.32574 23	.77572 -5	.24547 25	.39327 6
571	26329	19748	33401	75651	25193	40360
572	27042	20283	34246	73785	25853	41417
573	27772	20831	35109	71971	26527	42498
574	28519	21391	35991	70208	27217	43603
575	.29283 3	.21964 1	.36891 23	.68495 -5	.27922 25	.44733 6
576	30065	22551	37810	66830	28643	45887
577	30865	23151	38749	65211	29379	47067
578	31684	23764	39707	63636	30132	48273
579	32521	24392	40686	62106	30901	49506
580	.33377 3	.25034 1	.41685 23	.60617 -5	.31688 25	.50765 6
581	34252	25691	42705	59170	32491	52052
582	35148	26362	43746	57762	33311	53367
583	36063	27049	44809	56392	34150	54710
584	36999	27751	45892	55060	35006	56082
585	.37956 3	.28469 1	.46999 23	.53764 -5	.35881 25	.57483 6
586	38934	29202	48129	52503	36774	58914
587	39934	29952	49280	51276	37686	60375
588	40956	30719	50455	50081	38618	61868
589	42000	31502	51654	48919	39569	63392
590	.43068 3	.32303 1	.52876 23	.47788 -5	.40540 25	.64947 6
591	44158	33121	54124	46686	41531	66536
592	45273	33957	55396	45614	42543	68157
593	46411	34811	56693	44570	43576	69812
594	47574	35683	58016	43554	44631	71501
595	.48762 3	.36574 1	.59365 23	.42564 -5	.45707 25	.73225 6
596	49976	37484	60740	41601	46805	74985
597	51215	38414	62143	40662	47926	76780
598	52481	39363	63572	39748	49069	78612
599	53774	40333	65029	38857	50236	80481
600	.55094 3	.41323 1	.66514 23	.37989 -5	.51426 25	.82388 6
601	56441	42334	68028	37144	52640	84337
602	57817	43366	69571	36322	53879	86317
603	59222	44420	71143	35518	55142	88341
604	60656	45495	72745	34736	56430	90405
605	.62120 3	.46593 1	.74377 23	.33974 -5	.57744 25	.92510 6
606	63614	47713	76040	33231	59084	94656
607	65138	48857	77734	32506	60450	96845
608	66694	50024	79460	31800	61843	99077
609	68282	51216	81217	31112	63263	10135 7
610	.69901 3	.52430 1	.83008 23	.30441 -5	.64711 25	.10367 7
611	71554	53666	84832	29787	66187	10604
612	73240	54936	86689	29148	67691	10845
613	[illegible]	56224	88580	28526	69224	11090
614	76715	57540	90505	27919	70787	11340
615	.78504 3	.58882 1	.92466 23	.27327 -5	.72379 25	.11596 7
616	80330	60251	94462	26750	74002	11856
617	82191	61647	96495	26186	75655	12120
618	84089	63071	98563	25637	77340	12390
619	86025	64523	10067 24	25110	79056	12665
620	.87998 3	.66003 1	.10281 24	.24577 -5	.80805 25	.12945 7
621	90011	67512	10499	24066	82586	13231
622	92062	69051	10721	23568	84430	13521
623	94153	70619	10967	23082	86248	13817
624	96285	72218	11177	22607	88130	14119
625	.98457 3	.73848 1	.11411 24	.22144 -5	.90046 25	.14426 7
626	.10067 4	75509	11649	21691	91998	14739
627	10293	77201	11891	21249	93986	15057
628	10523	78926	12138	20818	96008	15381
629	10757	80684	12389	20397	98068	15711
630	.10996 4	.82476 1	.12643 24	.19986 -5	.10017 26	.15047 7
631	11239	84300	12902	19584	10230	16389
632	11487	86159	13166	19192	10447	16737
633	11740	88052	13434	18809	10669	17092
634	11997	89982	13707	18435	10894	17452
635	.12259 4	.91947 1	.13986 24	.18069 -5	.11123 26	.17820 7
636	12526	93949	14264	17712	11356	18193
637	12797	95987	14553	17363	11593	18573
638	13074	98062	14844	17022	11835	18960
639	13356	.10018 2	15140	16689	12080	19354
640	.13643 4	.10233 2	.15442 24	.16364 -5	.12330 26	.19754 7
641	13935	10452	15748	16046	12585	20161
642	14233	10675	16059	15735	12843	20576
643	14536	10902	16375	15431	13106	20997
644	14844	11134	16697	15134	13374	21426
645	.15158 4	.11369 2	.17023 24	.14844 -5	.13646 26	.21862 7
646	15477	11609	17355	14561	13923	22306
647	15803	11853	17692	14282	14205	22757
648	16134	12101	18035	14011	14491	23216
649	16471	12354	18383	13745	14782	23682
650	.16813 4	.12611 2	.18737 24	.13486 -5	.15078 26	.24156 7
651	17162	12872	19096	13232	15379	24638
652	17517	13138	19460	12984	15685	25129
653	17878	13409	19832	12741	15996	25627
654	18245	13685	20209	12504	16313	26134
655	.18619 4	.13965 2	.20591 24	.12271 -5	.16634 26	.26649 7
656	18999	14251	20980	12044	16961	27172
657	19386	14541	21374	11822	17293	27704
658	19780	14836	21775	11604	17630	28245
659	20180	15136	22182	11392	17973	28795
660	.20587 4	.15441 2	.22575 24	.11183 -5	.18322 26	.29353 7
661	21001	15752	23014	10980	18676	29920
662	21422	16067	23440	10780	19036	30497
663	21850	16388	23872	10585	19402	31083
664	22285	16715	24311	10394	19773	31678
665	.22727 4	.17047 2	.24756 24	.10207 -5	.20151 26	.32283 7
666	23177	17384	25209	10024	20534	32897
667	23634	17727	25667	98445 -6	20924	33521
668	24099	18076	26133	96691	21319	34155
669	24572	18430	26606	94973	21721	34799
670	.25052 4	.18791 2	.27086 24	.93291 -6	.22129 26	.35453 7
671	25541	19157	27572	91644	22544	36117
672	26037	19529	28066	90031	22965	36791
673	26541	19907	28568	88451	23392	37476
674	27054	20292	29076	86904	23826	38171
675	.27575 4	.20683 2	.29592 24	.85389 -6	.24267 26	.38878 7
676	28104	21080	30115	83905	24715	39595
677	28642	21483	30646	82451	25169	40322
678	29189	21893	31185	81027	25630	41061
679	29744	22309	31731	79632	26099	41812
680	.30308 4	.22732 2	.32286 24	.78265 -6	.26574 26	.42573 7
681	30881	23162	32848	76926	27057	43346
682	31463	23599	33418	75614	27546	44131
683	32054	24042	33996	74328	28043	44927
684	32655	24493	34582	73068	28548	45736
685	.33265 4	.24950 2	.35177 24	.71833 -6	.29060 26	.46556 7
686	33884	25415	35780	70622	29580	47388
687	34513	25887	36391	69436	30107	48233
688	35152	26366	37011	68273	30642	49090
689	35801	26853	37639	67133	31185	49960
690	.36460 4	.27347 2	.38276 24	.66016 -6	.31736 26	.50842 7
691	37129	27848	38922	64921	32294	51738
692	37808	28358	39577	63847	32861	52646
693	38497	28875	40240	62794	33437	53567
694	39197	29400	40913	61761	34020	54502
695	.39908 4	.29933 2	.41595 24	.60749 -6	.34612 26	.55450 7
696	40629	30474	42286	59756	35212	56412
697	41362	31023	42986	58783	35821	57388
698	42105	31581	43696	57828	36439	58377
699	42859	32147	44415	56891	37065	59380
700	.43625 4	.32721 2	.45144 24	.55973 -6	.37700 26	.60398 7

Temperature, °K	Cesium vapor pressure, N/sq m	Cesium vapor pressure, Torr	Vapor density, atoms/cu m	Mean free path, m	Impingement rate, atoms/(sq m)(sec)	Atom arrival rate (equivalent current), amp/sq m
700	.43625 4	.32721 2	.45144 24	.55973 -6	.37700 26	.60398 7
701	44402	33304	45882	55072	38344	61430
702	45190	33895	46631	54188	38997	62476
703	45991	34495	47389	53321	39660	63537
704	46802	35104	48157	52471	40331	64613
705	.47626 4	.35722 2	.48935 24	.51636 -6	.41012 26	.65704 7
706	48462	36349	49724	50818	41702	66809
707	49310	36985	50522	50014	42402	67931
708	50171	37631	51331	49226	43111	69067
709	51044	38285	52151	48453	43831	70219
710	.51929 4	.38950 2	.52981 24	.47694 -6	.44560 26	.71387 7
711	52828	39623	53821	46949	45299	72571
712	53739	40307	54673	46217	46047	73771
713	54663	41000	55535	45500	46807	74987
714	55600	41703	56408	44795	47576	76219
715	.56551 4	.42416 2	.57293 24	.44104 -6	.48356 26	.77469 7
716	57515	43139	58188	43425	49146	78734
717	58493	43873	59095	42759	49946	80017
718	59485	44617	60013	42105	50758	81317
719	60490	45371	60943	41463	51580	82634
720	.61510 4	.46136 2	.61884 24	.40832 -6	.52413 26	.83968 7
721	62544	46911	62837	40213	53257	85320
722	63592	47697	63801	39605	54112	86690
723	64655	48494	64778	39008	54978	88078
724	65732	49302	65766	38422	55856	89484
725	.66824 4	.50122 2	.66767 24	.37846 -6	.56745 26	.90905 7
726	67932	50952	67780	37280	57645	92351
727	69054	51794	68805	36725	58557	93812
728	70192	52647	69842	36179	59481	95292
729	71345	53512	70892	35643	60417	96791
730	.72514 4	.54389 2	.71955 24	.35117 -6	.61365 26	.98310 7
731	73699	55278	73031	34600	62324	99847
732	74899	56178	74119	34092	63296	10140 8
733	76116	57091	75220	33593	64281	10298
734	77349	58016	76335	33102	65278	10458
735	.78598 4	.58953 2	.77462 24	.32620 -6	.66287 26	.10620 8
736	79865	59902	78603	32147	67309	10783
737	81147	60865	79757	31682	68344	10949
738	82447	61840	80925	31224	69391	11117
739	83764	62827	82107	30775	70452	11287
740	.85099 4	.63828 2	.83302 24	.30334 -6	.71526 26	.11459 8
741	86451	64842	84511	29900	72613	11633
742	87820	65869	85734	29473	73714	11809
743	89207	66910	86971	29054	74828	11988
744	90613	67964	88223	28642	75956	12169
745	.92036 4	.69032 2	.89488 24	.28237 -6	.77097 26	.12351 8
746	93478	70113	90768	27838	78252	12537
747	94939	71209	92063	27447	79422	12724
748	96418	72318	93373	27062	80605	12913
749	97916	73442	94697	26684	81803	13105
750	.99433 4	.74580 2	.96036 24	.26311 -6	.83015 26	.13300 8
751	.10097 5	75732	97390	25946	84242	13496
752	10253	76899	98759	25586	85483	13695
753	10410	78081	.10014 25	25232	86739	13896
754	10570	79278	10154	24884	88010	14100
755	.10731 5	.80489 2	.10296 25	.24542 -6	.89296 26	.14306 8
756	10895	81716	10439	24206	90597	14514
757	11060	82958	10584	23875	91913	14725
758	11228	84216	10730	23549	93245	14938
759	11398	85489	10878	23229	94593	15154
760	.11570 5	.86778 2	.11027 25	.22914 -6	.95956 26	.15373 8
761	11744	88083	11178	22605	97336	15594
762	11920	89404	11331	22300	98729	15817
763	12098	90741	11486	22000	.10014 27	16043
764	12278	92094	11642	21705	10157	16272
765	.12461 5	.93464 2	.11799 25	.21415 -6	.10301 27	.16503 8
766	12646	94851	11959	21130	10447	16737
767	12833	96254	12120	20849	10595	16973
768	13022	97674	12283	20572	10744	17213
769	13214	99111	12447	20300	10895	17454
770	.13408 5	.10057 3	.12613 25	.20033 -6	.11048 27	.17699 8
771	13604	10204	12781	19770	11202	17947
772	13803	10353	12951	19510	11358	18197
773	14004	10503	13123	19255	11516	18450
774	14207	10656	13296	19004	11676	18706
775	.14413 5	.10810 3	.13471 25	.18757 -6	.11837 27	.18964 8
776	14621	10966	13649	18514	12001	19226
777	14832	11124	13827	18275	12166	19490
778	15045	11284	14008	18039	12332	19757
779	15260	11446	14190	17807	12501	20028
780	.15478 5	.11609 3	.14374 25	.17579 -6	.12672 27	.20301 8
781	15699	11775	14561	17354	12844	20577
782	15922	11942	14749	17133	13018	20856
783	16149	12112	14939	16915	13194	21138
784	16376	12283	15131	16700	13372	21424
785	.16607 5	.12456 3	.15325 25	.16489 -6	.13552 27	.21712 8
786	16841	12631	15522	16281	13734	22003
787	17077	12809	15719	16076	13918	22298
788	17316	12988	15918	15874	14104	22595
789	17558	13169	16120	15676	14292	22896
790	.17802 5	.13352 3	.16323 25	.15480 -6	.14482 27	.23200 8
791	18049	13538	16529	15287	14673	23507
792	18299	13725	16737	15098	14867	23818
793	18552	13915	16946	14911	15063	24132
794	18807	14107	17158	14727	15261	24449
795	.19066 5	.14300 3	.17372 25	.14545 -6	.15461 27	.24769 8
796	19327	14496	17588	14367	15663	25093
797	19591	14694	17806	14191	15867	25420
798	19858	14895	18026	14018	16073	25750
799	20128	15097	18249	13847	16282	26084
800	.20401 5	.15302 3	.18473 25	.13679 -6	.16492 27	.26421 8
801	20677	15509	18699	13513	16705	26762
802	20957	15718	18928	13350	16920	27106
803	21239	15930	19159	13189	17137	27454
804	21524	16144	19392	13031	17356	27805
805	.21812 5	.16360 3	.19627 25	.12874 -6	.17577 27	.28160 8
806	22103	16579	19865	12720	17801	28518
807	22398	16799	20104	12569	18027	28880
808	22675	17023	20346	12419	18255	29246
809	22996	17248	20591	12272	18486	29615
810	.23300 5	.17476 3	.20837 25	.12127 -6	.18719 27	.29988 8
811	23607	17707	21086	11984	18954	30365
812	23918	17940	21337	11843	19191	30745
813	24232	18175	21590	11704	19431	31130
814	24549	18413	21845	11567	19673	31518
815	.24869 5	.18653 3	.22104 25	.11432 -6	.19918 27	.31909 8
816	25193	18896	22364	11299	20165	32305
817	25520	19141	22627	11167	20414	32705
818	25851	19389	22892	11038	20666	33108
819	26185	19640	23160	10911	20920	33515
820	.26522 5	.19893 3	.23429 25	.10785 -6	.21177 27	.33927 8
821	26863	20149	23702	10661	21436	34342
822	27208	20407	23977	10539	21698	34761
823	27556	20668	24254	10418	21962	35185
824	27908	20932	24533	10300	22229	35612
825	.28263 5	.21199 3	.24816 25	.10182 -6	.22498 27	.36043 8
826	28622	21468	25100	10067	22770	36479
827	28984	21740	25387	99531 -7	23044	36919
828	29350	22014	25677	98408	23321	37362
829	29720	22292	25969	97301	23601	37810
830	.30094 5	.22572 3	.26264 25	.96209 -7	.23883 27	.38263 8
831	30471	22855	26562	95132	24168	38719
832	30852	23141	26861	94069	24456	39180
833	31237	23430	27164	93022	24746	39645
834	31626	23721	27469	91988	25039	40114
835	.32019 5	.24016 3	.27777 25	.90969 -7	.25335 27	.40588 8
836	32415	24313	28087	89964	25633	41066
837	32816	24614	28400	88972	25935	41549
838	33220	24917	28716	87994	26239	42036
839	33629	25223	29034	87029	26545	42527
840	.34041 5	.25533 3	.29356 25	.86077 -7	.26855 27	.43023 8
841	34458	25845	29679	85138	27167	43524
842	34878	26160	30006	84212	27482	44029
843	35303	26479	30335	83298	27801	44538
844	35732	26800	30667	82396	28121	45052
845	.36164 5	.27125 3	.31002 25	.81506 -7	.28445 27	.45571 8
846	36602	27453	31340	80628	28772	46095
847	37043	27784	31680	79762	29102	46623
848	37488	28118	32023	78907	29434	47156
849	37938	28455	32369	78063	29770	47693
850	.38392 5	.28796 3	.32718 25	.77231 -7	.30109 27	.48236 8

sistencies in the heat of condensation of the monomer at 0^{o} K. Tabulated values of the two vapor pressure relations are given in tables XV:2 and XV:3. Table XV:2 is the table recommended because of its thermodynamic self consistency. Table XV:3 is included as a concession to those who wish to emphasize vapor pressure data alone. The values given in table XV:3 are more consistent with those used in past thermionic research.

Included in the tables are related quantities of interest, namely, particle density, mean free path for electron-neutral collisions, and atom flux rate in terms of particles per square meter per second and in terms of an equivalent atom current density (atom flux divided by 6.24×10^{18}). The cross section used for the electron-neutral interaction corresponds to a reciprocal mean free path at standard conditions (P_c = 1400 cm^{-1}).

The aforementioned tables, being based on equilibrium liquid-vapor pressure measurements, must be modified for use at the conditions existent in the thermionic converter. Exact relations that describe the various properties are complex because of the many possible interactions that occur in the plasma.

A useful approximate relation is derivable from kinetic theory for use in the free molecule flow range. The result expressed in terms of a temperature multiplying factor R_T is

$$R_T = \frac{\sqrt{T_2 T_{Cs}} + \sqrt{T_1 T_{Cs}}}{2\sqrt{T_1 T_2}} \qquad \text{(XV:4)}$$

$$n(\text{interelectrode}) = R_T n_{Cs} \qquad \text{(XV:5)}$$

$$\lambda(\text{interelectrode}) = \frac{\lambda_{Cs}}{R_T} \qquad \text{(XV:6)}$$

where the subscript Cs refers to measurements of the vapor in equilibrium with the liquid. The flux equations to emitter and collector surface are unaltered since free molecular flow is assumed.

Similar correction factors for the continuum condition of constant pressure can be obtained. From the perfect gas law, there results

$$n = n_{Cs} \frac{T_{Cs}}{T_1} \qquad \text{(XV:7)}$$

$$\lambda = \frac{T_1}{T_{Cs}} \lambda_{Cs} \qquad \text{(XV:8)}$$

$$\nu = \nu_{Cs} \sqrt{\frac{T_{Cs}}{T}} \qquad \text{(XV:9)}$$

The transition between free molecule and continuum can be established by the extensions of the previous approach but are of questionable use because the unknowns related to plasma effects would probably mask these corrections. It should be noted that in many cases corrections due to poor conductance between the cesium reservoir and the interelectrode space introduce additional corrections of the nature illustrated previously.

XVI - CONCLUDING REMARKS

Thermionic converters cannot be constructed or analyzed in detail by the simple theories outlined in the preceding sections. Greater attention to the various complex interactions is required to achieve these ends; however, a very significant step can be achieved in the general understanding of the mechanisms at play in practical converters by the approaches outlined. The point of view used in each section was to emphasize or develop simple relations directly derivable from existent theory. Simplicity was emphasized because of the subsequent utility of the resulting equations, tables, or figures in treating experimental data. No new theories or analyses have been advanced. An attempt has been made to clarify, combine, compile, and suggest how to use theories and relations that are the basic foundation of thermionic converter analyses. The cesium-filled thermionic converter has been emphasized, and many of the relations were numerically evaluated for cesium because of the great promise of a cesium-filled converter. Nonetheless, the results presented are equally applicable to other systems with appropriate adjustments of physical constants.

XVII - SYMBOLS

E field strength, V/m

f fractional ionization

f function

h Planck's constant, 6.6242×10^{-34}, J-sec

I_F Schottky enhanced emission current, amp

I_O saturation emission current, amp

J current density, amp/sq m

$-J_B$ electron current density at arbitrary applied voltage V_B, amp/sq m

J_{MBL} current density at the Maxwell-Boltzmann limit (zero field at collector), amp/sq m

$+J_p$ random ion current density in isothermal plasma, amp/sq m

$-J_p$ random electron current density in isothermal plasma, amp/sq m

J_0 saturation emission current density (zero field at emitter) amp/sq m

$-J_0$ electron saturation emission current density (zero field at emitter), amp/sq m

K constant used in dimensionless distance parameter of space-charge relations, $(^oK)^{3/4}/amp^{1/2}$

k Boltzmann's constant, 1.3805×10^{-23} J/°K

m particle mass, kg

n particle concentration, particles/cu m

n_{Cs} cesium atom concentration, atom/cu m

$+n_p$ cesium ion concentration, ion/cu m

$-n_p$ electron concentration, electrons/cu m

P probability integral, $P(\psi^{1/2}) = \frac{2}{\sqrt{\pi}} \int_0^y e^{-y^2} dy$

P_c cross section parameter, cm^{-1}

p pressure, N/sq m

q electron charge, 1.602×10^{-19} C

R_T temperature ratio

S slope of Schottky plot (eq. IX:14)

T temperature, °K

T_{Cs} temperature of liquid cesium reservoir, °K

T_1 temperature of emitter, °K

T_2 temperature of collector, °K

V potential difference, V

V_B potential difference between Fermi level of collector and Fermi level of emitter, V

V_C contact potential difference between emitter and collector, V

V_i ionization potential of cesium, V

V_{MBL} potential difference between emitter and collector surfaces at Maxwell-Boltzmann limit, V

V_x potential difference relative to isothermal plasma potential, V

w distance between emitter and collector, m

w_{eff} effective distance between emitter and collector resulting from constant field assumption

x distance, m

x_M distance from minimum space-charge barrier to emitter surface (in emitter space), m

x_N distance from minimum space-charge barrier to collector surface (in collector space), m

$x_{\overline{V}}$ distance at which potential is equal to kT/q in Fowler sheath analysis, m

x_o distance from real to fictitious surface in Fowler sheath analysis, m

x_1 distance parameter used in Fowler sheath analysis, $5/\sqrt{10^6}$ Debye lengths

ϵ_o permittivity of free space, 8.85×10^{-12} $C^2/(N)(\text{sq m})$

λ mean free path, m

λ_{Cs} mean free path at T_{Cs}, m

μ isothermal plasma potential referenced to Fermi level, V

ν particle flux density, particles/(sq m)(sec)

ν_{Cs} particle flux density at T_{Cs}, particles/(sq m)(sec)

φ work function, V

φ_{MBL} barrier potential referenced to emitter Fermi level at Maxwell-Boltzmann limit, V

φ_1 emitter work function, V

φ_2 collector work function, V

χ dimensionless distance, $KJ^{1/2}x/T^{3/4}$

χ_C dimensionless distance in collector space (see fig. III:1)

$\chi_{C,N}$ dimensionless distance corresponding to x_N

$\chi_{C,O}$ dimensionless distance corresponding to zero field at emitter (saturated current)

χ_E dimensionless distance in emitter space

$\chi_{E,M}$ dimensionless distance corresponding to x_M

$\chi_{E,MBL}$ dimensionless distance corresponding to zero field at collector (MBL)

ψ dimensionless potential, qV/kT

ψ_C dimensionless potential in collector space

$\psi_{C,N}$ dimensionless potential corresponding to x_N

$\psi_{C,O}$ dimensionless potential corresponding to zero field at emitter (saturated current)

ψ_E dimensionless potential in emitter space

$\psi_{E,M}$ dimensionless potential corresponding to x_M

$\psi_{E,MBL}$ dimensionless potential corresponding to zero field at collector (MBL)

ψ_1 dimensionless potential $(\varphi_1 - \mu)/(kT/q)$ used in Fowler theory

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 26, 1965.

XVIII - REFERENCES

1. Langmuir, I.: The Effect of Space Charge and Initial Velocities on the Potential Distribution and Thermionic Current Between Parallel Plane Electrodes. Phys. Rev., vol. 21, Apr. 1923, pp. 419-435.

2. Nottingham, W. B.: Thermionic Emission. Rept. No. TR-321, M.I.T., Dec. 10, 1956.

3. Poritsky, H.: Electron Gas Equations for Electric Flow in Diodes. IRE Trans. Prof. Group on Electron Devices PGE-2, Jan. 1953, pp. 60-84.

4. Kleijnen, P.H.J.A.: Extension of Langmuir's (Xi, Eta) Tables for Plane Diode with Maxwellian Distribution of Electrons. Phillips Res. Rev., vol. 1, no. 2, Jan. 1946, pp. 81-96.

5. Ferris, W. R.: Some Characteristics of Diodes with Oxide-Coated Cathodes. RCA Rev., vol. 10, no. 1, Mar. 1949, pp. 134-149.

6. Schottky, Walter: Über den Austritt von Elektronen aus Glühderähten bei Verzögernden Potentialen. Ann. Physik, vol. 44, 1914, pp. 1011-1032.

7. Morris, James F.: Thermal Field Emission with a Terminated Image Potential. NASA TN D-2784, 1965.

8. Langmuir, I.: Nature of Adsorbed Films of Caesium on Tungsten. Phys. Rev., vol. 43, no. 4, Feb. 15, 1933, pp. 224-251.

9. Taylor, J. B.; and Langmuir, I.: Evaporation of Atoms, Ions and Electrons from Caesium Films on Tungsten. Phys. Rev., vol. 44, Sept. 1933, pp. 423-458.

10. Breitwieser, Roland: On the Relation of Ion and Electron Emission to Diode Diagnostics. Inst. Elec. and Electron. on Thermionic Conversion Specialists Conf., Oct. 7-9, 1963, pp. 17-26.

11. Nottingham, Wayne B.: Sheath and Plasma Theory of an Isothermal Diode. Rept. No. 4-62, Thermo Electron Eng. Corp., Oct. 1962.

12. Saha, M. N.: Ionization in the Solar Chromosphere. Phil. Mag., vol. 40, Oct. 1920, pp. 472-488.

13. Mayer, J. E.; and Mayer, M. G.: Statistical Mechanics. John Wiley & Sons, Inc., 1959.

14. Fowler, R. H.: The Restored Electron Theory of Metals and Thermionic Formulas. Proc. Roy. Soc. (London), ser. A, vol. 117, 1928, pp. 549-552.

15. Houston, John M.: Ion Current in the Retarding-Range Cesium Thermionic Converter. Rept. on Twenty-Fourth Conf. on Phys. Electronics, M.I.T., Mar. 25-27, 1964, pp. 211-223.

16. Luke, Keung P.; and Smith, John R.: Theoretical Study of Zero-Field Electron Work Function of Metal Immersed in Gas-Direct Application of Cesium Thermionic Diode. NASA TN D-2357, 1964.

17. Nottingham, W. B.: Cesium Plasma Diode as a Heat-to-Electrical-Power Transducer. Direct Conversion of Heat to Electricity, J. Kaye and J. A. Welsh, eds., John Wiley & Sons, Inc., 1960, pp. 8-1 - 8-37.

18. Honig, R. E.: Vapor Pressure Data for Solid and Liquid Elements. RCA Rev., vol. 23, no. 4, Dec. 1962, pp. 567-586.

19. Heimel, Sheldon: Thermodynamic Properties of Cesium up to 1500° K. NASA TN D-2906, 1965.

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