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CESIUM PLASMA DIODE

AS A

HEAT-TO-ELECTRICAL-POWER TRANSDUCER

BY

W. B. NOTTINGHAM



Chapter 8

CESIUM PLASMA DIODE AS A HEAT-TO-ELECTRICAL-POWER TRANSDUCER

Wayne B. Nottingham

Abstract

The new interest in the direct conversion of heat-toelectrical power has stimulated research in both the application of the high vacuum diode and the plasma diode to accomplish this purpose. The theory of the high vacuum diode is relatively simple and the experimental verification of the theory has been satisfactory. The plasma diode which depends on the ionization of cesium at a hot surface cannot be worked out in all of its detail at present because of the lack of certain fundamental experimental data. It is possible to make use of published results of Taylor and Langmuir and a detailed analysis of recent thermionic studies to carry the understanding of the plasma diode far enough to make a direct comparison with experiment. This analysis first involves an understanding of the phenomenon of surface ionization. General properties of a plasma and space-charge considerations control the delivery of ions to neutralize electron space charge. When applied to the experimental data available, an interesting result comes as an important simplification. Essential to the theory of the high vacuum diode is the knowledge of the emitter temperature and the diode spacing. The electrical characteristics of the plasma diode have been found to be very closely duplicated by those of a high vacuum diode characterized by an effective distance that is reduced from the actual diode spacing. This fact supports the opinion that the efficiency of the plasma diode may be tremendously improved over that of vacuum diodes of practical design.

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Introduction

An analysis of the high vacuum diode as a heat-to-electrical-power transducer has been worked out in detail ¹ based on theories presented in "Thermionic Emission" published some years ago². In the high vacuum diode it is of the utmost importance to have the lowest possible work-function on the collector and to have the smallest practical spacing. It is anticipated that under these conditions the work-function of the emitter will be practically without influence so long as the space-charge minimum in front of the emitter is of the order of V_T (the electron-volt equivalent of the temperature). Any further decrease in the emitter work-function will do neither good nor harm in controlling the usefulness of the device. In the plasma diode it is not so easy to generalize and since much of the most significant fundamental data relevant to the problem will not be available until additional research studies have been made. These remarks relevant to the plasma diode represent some of my own views on the subject in that they are being developed without the benefit of the experimental evidence needed.

8 - 2

In the high vacuum diode the understanding of the space charge is very important. It controls the properties of diodes that operate within the temperature limits set by available materials and the electron emission properties associated with them. The function of the positive ions in the plasma diode is to alter the effect of electron space charge. Even in the plasma diode there will be space charges near the boundaries of either the emitter or the collector or both.

Assume for the purpose of illustration that the emitter work-function is somewhat higher than the collector work-function and by some mechanism not specified for the moment exactly the right number of ions are available to reduce the space charge to zero. Assume furthermore that the spacing if sufficiently small in relation to the gas pressure so that the drop in potential over the plasma between the surface of the emitter and the collector can be neglected. This condition is represented diagramatically by Fig. 1. Here the true work-functions of the emitter and the collector are d_1 and $\overline{d_2}$. Note particularly that these are not the "Richardson" work-functions. The current emitted over the barrier d_1 is given by the equation:

> $-\frac{\phi_1}{V_T}$ $I_1 = 120 \times T_1^2 e \qquad amp/cm^2$

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Fig. 1-Motive of an electron with zero field between a and b.

In this equation T is the temperature of the emitter and V_T is its electronvolt equivalent defined by:

$$V_{\rm T} = \frac{\kappa T}{q} = \frac{T}{11,600}$$
 (2)

The available power is the product $I_1 V_0$. The total resistance in the circuit from the receiving surface on the collector through the external load and to the emitting surface of the emitter may be expressed for a unit area as

R

$$10 = \frac{V_o}{I_1}$$
(3)

If the tital resistance is less than R₁₀, then the current around the circuit will remain constant and the output voltage decrease, thus giving a smaller available electrical power. If the load resistance is made greater than R₁₀, then the output voltage increases while at the same time the current decreases. Identify this increase in voltage by the symbol v. The following equation serves to relate these quantities for the calculation of maximum power.

$$-\frac{v}{V_{T}}$$

$$P = I_{1} e \qquad (V_{0} + v)$$

Equation 4 may be differentiated to obtain an expression for the deviation in the power as a function of v. A maximum of power

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$$\frac{T}{T} = \frac{T\pi}{p} = \frac{T}{10,000}$$

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$$v_{m} = V_{T} - V_{o} = V_{T} - (\phi_{1} - \phi_{2})$$
 (5)

The physical meaning of this equation may be considered in its relation to Fig. 1. If the work-function difference $(\phi_1 - \phi_2)$ is greater than V_T then v_m is zero or stated in other words maximum power is delivered to the external load when the resistance is chosen to satisfy Eq. 3 and the overall output voltage is <u>exactly</u> the difference between the work-functions. Under the circumstances in which the receiver work-function is actually greater than the emitter work-function, the power output is a maximum when the voltage available is V_T . This situation is illustrated by the diagram of Fig. 2 and the total available power is expressed by

$$P_{max} = 120 \times T^{2} e^{-\frac{\phi_{2} + V_{T}}{V_{T}}} V_{T} w/cm^{2} (6)$$

In the range of work-function difference for which $(\phi_1 - \phi_2)$ is equal to or less than V_T even though ϕ_1 is greater than ϕ_2 , maximum power will occur with an available voltage of V_T and Eq. 6 applies.

These statements may be summarized as follows. For work-function differences greater V_T in which the emitter workfunction is larger than the collector work-function, maximum power is available at an overall voltage level equal to the difference in the work-functions, whereas in all other cases the maximum power occurs with an available voltage of V_T .

It will be the purpose of the following sections to discuss the problem of ion production as well as the delivery to the plasma of the ions and the current flow expected in the presence of atoms and ions.

Ionization of Cesium at Heated Surfaces

The classic work on the ionization of cesium at heated tungsten surfaces was largely due to Langmuir and his collaborators. One of the latest in that series of researches was reported by Taylor and Langmuir³. This work serves as the basis of many of the deductions made here. If the arrival rate of cesium atoms for each square centimeter of a heated tungsten surface is output will be found when the differential (dr. 140) is sere and the vehicle of r an determined is identialed as vm. The result is given

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In the range of work-function difference for which $\{d_{1}, \dots, d_{n}\}$ is replaced to a less than V, even though d_{1} is greater than d_{2} , minimum power will secur with an available voltage of V_{T} and P_{n} is inplied.

These statemonts may be summarized as follows: For a solution differences grants of T_T in which the emlites worktensities is large? then the collector work-function, as zimum power is qualitable at an overall voltage level equal to the difference in the work-functions, whereas in all other cases the maximum [1] power occurs with an available voltage of V_T .

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This statement should not be attributed to Taylor and Langmuir but does depend on an analysis of their data which was made available in their Fig. 18. Since no other data are available, these are used to yield a relation between the atom arrival rate μ_a expressed in atoms per second for each square centimeter and the minimum temperature for which a negligible surface film will form on tungsten. At this temperature practically every atom that arrives will leave the surface as an ion. An empirical equation has been derived to relate this minimum temperature to the atom arrival rate and is

 $T_{min} = \frac{14,100}{27.56 - \log_{10}\mu_{a}}$

At any given arrival rate, the production of ions is discontinuously reduced by approximately a factor of 10 if the tungsten surface is at a temperature slightly below the minimum temperature given by Eq. 7.

The ideal gas laws are used to convert cesium vapor pressure data to atom arrival data. The following formula relates atom arrival to the temperature of the liquid cesium in equilibrium with its vapor.

$$\log_{10}\mu_a = 27.48 - \frac{3900}{T_{Cs}}$$
 (8)

(7)

The corresponding formulae in the exponential form are given in Eqs. 9 and 10.

$$\mu_{a} = 3 \times 10^{27} \times 10^{10} \text{ Cs}_{a \text{ toms}/\text{cm}^{2}}$$
(9)

$$\mu_{a} = 3 \times 10^{27} e^{\frac{-\frac{8980}{T_{Cs}}}{T_{cs}}} \text{ atoms / cm}^{2}$$
(10)

lars than 10¹² atomic per second (Desium rondenestion temperature .0⁹G), a tosgeter illument at 970⁹K valit have a religible murices coverage of cestum storm and every costum atom that arrives will leave as a cestum ion. As the arrival rate increases to 10¹⁸ storms/ acc-cm², the minimum temperature for complete conversion of atomic to ions is approximately 1675⁹R.

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The ideal gas have are used to convert section vapor previous data to atom arrival data. The following formula relates atom arrival so the temperature of the liquid costum in equilibrium with its vapor. It is an interesting fact that Eqs. 7 and 8 may be combined to yield a very simple relation between the temperature of the liquid cesium and the minimum temperature of the heated tungsten surface at which complete ionization takes place. This relation is:

 $T_{m} = 3.6 T_{Cs}$

The fact that the minimum temperature at which all cesium atoms are converted to ions is linearly related to the temperature of the liquid cesium may not be a pure accident of numbers. In the broader sense of the word both the evaporation of atoms from the liquid and the evaporation from a tungsten surface may possibly involve atomic attractive forces that are not so different from each other. This would imply that their vibrational frequency before evaporation might be characterized by a force function not unlike that of a vibrating molecule. In the molecular case there is a dissociation energy whereas in the case of atomic evaporation there is the latent heat of evaporation which is dominated by a quantum state of vibrational activity which is the maximum that can be attained by the atom as it is on the border line between continued adherence to the surface and evaporation. If the equations of motion are not too dissimilar then the factor that relates these two critical temperatures could well be the ratio of the "activation" energies. Equation 8 implies an activation energy for evaporation from the liquid state that is not too far from 0.773 ev. Taylor and Langmuir deduce from their studies of cesium evaporation from tungsten that the heat of evaporation is 2.83 ev if the fraction of the surface coated is small. Note that the ratio (2.83/0.773) is 3.65 which is consistent with the empirical results presented in the form of Eq. 11.

Results of the Taylor-Langmuir experiments as they relate to the yield of ions from surfaces that have an appreciable fraction covered by adsorbed cesium atoms show an extremely small yield of ions. A detailed analysis of the experimental data available yields some interesting results. The equations to be presented fit quite well over the range of cesium pressures and tungsten surface temperatures studied by Taylor and Langmuir. The purpose in deriving empirical equations to represent their data is to permit computations to be made under conditions that involve considerable extrapolation into unexplored areas. The philosophy here is that estimates based on an extrapolation from existing data are better than pure guesses without a systematic relation to establish facts. The ion production rate \mathcal{V} expressed as the number of ions produced per second for each square centimeter area is expressed by the set

(11)

it is an interesting fact that Equ. 7 and may be combined to viola a very simple relation between the temps rature of the liquid cestars and the minimum temps rature of the heated tangston surface at which complete fontsafes takes place. This relation is:

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$$v_{p} = \frac{1.45 \times 10^{54}}{\mu_{a}} 10^{-\frac{26,600}{T}} (12)$$

$$v_{p} = \frac{1.45 \times 10^{54}}{\mu_{a}} 10^{-\frac{26,600}{T}} (13)$$

$$v_{p} = \frac{1.45 \times 10^{54}}{1113} e^{-\frac{5.28}{V_{T}}}$$

$$v_{p} = \frac{1.45 \times 10^{54}}{1113} e^{-\frac{5.28}{V_{T}}} (14)$$

Attention may be directed specifically to the results shown as Eq. 13. The ion yield decreases rapidly with a decrease in the temperature of the surface for the range below the temperature T_m introduced in Eq. 7 and related to the liquid cesium temperature by Eq. 11. Equation 13 has no significance at temperatures higher than T_m since then the ion yield is precisely equal to the atom arrival rate µa. It is evident from this equation that at a fixed surface temperature T, the ion yield decreases almost linearly (1.113 power) with the atom arrival rate. Stated in another way this equation shows that the probability of ionization at a given surface temperature decreases with the 2.113 power of the arrival rate. The physical explanation for this result depends on the fact that at a given surface temperature the fraction of the surface covered by adsorbed cesium atoms increases as the rate of arrival of neutral atoms increases. This increase in surface coverage brings about a decrease in the average work-function of the surface. The probability that a cesium atom will evaporate as an ion instead of neutral atom is strongly influenced by the work-function of the surface. Since the ion yield decreases as the average work-function decreases, it is to be anticipated that a relation not unlike that of Eq. 13 might hold. The insertion of numbers into these equations and a comparison with the published data of Taylor and Langmuir may convince the reader that over the range of temperature and cesium arrival rate for which good data exist, the equations represent the observations. It is thought that the failure to represent the true facts over the ranges of the variables likely to be encountered in association with the plasma transducer problem will be less than an order of magnitude, that is a factor of ten. It is hoped that the error will be much less than this in many examples that are of practical interest.

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Kinetics of Ions Formed at Hot Surfaces

The reader should be reminded that when drawings are made which show energy relations of electrons in diode structures, these drawings really relate to the "motive function" of an electron. That is, lines and energy levels apply to the potential of an electron in the space of interest. Figure 1 may be used as an example. We start at the Fermi level in the emitter and the line a' - a represents the potential function of an electron in the neighborhood of the surface. The energy difference between the Fermi level and the surf ace potential at a is the true work-function ϕ_1 of the emitter. In this energy diagram the surface of the emitter is joined to the surface of the collector by the line a-b and since that line is drawn horizontally it represents the potential energy of an electron in the field-free space between the emitter and the collector. The workfunction of the collector is shown by ϕ_2 as the energy difference between the Fermi level in the collector and the potential energy of an electron at its surface at the point b. The misalignment of the Fermi level of the emitter with respect to that of the collector is indicated by Vo. This separation of Fermi levels can be maintained only by having some auxiliary and external source of power and may be measured directly by a voltmeter connected between the emitter and the collector electrodes. The kinetic energy of an electron in this diagram is represented by the fact that the electron is in an energy level which would exist in the diagram below the horizontal line a-b. The separation between the electronic energy level and the line a-b is a direct indication of the actual kinetic energy of the electron associated with the motion across the space from a to b. This direction is taken as the x direction whereas the y and z directions are taken perpendicular to this one and therefore parallel to the planes of the emitter and the collector. We can show in this diagram only the kinetic energy associated with the motion in the x direction. It is not suitable to try to show the kinetic energy associated with the other directions in this one-dimensional diagram. Energy levels do not exist for electrons in the space between the electrodes that would be represented by electron levels above the a-b line. Such levels do exist within the conductors but not outside of them.

This same potential diagram applies equally well to ions that might be in the space bet ween a and b. Specifically an ion at rest would be represented as being on an energy level coincident with the line a-b, whereas one which is moving in the x direction with some kinetic energy would be occupying an energy level in this diagram above the line a-b. No positive-ion energy levels exist that would be represented by states drawn below the line a-b. These remarks are made to anticipate the discussion with reference to the energy distribution of ions created at a hot surface. One of the few sets of measurements on the ion energy distribution that exists in the literature is that of Fig. 16 of Taylor and Langmuir. Their data are reproduced as Fig. 3. The plot shows the ion current received at a coaxial collector as a function of the applied voltage with the emitter temperature held constant and the rate of arrival of neutral atoms established by a constant bath temperature of 275°K. The critical temperature for this rate of arrival of atoms is 990°K and therefore since the measurements were made at 980° K it was probable that the ion yield was less than 10 per cent of the atom arrival rate. Under this condition the average work-function of the emitter was very close to 3.4 volts. Other evidence would indicate that the work-function of the collector was very close to 2 volts. Therefore under these circumstances, the contact difference in potential was close to 1.4 volts. This fact is exhibited reasonably well by the data of Fig. 3. Under the conditions of the experiment, the heated tungsten surface undoubtedly had considerable nonuniformity in work-function, and also space-charge effects reduce the ion current at zero field. It may be assumed that these two factors account for the relatively poor saturation of the ion current. The evidence seems to be satisfactorily clear that the application of an ion retarding voltage of a fraction of a volt is sufficient to inhibit the flow of ions from the hot tungsten surface over to the collecting electrode. The slope of the semi-log plot is in agreement with the temperature of 980°K.







Fig. 2. Flasher diode with high collector work-function



Fig. 3-Ionization rate as a function of applied volts observed by Taylor and Langmuir.



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In Fig. 4 the emitter work-function ϕ_1 is assumed to be uniform. The collector work-function is ϕ_2 ; the Fermi level of the collector is V more negative than that of the emitter. Electrons are being emitted from the surface a-a' and those that impinge on the surface from inside the metal at an energy level ϕ' with respect to the Fermi level have a chance of escaping across the spacecharge barrier at B. If the electron has an excess energy V_T as it passes the barrier, then its energy state is represented by the dot-dash line of Fig. 4. Cesium ions will evaporate from the emitter surface in an appreciable number if the work-function ϕ_1 is high enough and the temperature suitable. An ion which originates at the emitter surface with practically no kinetic energy associated with its motion in the x direction would find itself excelerated by the electrostatic field created by the electron space charge and acquire kinetic energy so that as it passes through the region B it will have acquired a maximum of kinetic energy represented by the vertical distance between the solid potential line and the dotted line of the diagram. If the ion evaporates from the surface with an initial kinetic energy of V_{T} , its energy level will be that of the dash-plus line. In either case the ion will be accelerated across the space, impinge on the collector with considerable energy, and probably absorb an electron from it and evaporate off as a neutral atom. It is presumed that the collector will be at a higher temperature than the liquid cesium surface somewhere within the tube envelope and therefore maintain a surface coverage of less than a monolayer. As the pressure of the cesium is increased, the production rate of ions may increase or decrease depending on the temperature of the heated surface and the rate of arrival of cesium atoms.



Fig. 4-Motive curve with electron space charge.

This discussion indicates that if the cathode has a uniform work-function structure, ions may be produced at the energy level a or above and will not be as effective in neutralizing space charge A Generalized Disputsion of the Simultaneous Emirator of Directeors

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as they would be if they could become trapped in the electronic space-charge potential minimum at B. As the cesium pressure is increased, there will be a greater and greater probability that the cesium ion will encounter a neutral cesium atom in such a way as to deliver energy to the atom and thus find itself in an energy level below the surface potential of the collector shown in the diagram at b.

The interaction between the neutral cesium and the ionized cesium may follow either one of two mechanisms. The cesium ion may collide with the cesium atom with an energy-sharing and momentum-conserving collision. The subsequent products then would be a slower-moving ion which might then become trapped, and a faster moving neutral atom. An alternate mechanism which also could have a good probability of occurring would be that the fastmoving ion would come into the neighborhood of a slow-moving cesium atom, absorb the electron from the atom, and continue on its way as a neutral atom with a relatively high kinetic energy. The ion thus created would be a slow-moving ion and therefore lie close to the electronic motive function and be trapped. Either of these processes would accomplish the desired result, namely, that of altering the energy level of the ion to bring it into a state that is below the energy level of the most negative surface. In the example shown in Fig. 4 this is the energy level at b.

As the cesium pressure is increased, the probability of such energy-losing collisions increases in direct proportion to the concentration of cesium atoms in the space between the two electrodes. It may therefore be of some interest to have equations by which this concentration may be estimated with reasonable accuracy. These equations in turn can be combined with an estimated "cross-section" associated with the energy-losing transition to try to determine the fraction of the ions produced that find their way into the space-charge minimum. Finally in the steady state situation as the space-charge nimimum is reduced, the rate of arrival of ions into the plasma will equal their rate of loss. If the ion concentration builds up to be practically equal to the electron concentration then the main space-charge field will be wiped out and the only fields that will remain will be spacecharge fields near one or the other of the two electrodes or both and the "drift" field needed to carry the electrons across the space from the neighborhood of the emitter space-charge sheath to the surface of the collector.

Atom Concentration in the Space Between the Emitter and the Collector

In order to calculate an ion mean-free path it is first necessary to have an approximate formula for determining the as they would be if they could become trapped in the electronic space charge potential minimum at 3. As the centam pressure is increased, there will be a greater and greater probability that the centum for will encounter a neutral centum atom in such a way as to deliver emergy to the atom and thus find itself in an energy level befow the surface potential of the collector shown in the diagram

The interaction between the neutral cestum and the tomzed cestum may follow sither one of two mechanisms. The cestum ton may collide with the cestum atom with an energy-shering and momentum-conserving collision. The rubsequent products then would be a slower-moving for which might than become trapped, and a faster moving neutral atom. An elternate mechanism which also could have a good probability of occurring would be that the fastmoving ton would come into the torph betweed of a slow-moving the way as a neutral otom with a relatively high binetic energy. The ion that created would come into the torph betweed of a slow-moving the way as a neutral otom with a relatively high binetic energy. The ion that created would be a slow-moving ton and therefore lie close is the electronic motion and be trapped. Ether of these processes would accompliab the desired result, namely, that of a thereing the anergy level of the inest or bring it into a state that is a below the energy level of the most negative surface, in the state shown in Fig. 4 this is the most negative at bi-

As the content of continuous prevenue is increased, the prominitity of the <u>contentration</u> of continuous intereases in direct proportion is electrodes. If now therefore he of semi- intereast to have equations by which this contentration may be calimated with reasonable accuracy. There equations in two can be combined with an estimsted "cross-encilian" associated with the energy-lowing transition to try to determine the fraction of the iom produced that find their way into the space-charge minimum. Finally is the state state entimation as the space-charge minimum is reduced, the rate of arrival of bins into the piecine will equal their rate of ionelectron noncestration the piecine will equal their rate of ionwiged out and the only the main will be practically equal to the state state into the space-charge attainant is reduced. The rate of arrival of bins into the piecine will equal their rate of ionelectron noncestration the that will remain will be spaceand the 'dufft' field mediat that will remain will be spaceand the 'dufft' field mediat the carry the electron at rote in the 'dufft' field mediat to carry the electron at rote in a space from the rate photocol of the the entities and the space from the rate booth of the dufft of the two electrons across the is the sourties of the calles the entities and the two electrons across the

Atom Concentration in the Space Delwars the Emitter and the

in order to calculate an incan-free pain it is first excession to have an approximate formula for determining the atom density in the immediate neighborhood of liquid cesium in equilibrium with its vapor at a temperature T_{Cs} . This concentration is given by:

$$n_{Cs} = 2.7 \times 10^{23} e$$
 atoms/cm³ (15)

A useful form of this equation for calculation purposes is:

$$\log_{10} n_{\rm Cs} = 23.44 - \frac{3800}{T_{\rm Cs}}$$
 (16)

The fact that the exponents of Eq. 10 and Eq. 15 are different is not an error but results from the inclusion of a temperature coefficient term into the exponent. Although the above two equations serve to give the density of cesium atoms in equilibrium with the liquid, a correction should be used to relate the estimated temperature in the space between the emitter and the collector to the temperature at the cesium liquid surface.

A suitable form of this correction term is given as:

$$n_{s} = n_{Cs} \left(\frac{2 T_{Cs}}{T_{E} + T_{C}} \right)^{1/2}$$
(17)

This equation takes this form on the assumption that the effective temperature in the diode space may be taken as the average of the emitter temperature T_E and the collector temperature T_C . To give some idea of the magnitude of this correction, assume for example that the emitter temperature is 1600° K and the collector temperature is 900° K when the cesium temperature is 500°K. The correction factor is then 0.63.

In order to estimate the mean-free path of an ion it is necessary to know the effective cross-section for an energy-losing collision. This quantity is undoubtedly energy-dependent and therefore any statement concerning its value should preferably be backed by experimental data not known accurately at present. For the purposes at hand, the assumption will be made the cross-section for energy-losing collisions is 2×10^{-14} cm². This assumption is the equivalent of stating that is a fast-moving ion comes close enough to a slow-moving atom for the center-to-center distance to be 8×10^{-8} cm, there will be a high probability that an exchange of some sort will take place between the two in a manner to leave as a product a slower-moving ion. If the cross-section is represenatom density in the immediate neighborhood of liquid centum in equilibrium with its vapor at a remumature Tea tration is given by:

A neofal form of this squallon for calculation purposes is:

The fact that the exponents of Eq. 10 and Eq. 15 are different to not an error but results from the inclusion of a temperature coefficient term lists the exponent. Although the above two equation serve to give the density of casium atoms in equilibrium with the liquid, a correction should be used to relate the estimated temperature in the space between the emitter and the collector to the densities at the cesium liquid surface.

A railable form of fills correction farm is given as

$$= c_{s} \left(\frac{z T_{cs}}{z_{s} + T_{c}} \right)^{\frac{1}{2}} = c_{s}$$

This equation takes this form on the assumption that the affective temps return in the diode space, may be taken as the average of the emitter temperature T., and the collector temperature T. give some idea of the unrelated of this correction; assume for example that the traitter temperature is 1000° K and the collector temperature is 500° K when the collector is 1000° K and the collector correction factor is then 0.63.

In article of an inter to contrast the mean-free path of an ion it is necessary to how the effective tross-section for an energy-lowing calificion. This quantify is undenshedly energy-dependent and therefore any activatent concerning its value should preferably to bioleed by experimental data not known accurately at present. For the perpensioner at himd, the anaunption will be made the cross-section for an ergy-lowing collisions is it a 10⁻¹⁴ cm². This assumption is the depresent of stating that is a last-moving ion contex close the depresent of stating that is a last-moving ion contex distance to be it allow environs atom for the contex to contex distance to be it allow environs atom for the contex to contex distance to be it allow environs atom for the contex to contex distance to be it allow environs atom for the contex to contex distance to be it allow environs atom for the contex to contex distance ted by σ_{\mp} , and the density of atoms by n_s , then the best estimate for the mean-free path for the ions is given by:

$$\overline{\lambda}_{+} = \frac{1}{n_{g}\sigma_{+}} = \frac{5 \times 10^{13}}{n_{g}} \text{ cm}$$
(18)

Equations 16, 17, an.d 18 may be combined for numberical calculations. Since the correction term in Eq. 17 is hardly great enough to be compared with the uncertainty in the collision crosssection, an equation can be written which neglects this factor and serves as a quick means of estimating the ion mean-free path in terms of the cesium-condensation temperature. The equation is:

$$\log_{10} \lambda_{+} = \frac{3800}{T_{Cs}} - 9.7 \tag{19}$$

A second useful form of this equation serves to determine the condensation temperature needed to approach a desired mean-free path. This equation is:

$$T_{Cs} = \frac{3800}{9.7 + \log_{10} \lambda_{+}}$$
(20)

This equation yields the result that approximately 1 mm meanfree path will be associated with the condensation temperature of 437° K and one-tenth of a millimeter will be the approximate meanfree path at 493° K.

If these calculations and estimations are valid, they may be helpful to the designer of a practical heat-to-electrical-power transducer that ope rates according to the plasma principle. It has been pointed out ⁽¹⁾ that the high vacuum transducer <u>must have</u> a very small spacing in order to operate with satisfactory efficiency. The conclusion that one would draw from this discussion is that a small spacing could work as a definite disadvantage in the plasma transducer.

For illustration purposes, assume a spacing of 0.5 cm for a diode and a cesium pressure adjusted so that the ion-free path would be approximately half this distance or 2.5 mm. The cesium temperature would be 418° K. Equation 11 is used to estimate the minimum temperature of the cathode for moderately efficient ion production. This temperature is T = 1500° K and is seed by reprint the dimnity of atoms by a set that the bast astimute .

Bequations 16, 17, and 18 may be combined for number hal calculations. Since the correction term in Eq. 67 is hardly great enough to be boundared with the uncertainty to the collision crossaction, an equidant can be written which deglects this factor and server as a quick means of estimating the ine mean-free path in bermu of the condensation termiser aros. The equation in

A provind usered form of this equation serves to determine the condensation lampetature needed to approach a destred mean-free path. This equation ta:

transhulling that one inters according to the plauma principle. If have been pointed out 11 eight the high vacuum transducer must have a mate simily specing in order to ope rate with satisfactory efficience The conclusion that one vauld dears from this discussion is that is small, specing could work as a dufinite discussion is the plasma

Southing at the purpose subset of annual a specing of 0.5 cm for a flode and a basism preserve adjusted so that the four free path would be approximately half have distance or 2.3 mm. The evolute integrations would be 415 R. Equation it is rased to a continuate the unishmin temperature of the cathode for moderately efficient for production. This terms within is T = 1500° R and is

a reasonable one for a dispenser-type cathode. If its average work-function is approximately 2.5 ev, then the available electron emission would be about 1 amp/cm². Assume that a space-charge sheath near the surface of the emitter added an additional 0.4 volt step to make the effective value of ϕ' shown in Fig. 4 equal to 2.9 ev. This would reduce the available electron emission a factor of 20 and bring it to 0.05 amp/cm^2 . This current density would be 25,000 times the current density that would have been available from the same cathode in a high vacuum diode of this spacing when the space-charge minimum coincided with the collector. Again with this cathode operating at this temperature. the current density of 0.05 amp. cm² implies that the location of the space-charge minimum, would be approximately 30 microns from the emitter. The point in mentioning these figures is to lead the way toward an evaluation of the production rate of ions needed to hold the space-charge minimum at this point and give a very small potential difference between the minimum point at B and the electron collector surface at b. The next section will attempt to evaluate these factors.

Ion and Electron Evaporation from a Nonuniform Cathode

The motive diagram shown in Fig. 4 is a one-dimensional diagram suitable for an emitter and a collector, each of which has a uniform surface work-function. In many practical examples of emitters this situation does not represent the facts. Specifically for pure tungsten the variation of work-function even without the adsorption of films may range from 4.3 to 5.3 ev. Adsorbed films may result in still wider differences. Details concerning dispenser cathodes are very uncertain. Specifically one may picture a work-function structructure of a dispenser athode as one in which there are many islands or wells of strong electron emission to be found at crystal boundaries between the sintered crystals of which the structure is made. Each of the individual pieces of the powdered tungsten used in this fabrication may exhibit considerable range in work-function. In order to illustrate this point, the sketch in Fig. 5 has been produced and represents a completely hypothetical situation which may not differ too much from reality to be worth considering. The line s on the diagram represent imaginary crystal boundaries between the solid tungsten crystalites or sintered powder particles and the shading is related to the thermionic emission. Regions that are white represent strong electron emission and regions that are dark represent high work-function areas of weak electron emission. The scale used on this figure implies that each of the individual particles of tungsten that were sintered together to make a porous block had an average linear dimension of approximately 10 microns. The activation material is assumed to have migrated out between the

a reasonable one for a dispensar ives collected. If the average work-function is approximately 7.5 av, then the available electron emission would be about 1 amp/cm² Assume that a space-charge abeath near the carface of the rm liter added an additional 0.4 volt step to make the effective value of d' shown in Fig. 4 equal to 2.9 ev. This would reduce the a valiable electron emission a would be 25,000 times the current density that would have been available from the same cathode in a high vacuum diode of this apacing when the space-charge relations to include with the collector. Again with this cathode operating at this temperature, the current duratily of 0.05 amp com² implies that the location of the space-charge malimum, would be approximately 30 microns the space-charge malimum, would be approximately 30 microns is a very small potential difference between the minimum point and avery amaline collector collector entry in the point and hand the effective restored at the production rate of the present the space-charge malimum, would be approximately 30 microns is a very small potential difference between the minimum point at a very small potential difference between the minimum point at a stimum to walk the space charge minimum at this point and give it and the electron collector surface at b. The next section will attempt to walk these factors at a surface at b. The next section will attempt to walk to see factors.

Ion and Electron Evaporation from a Monuniform Cathode.

The motions of the an emilter and a collector, each of which has a uniform surface work-function. In many practical examples be anisters this situation does not represent the facts. Specifically of anisters this situation does not represent the facts. Specifically doe pars taggetes the variation of work-function even without the material of films may range from 4.3 to 5, 3 ev. Adapted dispenser cathodre are vary uncertain. Specifically one may pleture is work function structurentate. Specifically one may not be found at crystal boundaries between the state concertain able target to the structure of a dispenser of dode at one pleture is work function in order the individual please of the in which there are many felturer or wells of strong electron anizerio able target to work-function. In order to fine individual please of the shirts in Fig. 5 has been produced and represents a completely to be found at crystal boundaries between the athered trystals of able target to work-function. In order to illustrate this point, the shirts in Fig. 5 has been produced and represents a completely in approximatical elemented. The the second degram represent to be worth considering. The the second degram represent in a product an indict may not differ too touch from reality is a state of the structure is made. The the second to the shirts at fig. 5 has been produced and represents a completely is a state of the structure of the state of the structure of a state of the state of the state of the state anisation and regime that are dark represent ingo work-function areas of weak electron emission. The sected are work-function areas of weak electron emission. The state and the state of the individual particles of an average linear and regime that area dark represent ingo work-function areas of weak electron emission. The state areas index and a spirous model to the too an average linear and a spirous and the state of the too and the too. The state areas of weak a spirous hole had a state of the tof the too the too. tungsten particles and activated them locally. The higher the temperature that the cathode is operated, the more likely a situation of this kind exists.

It is important for this discussion to attempt to represent in a two-dimensional diagram a motive function to be associated with this situation. It is quite evident that it is impossible to draw an exact representation but Fig. 6 may help to bring out the ideas that are involved.



Fig. 5-Hypothetical electron emission distribution over the surface of a very hot dispenser cathode.

In Fig. 5 one of the strongly emitting regions is identified as the "a" region, while a neighboring dark region is identified as the "b" region. The work-function of the "a" region is taken to be ϕ_a and the "b" region ϕ_b .

These work-function steps are shown in Fig. 6. If the a and b regions are of comparable size, then the motive function becomes something close to the average at a distance comparable to the average dimension of the patches of high work-function and low work-function area. This is illustrated by Fig. 6 by the fact that one line starts at ϕ_a and the other line starts at ϕ_b and they come together at a distance just outside the emitter comparable with the size of the individual patches involved. If the required potential is applied, shown as V_O , and the work-function of the collector is ϕ_2 , the motive function the rest of the way across the diode has no slope and therefore corresponds to the zero field condition. If the emitter is heated sufficiently to cause a strong electron emission, then the motive function will take on a form similar to that shown in Fig. 7. timgeten particles and activated them locally. The higher the temperature that the cathode is operated, the more likely a situation of this bird exists.

It is important for this discussion to attempt to represent in a two-dimensional disgram a motive function to be associated with this vituation. It is quite avident that it is impossible to draw an eract representation but Fig. 5 may halp to bring out the ideas that are involved.



Fig. 5-Hypothetical electron emission distribution ever the excises of a very bot dispensor cathoday

In Fig. 5 and at the strength emuting regions is identified as the "b" region, while a catabhoring dark region is identified as the "b" region. The work is often in Fig. 6. If the a and b to be d₀ and the "b" region 0; regions are of comparable size, then the molify function becomes regions are of comparable size, then the molify function and b work intelled to average at a distance comparable to the swarege dimension of the parameter of hup work-function and low work intelled area. This is illustrated by Fig. 6 by the fact that the size of the anticles is a state of the society of the swarege dimension of the parameters of hup work-function and low work intelled area. This is illustrated by Fig. 6 by the fact that the size of the individual sate is the molifier to emparable with the size of the individual sate is the molifier to be written to make that is a solution of the individual sate is the individual to the second the size of the individual sate is the individual to the second of the the size of the individual sate is a base of the second of the required potention is do, the motive function to rear of the way across the float is a size is do, the motive function to rear of the way across the float is a size is do into the real of the condition of the way across the float is the size of the real of the real of the second of the way across the float is the size of the real of the real of the second of the way across the float is the size of the real of the real of the second of the second of the second the size of the real of the second of the second size of the is the size of the real of the real of the second size of the second size is the size of the real of the second of the second size of the second size is the size of the size of the second size of the second size of the second size is the second size of the second size is the second size of the s



Fig. 6-Motive curves for non-uniform emitter no space charge - zero field.

A word description of Fig. 7 may be in order. The cruvature of the motive function indicates the existence of space charge. The minimum in the motive function found at B established the minimum electron energy within the interior of the emitter for which electrons can escape from the emitter to the collector. The value of this energy is shown as ϕ' . Thus any electron emitted from the high work-function area ϕ_h is accelerated into the space and moves over to the collector. It is to be expected that there will be a gradation in work-function from ϕ_a to ϕ_b close to the boundaries of the activated area. It is impossible to show in this diagram that additional detail, and therefore only the extremes of the motive function are illustrated. Note that in this figure there is an energy level indicated at ϕ_{\perp} which represents a peak in the motive function. Any positive ions generated at the surface will have to traverse this peak in order to find themselves in the space-charge region near B. This quantity ϕ_{\pm} is very important because of the fact that if it is less than 3.9 ev then the difference (3.9 - ϕ_{\perp}) V_T is related exponentially to the probability that an ion produced at the surface of the emitter will be able to pass into a region between the emitter and the collector. It is only here that it can be at all effective in reducing space charge.

The next problem to be considered in this qualitative manner is the influence of cesium vapor introduced at a moderately low density. Equation 19 indicates that at a cesium temperature of 390°K, the approximate mean-free path for cesium ions will be 1 centimeter. Furthermore, the relation given as Eq. 11 indicates that the minimum temperature for a pure tungsten surface to remain, on the average, in a state for which good ionization can take place will be 1410° K. It follows from this that a dispenser cathode operating at 1500° K will not be expected to adsorb an

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A word cancer joint of Fig. 7 may be in order. The crust, thus of the mether function indicates the existence of space charge. The minimum electron tenergy within the interder of the amiltar for which also tenergy is above as of . Thus any electron emitter is and moves even to the centre of . Thus any electron emitter is and moves even to the centre of . Thus any electron emitter will be a graduitor in work (unaction from ϕ_{0} to be expected that interbars discover as the centre of the centre of the source of the and moves even to the centre of the tener of the ϕ_{0} close to the bars discover even to the centre of the tener of the ϕ_{0} close to the discover of the electron is work (unaction from ϕ_{0} to ϕ_{0} close to the the discover of the electron of the tener of the space of the discover of the electron of the tener of the tener of the figure of the motive tener of the tener indicates at the tener of the space of the motive tener of the tener of the state is and the tener of the motive tener of the tener of the state is the figure of the motive tener of the tener of the state is the discover of the motive tener of the tener of the state is the state of the motive tener of the state is an of the collector of the tener is an experiment of the state of the state is the discover of the difference of the state of the state of the state is an of the difference of the state of the state of the state of the state of the difference of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the state of the state of the state of the state of the tener of the appreciable coverage of cesium. The low work-function areas will be very poor absorbers in any case, and they will also be very poor ionizers. The most efficient ionization will take place over those regions of the cathode for which the work-function is greater than 3.9 ev. Figure 8 attempts to illustrate in a qualitative manner the various influences which the presence of cesium is likely to have if the cesium pressure is controlled by a temperatureT_{Cs} equal to 392° K, and the emitter temperature is maintained close to 1500° K. The emitter to collector spacing is assumed to be approximately 1 mm.



Fig: 7-Motive curve for a nonuniform emitter with electron space charge.

In Fig. 8 the dotted lines are a superposition of Fig. 7 on Fig. 8 so that it will be easier to see a comparison of the two. Note that ϕ_a and ϕ_b are the same whereas ϕ_2 shows a measurable decrease to $\phi_2^{"}$. This decrease is the result of the adsorption on the collector of a film of cesium which in all probability will reduce the work-function on the collector by 0.4 ev. or more. If no other change took place as a result of the cesium, this would be distinct advantage. The new work-function is designated by $\phi_{2}^{"}$. In the drawing of Fig. 8, it is assumed that some of the ions produced at the hot emitter surface will find their way into the neighborhood of the potential minimum at B which in turn acts as an ion trap. In other words once that an ion is caught at an energy level lower in the diagram of Fig. 7 and ϕ_{\perp}^{\prime} , it will remain in that area more or less indefinitely since recombination between ions and free electrons is such an improbable event that the ion will remain trapped there, the potential minimum for a very long time. As additional ions are trapped there, the potential minimum will rise. This is illustrated schematically in

appreciable opverage sirvation. The low work function areas will be very poor absorbers in any name, and they will also be very poor tonizate. The use i efficient insiration will take place bies there regions of the callode for which the work-function is genetics then 1.9 av. Figure 6 attempts to illustrate is a qualitative mannar the vertees influences which the presence of cestum is likely to invaria if the continuences which the presence of cestum turat (a equal to 332° R, and the emitter temperature is mains turat (a equal to 332° R, and the emitter temperature is mains tained close to 100° K. The emitter to collector spacing is assumed to be attended to incluse the instruction of the second of the second of the beater stated in the rest of the second of t



Rig: 7-Motive-curve for a summineral emitter with

In Fig. 5 so that it will be excite to see a superposition of Fig. 1 on Fig. 5 so that it will be excite to see a comparison of the two. Note that is, and a, are the some wiscress of shows a matautable description to At. This description is the sil probability it as the collectul of a titu. of contine which is all probability will reduce the wark demokan as it continees by 5. 4 so. or more be distinct maximize to at Fig. 8, it is as somed in a designated be distinct assumed at the potential mathema is designated to a second distinct of the second of the context in the second be distinct maximize of Fig. 8, it is as somed into a some of the strong produced at the potential mathema at 3 which in their the remain in the trap. In other words make that some of the second distinct of the potential mathema at 3 which in the second distinction of the potential mathema at 3 which in the second distinction of the potential mathema at 3 which in the second distinction of the potential mathema at 3 which in the second distinction of the potential mathema at 3 which in the second distinction of the potential mathema at 5 which in the second distinction of the potential mathematic as induces that as and the second distinction of the second distinction of the second distinction of the second distinction of the second remain induces the second distinction of the second that the test second distinction of the second distinction that the test second distinction of the second distinction that he test second distinction is a second distinction of the second distinction of the second distinction of the second that the test second distinction of the second distinction that the test second distinction of the second distinction that the distinction of the second distinction of the second that the distinction of the second distinction of the second that the distinction of the second distinction of the distinction of the second dist

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Fig. 8 in that the potential minimum changes from B to B". This change in the potential minimum results in a corresponding change in the value of the limiting electron energy needed to transfer current from the emitter to the collectro. The new level is at ϕ'' . An objectionable change, from the point of view of being able to deliver ions to the space-charge minimum, is that indicated by the rise in the level diagram associated with ϕ''_{+} . Thus the rise to "B" because of the trapped ions results in a change of the motive function which inhibits the delivery of additional ions. Finally a balance takes place at which the delivery rate of ions is exactly equal to the loss rate. This condition more or less inevitably gives a rise in the electron minimum from B to B". This change results in a distinct gain in efficienty of the unit as a heat-to electrical-power transducer.



Fig. 8-Motive functions plasma diode compared with vacuum diode.

It will be assumed for the present that if the transducer is working under the most favorable conditions the voltage output V_O added to the receiver work-function $\phi_Z^{"}$ will actually be less than the energy difference from the Fermi kvel of the emitter to the "hump" in the potential function shown as $\phi_{\perp}^{"}$ in Fig. 8. In those circumstances the loss of ions from the space-charge region will be back to the hot emitter and not to the collector. If the problem were as simple as this then the density of ions at B" could be related to the ionization potential V_i by: Fig. 3 in that the potential minimum changes from B to B". This change in the potential minimum results in a corresponding change in the value of the limiting electron energy meded to transfer current from the emitter to the collectro. The new level is at 6". An objectionable change, from the point of view of being able to deliver ions to the space-charge continuum, to that indicated by the view in the level disgram ansociated with 4". Thus the rise to "B" because of the trapped tone musits in a change of the motive function which inhibits the delivery of additional ions. Finally a balance taken place at which the delivery rate of lone is exactly equal to the the electron minimum from B to B". This change results in a distinct gain in afficienty of the motive to the there is a taken the delivery of additional ions. Finally a balance the electron minimum from B to B". This change results in a distinct gain in afficienty of the multi as a nest-to electrical-power.



8-Morave functions plasma diada compared, with vacuum diada.

It will be assumed for the massent that if the transducer is working under the most lavarable conditions the voltage output Vo added to the receiver work functions, will actually be lease than the energy difference from the Fermi trial of the statter to the "bump" in the potential function above an eV in Fig. 8. In those circumstances the loss of ions from the space-charge ration will be back to the hot smitter and not to the collector. If the problem were as simple as this from the domain of ions at B' could us related to the ionization gotuntial V av



In this equation V_i is the ionization potential of cesium of 3.9 volts; n_s is the density of atoms in immediate neighborhood of the ionization surface, and the factor (1/4) is a guess made up of a combination of two facts. In the use of an equation of the form of Eq. 21 a factor of 1/2 is usually introduced as a so-called statistical weight and an additional factor of 1/2 is being introduced because of the fact that only part of the cathode is capable of producing ions. Once they are produced and caught in the potential minimum, the entire region is available for their occupation. This equation cannot be said to be exact but is offered here as a reasonable guess.

An additional fact needs to be considered which is that the ion production process will be characterized by the temperature T of the emitter, whereas the temperature that characterizes the distribution in energy of the ions that are <u>trapped</u> can very well be a lower temperature. This lower temperature could approach that of the neutral cesium vapor outside of the emitter-collector region for experimental tubes in which the spacing between the emitter and collector is not considerably smaller than the diameter of these surfaces. On the other hand, if the spacing is small compared to the diameter, then the characteristic temperature for the ions in the trap should be assumed to be approximately the mean temperature of the emitter and the collector.

In spite of the fact that the discussion applies to the conditions under which the mean-free path is large compared with the spacing, the ion may nevertheless come to thermal equilibrium with the atoms in the space because of the fact that it can oscillate back and forth many times and can therefore have a total distance of travel during its lifetime in the potential minimum much longer than the mean-free path. This detail can be considered to be a refinement which acts in the favorable direction from the point of view of the making of a practical and effective transducer.

Influence of Cesium Pressure in Association with a Nonuniform Emitter.

Under the circumstances illustrated in Fig. 8 an increase in cesium pressure will increase the rate of arrival of cesium atoms at the emitter. This increase in arrival rate will result in more adsorption of cesium on the high work-function areas. Once the cesium is adsorbed there, these areas will no longer be

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In this equation V is the ionization potential of contum of 3.9 voltaon, is the domaity of atoms in immediate telephorbood of the locatetion environce, and the factor (1/4) is a guage and de up of a combination divergent in the use of an equation of the form of Eq. 21 atom of 1/2 is usually introduced as a so-called statistical weight and an additional factor of 1/2, is being introduced because of the fact that only part of the contode is capable of producing ions, Gave they are produced and eaught in the potential minimum, the entire region is available for their occupation. This equation canting region is available for their occupation.

the ion production process will be characterized by the temperature T of the emitter, whereas the temperature that characterizes the distribution to margy of the least has are trapped and vary well he a lower temperature. This lower temperature could approach that of the neutral casime vapor outside of the emitter-collector region for experimental tubes in which the spacing between the emitter and collector is not considerably smaller than the dameter of the neutral to be the other hand, if the spacing is small compared to the disturter, then the characteristic temperature for the toms in the temperature and the considerably and ler the product compared to the disturter, then the characteristic temperature for the toms in the temperature and the constants to be approximately the mean the temperature of the constants and the collector.

In runse of the man-free path is large compared with the ditions under which the man-free path is large compared with the special, the tot hat neverthelers come to the main equilibrium with the assume in the space because of the fact that it can occillate back and forth mannet three must can the reform have a total distance of travel during the biforime to the parential minimum much longer than the mero-side path. This detail can be considered to hela refinement which and is the foromable direction from the point of refinement which and a practical and effective transducer.

Influence of Gasiam Francist in Association with a Nonuniformi-

Index he circumonances illustrated in Fig. 6 an increase in cestion pressure will increase the rate of arrival of cestum atoms at the unliter. This increase in arrival rate will result to in more adaption of register on the high work-lunction areas. . Once the castum is attached there, these areas will no looser be very effective at producing ions. The effect to be anticipated then will be a raising of the limiting level ϕ''_{+} . This change will work to disadvantage in that it makes it more difficult for the ions that are produced to find their way to the region marked B". The lack of a suitable ion density at B" will result in a lowering of this level or an increase in the value of ϕ''_{-} . Thus it is to be anticipated that other things being equal, the increase in cesium pressure will first result in a raising of the potential minimum for electrons from B toward B" with an increase in cesium pressure toward its <u>optimum</u> but additional cesium pressure will result in a decrease in the available current for the transducer. The important point is to try to establish the optimum pressure and this

out indicates that an optimum is likely.

Loss of Positive Ions to the Collector

As the output voltage V_0 is increased at the expense of some decrease in electron current, the difference in potential between the potential minimum at B'' and the surface of the collector at b will decrease. At the critical condition expressed by:

may be possible only by experiment. The theory as so far carried

$$V_{O} + \phi_{2}'' = \phi_{\perp}''$$
 (22)

ions will begin to escape to the collector to the same extent that they escape to the emitter. If V_O is made still larger, then the principal loss of ions will be at the collector surface and this rate of loss must be supplied by the ions which are able to pass over the ion barrier at ϕ_+^{u} . As V_O is made larger, it will be slightly easier for ions to escape from the emitter. This increase in yield may not be sufficient to maintain the desired trapped ion density.

Under the conditions shown in Fig. 8 there is a difference in potential between the space-charge minimum at B" and the surface of the collector which is numerically equal to

$$\phi''_{-} - (V_{0} + \phi''_{2}) = V_{0}. \qquad (22a)$$

This potential difference does not represent a loss of energy by the electrons because of the presence of the neutral cesium atoms, but is simply a difference needed to satisfy the space-charge relations. The reader must be reminded that the situation in this part of the plasma discharge is an entirely different one from that found in self-sustained low voltage arcs, because there the difference in potential along the plasma column is one that is will be a rateing of the limiting lovel 42. This charge will work to disadvantage in that it musces it more difficult for the ions that are produced to find their way to the region marked IP. The fack of a suitable ion density at BP will result is a lowering of this level of a suitable ion density at BP will result is a lowering of this level of a suitable ion density at BP will result is a lowering of this level of a suitable ion density at BP will result is a lowering of this level if an increase in the value of 62. Thus it is to be anticipated that thest result in a relating of the potential minimum for electrons from B toward BP with an increase in costium pressure will from B toward BP with an increase in costium pressure to a it optimum but additional estima pressure will treat in a duritant is to tre to establish the optimum pressure and this and point is to tre to establish the optimum pressure and this and point is to tre to establish the optimum pressure and this

Loss of Positive Inta in the Collector

As the output valless of a intraced at the expense of autre decrease in electron carrient. The difference in potential between the potential minimum at 3' and the surface of the collactor at b will decrease. At the critical coulding expressed by:

ions will begin to excape to the collecter in the same extent that they excape to the emitter. $V Y_{ij}$ is made all larger, then the principal loss of the volities of the collector surface and this est of loss must be supplied by the tone which are able to pass over the ion isrriter at δf_i . As V_{ij} is much theger it will be alightly essible for time to accape from the emitter. This increase in yield may not be sufficient to maintain the desired rangend in density.

Under the conditions shown in Fig. 6 there is a difference in potential between the space-charge filmliftum at D" and the surface of the collector which is numerically equal to

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This potential difference done has represent a loss of energy by the electrons broages of the privating of the neutral centum atoms but is simply a difference anoded to setisty the space charge relations. The restairmust he reminded that the situation in this part of the plasma discharge to an outingly different one from that found in self-substained low voltage area, because there the difference in potential along the plasma column is one that in determined by the rate at which energy must be put into the system in order to maintain the excitation and ionization of the plasma. In the transducer, no ionization whatsoever takes place in the space since all of the ions are produced at the heated emitter surface unless some auxiliary electrode is introduced. For the present discussion it is assumed that the only two electrodes in this diode are the nonuniform emitter and the uniform collector.

An Interpretation of Data Taken on An Experimental Diode

A diode was constructed for study by Mr. Thomas Robinson of the Thermo-Electron Engineering Corporation which had two dispenser-type cathodes, each 3 mm in diameter separated from each other a distance of 0.68 mm. One of these dispensers was heated to 1520° K and before cesium was admitted to the tube, a current voltage characteristic was obtained over the range of applied voltage from zero to -2.2 volts with the receiving electrode negative with respect to the emitter. These data were plotted as shown in Fig. 9 and compared with the ''master curve''⁽²⁾. The solid line of this figure is the master curve and the index of that curve establishes the value of (V_R/V_T) of 10.4 and a corresponding value of V_R of 1.37. These numbers combine in the formulae given here as Eqs. 23 and 24 permit the calculation of the maximum power available from this diode and the voltage output at which maximum power occurs.

$$P_{\text{max}} = 3.7 \times 10^{-6} V_{\text{T}}^{1/2} \frac{\text{R}}{\text{w}^2} \text{ watt/cm}^2$$
 (23)

$$V_{\rm O} = \frac{0.383 \left(\frac{V_{\rm R}}{V_{\rm T}}\right) V_{\rm R}}{1+0.31 \left(\frac{V_{\rm R}}{V_{\rm T}}\right)^{4/3}}$$
(24)

In Eq. 23 the distance w is expressed in centimeters for the calculation of the maximum power available in watts/cm². The insertion of the figures mentioned gives a predicted $P_{max} = 5.5 \times 10^{-4}$ watts/cm₂ and the voltage output at the maximum power is 0.683. The current at maximum power is given by;

$$I_{max} = I_{m} \left[1 + 0.31 \left(\frac{V_{R}}{V_{T}} \right)^{4/3} \right]$$
 (25)

account to marinera the excitation energy must be put into the system is could in marinera the excitation and ionization of the planta halfs similarity of the ions are moduced at the heated emilter system there exit of the ions are moduced at the heated emilter system if directed to is accurated that the only two electrodes in standard directedes in accuration that the only two electrodes in standard directedes in accuration emiliary mathematics and the militer to the standard directedes in accurated that the only two electrodes in standard directedes in contactors and the uniform collector.

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In Eq. .24 the distance wis expressed in centimeters for the salculation of the site structure power available in watts /cma. The inserriezed the diguess mentioned gives a predicted Press 15.5 x 10⁻⁴ mits irms and the voltage outget at the maximum power is 0.683. The current at meatimum power is given by:

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Robinson measured the power delivered to the load in his experiment as a function of the output voltage and obtained the curve designated "without cesium" of Fig. 10. It is clear that the maximum power was correctly calculated by theory and the voltage output at maximum power was correct as shown by the circle on that graph. Later cesium was admitted to the tube and the available power again measured as a function of the voltage. This result is also shown in Fig. 10 and it is very evident that the favorable action of the cesium increased the power a factor of 10.

Before the details concerning this second experiment are discussed, a few additional computations should be made relative to the high vacuum experiment. A calculation chart, shown here as Fig. 11 shows that with this operating temperature and spacing, a current density of 100 microamperes per square centimeter should have been expected in terms of the temperature-spacing relation for the critical current density I_m which flows to the collector with a space-charge minimum coinciding with it. This situation is illustrated by the dotted lines of Fig. 12.

8 - 23

For the present experiment Imax = 7.96 Im.



Fig. 9-Experimental results and cumparised with space-charge theory for vecture diede. Data from Robinson of T&E.

Relations measured the power delivered to the load in his experiment as a function of the output voltage and obtained the curve designated "without casim," of Fig. 10. It is clear that the manimum power was correctly calculated by theory and the voltage output at maximuch power was correct as shown by the circle on that graph. Later casim, was admitted to the tulk and the sould be size along the measured as a hupetion of the voltage. This yeards is also along in Fig. 10 and it is very evident that the discussed, a few additional concerning this meaned experiment are before the high recurs descripted the power a factor of 10. This yeards is few additional concerning this meaned experiment are descripted to find a set with the operating temperature and stacting, the he high recurs that with the operating temperature and stacting, are the high recurs of the relative the temperature and stacting, with a space-charge minimum of the temperature-spacing relation to the time expected in the term of the temperature and the state of the context of the temperature of the collector with a space-charge minimum of the temperature-spacing relation to the time expected in the me of the temperature spacing relation

for the present experiment limit T. Sh In



Fig. 10-Plasma diode (with cesium) vacuum diode (without cesium).

The actual value of ϕ_R applicable to this experiment may be calculated by:

$$\phi_{\rm R} = 2.3 V_{\rm T} \left[2.08 + 2 \log_{10} T - \log_{10} I_{\rm m} \right]$$
 (26)

The value of ϕ_R is 3.73 ev. The fact that the observed current voltage characteristic follows the "master curve" so well, as is illustrated by Fig. 9, indicates that the inhomogeneity of the collector is relatively small but does seem to be present, and furthermore, such inhomogeneity as may exist at the emitter probably represents a small part of the area. It will become evident as the calculation proceeds that it will be desirable to invoke the concept that some inhomegeneity does exist and that potential functions not unlike those shown in Fig. 7 and 8 will be involved as a step in the analysis to explain the increased power shown by the curve in Fig. 10 in the presence of cesium. The numerical data mentioned are summarized in Fig. 12

8 - 24





The authal value of vig applicable to this experiment may

An = S.1 Vr [2.08+2-10 mg - log int

The value of $\frac{1}{20}$ is 3.73 ev. The fact that the observed current voltage characteristic follows the 'master curve' so well, as is illustraised by Fig. 7, indicates that the inhomogeneity of the collector is relatively small but does seem to be present, and (gruber more, such inhomogeneity as may exist at the emitter press biy inpresents a small part of the area. It will become routers as the cilculation proceeds that if will be desirable to present in the information of an information in the least invident as the cilculation proceeds that if will be desirable to protential finantions and units the oreact in Fig. 7 and 8 will be above by the curve in Fig. 10 in the presence of occlumn. The above by the serve in Fig. 10 in the presence of occlumn. The

		Spacing
The state and the state and	Current density	0.01cm - 1 µ
	current /cm ²	
Temperature	10 m a - 100 amp - 80 - 60	İ.
TOK V AN	40	T 2
	- 30	+
0.30	- 20	+ 3
10.20		5
	Ima + 10 amp	
2800 - 0.24	+ 6	T 4
2600 - 0.22	4	+ 5
- 0.20	- 3	
2200 + 0.19	- 2	+ 6
2000 - 0.17	1	+
0.16	100µa - 1 amp	+ 8
1800 - 0.15	T 0.6	+
1600 - 0.14	0.4	0.1cm - 10 µ
1500 - 0.13	- 0.3	
1400 - 0.12	+ 0.2	West The State
1300 - 0.11	Bar Statement	Ť
1200-01	10 µ a + 0.1 amp	
1100-	1 0.08	+ 20
+ 0.09	0.00	· · · · · · · · · · · · · · · · · · ·
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(for w in cm) w	1 0.004	+ 60
Hand. der Physik, XXI (1956).	am, 0.003	1
Chart gives distance to space-charge minimum as a	1 0.002	- 80
than w.	0.140 - 0.00100	
		1 cm - 100

Fig. 11-Current density-Temperature-Spacing relation in ideal high vacuum diode for onset of space-charge limitation (zero field at surface of collector).



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Fig. 12-Motive curve in experimental highvacuum diode.

The basic data upon which the remaining part of this analysis depends are illustrated in Fig. 13. The two curves on this figure show the current-voltage relations as observed with and without the cesium. The liquid cesium temperature was 316° K and this according to Eq. 9 gives an arrival rate at the emitter of 1.4×10^{15} atoms per second for each square centimeter. The estimated collector temperature was 780° K. A sufficient coating of cesium was adsorbed on the collector to <u>reduce</u> its work-function by 0.45 volts as indicated by the horizontal shift in the retarding potential range when one compares the two curves. This yields a collector work-function of 1.9 volts. If the entire curve had shifted horizontally only, then the change in power output would have been due only to the lowering of the work-function of the receiver. The new curve is not one obtained by a parallel shift.

The cesium data when plotted as in Fig. 14 can again be reasonably well represented by the "master" space-charge curve for electrons. The main difference on analysis, however, is that the current under the critical condition of zero space-charge at the collector is one which would have been associated with a shorter distance than the actual one. The chart on Fig. 11 permits a quick calculation of this distance to be 0.23 mm. It is to be noted by reference to Fig. 12 that the new condition, in the presence of some space-charge neutralization from cesium atoms, is practically as though a diode had been created with the collector located precisely at the potential minimum illustrated in Fig. 12 for the condition of maximum power. This result suggests the drawing of the potential distribution as shown in Fig. 15. The number of electrons that cross the boundary at B per second for a unit area is 5.6 x 10¹⁵. This current would correspond to a density of

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Fig. 13-Motive curve in experimental ligh-

The basic data upon which the remaining part of this markets depends are illustrated in Fig. 13. The two curves onvise figure show the current-voltage relations as observed with and visions the commen. The liquid costant managerature wat hick is and this accurding to fig. 9 given marrival rate at the emitter of it 5 a 10¹⁰ status per escond for each square creatments. The estimated cellector temperature was 780° K. A sufficient coating to a content when one comparents was 780° K. A sufficient coating by V. 45 volta as failented by the horizontal shift in the retating a collector when and compares the two curves. This visites to collector when and compares the two curves. This visites to a collector when and compares the two curves. This visites a collector when the lowering of the work-function of the sector weather the lowering of the work-function of the sector weather and the lowering of the work-function of the sector weather and the lowering of the work-function of the sector weather when and compares the two curves of the sector with a the lowering of the work-function of the sectors. The two dates are status and the receiver. The two dates are status work-function of the sectors.

remembly will represented by the "mastar" space charge curve for electrons. The main difference an analysis, however, is that the collector is one which would have been associated with a shorter distance than the actual one. The chart on Fig. 11 justmiss a quick calculation of this distance to be 0.23 mm. It is to be noted by reference to Fig. 12 that the new condition, in the presence of the condition of the distance to be 0.23 mm. It is to be noted by the condition of the distance to be 0.23 mm. It is to be noted by the total presence of the prime fight is the master of the space of the prime is a marked to be noted by there is a the prime distance to be noted by the total presence of the prime is and the presence of the fight is the prime is a shown on Fig. 12 the total presence of the prime is a shown on Fig. 13 for the condition of maximum is an indicated to Fig. 13 the total presence of the prime is a shown to Fig. 15. The director is a start of the prime is a shown to Fig. 15. The





Fig. 13-Current-voltage relations observed in vacuum diode and plasma diode at 1520°K. Data from Robinson of TEE.







Fig. 14-Experimental results and comparison with space-charge theory for plasma diode. (Vacuum diode for comparison). Data from Robinson of TEE.



throwy for plasma dioda. (Vacuum discis for compar-

electrons of 4.6 x 10^8 electrons per cubic centimeter. This calculation is based on the estimated average velocity of a Maxwellian group of electrons characterized by the temperature 1520° K to be 1.2 x 10^7 centimeters per second.



Fig. 15-Experimental plasma diode with zero field at the collector.

With no more data than we have at present, it is altogether reasonable to assume that with an arrival rate of neutral atoms at the heated surface, in the neighborhood of high work-function territory, of 1.4×10^{15} atoms per second for each square centimeter the density of ions right at the surface will be 1.25×10^{11} ions per cc. This calculation depends on the assumption that very close to the high work-function area, the "random current" of ions given by the equation

$$I_{p} = n_{po} \left(\frac{kT}{2\pi M}\right) \quad (ions/sec) / cm^{2} \qquad (27)$$

Under this condition ion production is exactly equal to ion annihilation and the production rate depends on the atom arrival rate. In Eq. 27, I_p is the random ion current expressed in ions arriving at the surface per second for each square centimeter. The density n_{po} is taken to be the ion density in the immediate neighborhood of the surface. The ion mass is M.

The experimental data permits the calculation of the energy difference between the Fermi level of the emitter and the limiting barrier B to be 3. 47 ev as shown in Fig. 15. If the density of ions there is taken to be equal to the density of electrons, the energy difference between B and the average surface at which ions are produced can be approximately 0. 61 ev. Under this condition, the effective surface potential will be close to 4. 1 ev. Fig. 15 has been prepared on the assumption that a surface for ionization does, in fact, exist at 4. 1 ev away from the Fermi level of the emitter. On the basis of present knowledge with regard to these surfaces, any ionization surface with a work-funcelectrons of 4. 6, p.102 electrons per cubic centimeter. This calculation is based on the estimated average velocity of a Maxrealising group of electrons characterized by the temperature 1920°R to be 1.2 x 10⁷ centimoters per second.



Fig. 15-Experimental plasma diede with zero

With no more data than we have at present, it is altogether reaccomble to assume that with an arrival rate of neutral stoms at the heated surface, in the neighborhood of Figh work-function territory, of 1.4 x 10¹² atoms per succed for each square centimeter the density of ions right at the surface will be 1.25 x 10²¹ ious per co. This calculation depende on the assumption that very close to the high work-function area, the "random surrent" of ions given by the equation

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The experimental data parmits the calculation of the avergy difference between the Fermi level of the eminer and the limiting barrier & to be 3. 47 as as shown in Fig. 15. If the density of four three is taken to be equal to the density of electrons, the energy difference between B and the average christs at which isses are preduced can be approximately 0. 51 as. Under the quadities, the affective surface potential will be close to 4.1 ev. Fig. 15 has been prepared on the essent piller that a surface for invitable dees, to last, exist at 4.1 as away from the Fermi jevel of the contract. On the basis of present knowledge with reserved to these services, any ionization surface with a work-timetion greater than 3.5 ev could deliver ions to the region at B with approximately the same efficiency. When the work-function is less than 3.9, then many of the neutral atoms that arrive at the surface are likely to leave as neutral atoms and therefore the ion production will not be as great as it would be if the workfunction were higher. Thus, as the work-function increases, the effectiveness of the surface as an ion producer increases but the fraction of those ions produced that can find their way over the ion barrier identified here as ϕ''_+ is reduced by an exponential function of the type exp - $(\phi_b - \phi''_+)/V_T$.

Since the data shown in Fig. 14 fit the idealized master curve within experimental error, the numbers derived from it may be used to compute the maximum power to be expected from the device. The value of (V_R/V_T) for this curve is 11.8. The corresponding value of V_R is 1.53 ev. Eqs. 23 and 24 may be used to compute the maximum power and voltage output at maximum power. The results thus obtained are $P_{max} = 6.15 \times 10^{-3}$ watts per cm² and the voltage output is 0.73 v. These calculated results are represented by the cross with the circle in Fig. 10 and agree well with experiment. The electron current density at maximum power is 8.4 x 10⁻³ amp/cm².

Determination of the Optimum Cesium Temperature

It is impossible to predict with confidence the optimum cesium temperature because of the lack of needed experimentally determined data applicable to this problem. This section will, therefore, have to depend on the making of a few simple assumptions and if these hypotheses are proven wrong, then the predictions based on them will certainly be in error.

The first assumption is that the zero field condition illustrated by Fig. 15 is determined by the equality of the positive ion and the electron densities. For equality, the arrival rate of ions and electrons must be related by:

$$\left(\frac{v_{-}}{v_{+}}\right)_{\text{at B}} = \left(\frac{M}{m}\right)^{1/2}$$

(28)

In this equation M is the mass of an ion and m is the mass of an electron. The relations represented here imply that both ions and electrons leave the region by going to the collector and since the velocities are inversely proportional to the square root of the mass ratio the ion current will be correspondingly lower for the zero space-charge condition. In order to use this assumption in a numerical calculation, the "effective" average work-function of the ionization region must be know. The experiment described in the previous section gave a value as $\phi_b = 4.1$. The equation which will relate the important quantities is the follow-ing:

then greater than 3.3 ev bould deliver tone to the region at a with approximately the same efficiency. When the work-function is least their 3.9, their many of the neutral atoms that arrive at the sortace are likely to leave as neutral stame and therefore, the lar production will not be 28 great as it would be if the workfunction were higher. Thus, as the work-function for rease the disctiveness of the surface at an ten preducer increases in the fighting of the surface at an ten preducer increases in the fighting of the surface at an ten preducer increases in the fighting of the surface at an ten preducer increases in the fighting of the surface at an ten preducer increases in the fighting of the surface at an ten preducer increases in the fighting of the surface at a t_{1} to reduced by an exponentthe increase of the type $t_{1} = t_{1} = t_{1}^{2}$. We

Determination of the Optimum Certain Tumperature

It le impossible to predict with conficence de animum issetempleratore because of the lack of meded capitrimentally debrimined data applicable to this problem. This section will, therefore, have to depend on the making of a few simple assumptions and if these bypotheses are proven wrong, then the predictions based on them will certatoly be in error.

The first assumption is that the serve itsid concluded then that dd by Fig. 15 is determined by the equality of the positive ion and the electrons these these. For equality, the arrival rate of inte and piectrons thus the related by:

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In this equation is in the mass of an ion and m is the mane of an electron. The relations represented here imply that both ions and electrons leave the region by going to the collecter and since the velocities are inversely proportional in the square root of the mode ratio the less corrects will be correspondingly lower for the were enter others condition. In order to one this resumption is a numerical relation, the "elloptice" everage workthe function of the contents region name to know. The experiment dimetion which will relate the temperature or allow is the follower equation which will relate the temperature quantities is the follow-

$$\phi_{\rm R} = \frac{\phi_{\rm b}}{2} - 10.68 \, {\rm v_T} + 2.3 \, {\rm v_T} \, \log_{10} \, {\rm T} + \frac{4490}{{\rm T_{Cs}}} \, {\rm v_T}$$
 (29)

The numerical validity of this equation may be tested by inserting into it the values associated with the experiment described in the previous section. When this is done the calculated value of ϕ_R is 3.47 ev on the assumption that ϕ_b is 4.1.

In order to determine the optimum value of T_{Cs} , use is first made of the relation shown as Eq. 11. The implication here is that unless some other factor interferes, the best choice of the cesium temperature will be the highest that will result in effective ionization on a tungsten surface. Certain interfering factors will be discussed later in this section.

According to Eq. 11, the maximum cesium temperature is 425° K for an emitter temperature of 1520° K. These two figures are supplemented by the assumption that the previously determined value of $\phi_{\rm b}$ of 4.1 is suitable. The predicted value of $\phi_{\rm R}$ at this higher condensation temperature of cesium is then 3.0 ev. This new value represents a reduction in $\phi_{\rm R}$ of 0.47 and a corresponding increase in electron current delivered to the collector by a factor of 36. The current density expected is 3.2×10^{-2} amp/cm². The chart of Fig. 11 may now be used to determine that the effective spacing of the diode in the presence of this increased cesium pressure will be 39 microns.

At the lower cesium pressure the average work-function of the collector was found to be $\phi_2 = 1.94$ ev. There is no way to know for sure that an increase in cesium pressure will decrease this average work-function still more but for the purpose of illustration at least, it will be assumed that the increase in pressure will reduce the work-function to 1.70. The predicted value of V_R is then:

$$V_{\rm R} = \phi_{\rm R} - \phi_2 = 3.00 - 1.70 = 1.30$$
 (30)

The corresponding value of (V_R/V_T) is 10.

The next assumption is that having established the equivalent spacing of a vacuum diode which would have the same current density as the cesium diode the current voltage characteristics will follow the vacuum diode curve associated with this reduced spacing. The new spacing for this calculation is the one given as 39 microns. Eqs. 23 and 24 may be used to determine the predicted maximum power output and corresponding voltage output. The values obtained are $P_{max} = 0.15 \text{ w/cm}^2$ and V_0 is 0.65. The current density is 0.23 amp/cm². The corresponding value for ϕ''_{-} is 2.74 ev. It is implied in these calculations that the true work-function of the emitter ϕ_a is less than 2.6 ev. The chief advantage in having a smaller value of ϕ_a for the electron emitting portion of the emitter is its influence on the value "The numerical validity of this equation may be tested by inserting fute it the values associated with the experiment described "A vie previous contine. When this is done the calculated value of the 1. If a v an the accuration that the is done the calculated value (A redevice the accuration that the is done the calculated value of the redevice of the relation at high 11. The implication has there made of the relation shown as high 11. The implication has a thirt unless nome other factor interforms, the best choice of

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sab⁴U: for an amilitar temperature of 1550⁴U. These two figures are supplemented by the assumption that the previously jetermaned value of on of 5.1 is subtable. The predicted value of § at this higher condensation temperature of centum is then 3.0 ev. This new value represents a reduction is dg of 0.47 and a corres purched increase to electron current delivered to the collector by a factor of 36. The current density expected is 3.1 × 10⁻² amplomed. The chart of Figs 11 may now be used to determine ther the discrive spacing of the flow in the presence of thus increased centum pressure will be 39 microirs.

At the invest negative pressure the average wave-tenetion of the collector was found to be dy 2.1.94 cv. There is no way to know for sure that an intrease in cathom pressure will decrease this average work-function will be assumed that the increase in pressinterval reduce the work-function to 1.70. The predicted value of Ve for there

 $X_{22} = V_{23} + V_{23} = 0.100 + 1.100 + 1.300$

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The next assumption is that having establighed the equivalent specing of a vacuum diode which would have the same current density as the ceatum diode the surrent voltage characteristics will follow the vacuum diode corve associated with this coduced botting. The new spacing for title calculation is the one given at 37 miterone. Eqs. 23 and 54 may be used to determine the predicted maximum power context and corresponding voltage outtractice the trac voltage obtained are $P_{max} = 0.15$ w/cm² and V_0 is 0.55. The correspondence of the implied in these calculations that the trac voltage is baving a smaller of the the set that 2.5 evithet the trac voltage is having a smaller of the the electracted disting the baving a smaller of the the elec-

(25).....

of ϕ' , which is the hump in the diagram of Figs. 15 and 16 that inhibits the loss of ions to the emitter and thus helps maintain the space-charge reduction.

This prediction that an additional 24-fold increase in power is available in the cesium diode over that actually obtained as a result of increasing the cesium pressure is probably optimistic. The calculation has been made in this manner in order to indicate the potential advantages in choosing the most favorable value of the cesium condensation temperature. At this higher temperature Eq. 19 permits the estimation of the cesium ion meanfree path to be 1.8 mm. Since the electron mean-free path is undoubtedly longer than this, the implication is that a diode spacing of 1 mm would be just as effective in the presence of cesium as a diode spacing of 100 microns. Associated with the current density of 0.23 amp/cm², the chart on Fig. 11 permits the location of the space-charge minimum to be calculated as 14.4 microns.

In the calculations of this paper, electron energy steps are expressed in terms of their true values at the temperature involved. Therefore the fundamental equation obtained directly from the statistical analysis expresses the current density in the following form:

$$I = 120 T^2 e^{-\frac{\phi}{V_T}} amp/cm^2$$
(3)

This is the Richardson type of equation and carries with it the number 120 instead of some empirically-determined constant that could be designated as AR to indicate that it is the Richardson constant found empirically to make the data fit for some set of observations for which the Richardson work-function would be appropriate. Since "true" values of ϕ are used in the analysis given here, the coefficient 120 is the only correct one to use.

For calculations in which it is the purpose to determine the temperature at which a certain emission density will be obtained, Eq. 31 is not the most convenient one to use. The theory behind the transformation to a simple equation is given in Section 50 of "Thermionic Emission" and two useful equations may be obtained from Eq. 31 to be applied over the emitter temperature ranges associated with each of these equations:

Range $1150^{\circ}K < T < 2500^{\circ}K$ $T < 2500^{\circ}K$ I = $3 \times 10^{9} - (5.04\phi + 1.6) \frac{1000}{T} \text{ amp/cm}^2$ (32) $\log_{10}I = 9.48 - (5.04\phi + 1.6) \frac{1000}{T}$ (32a)

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of any which is the builty in the disgram of Niger 15 and 16 that individual the loss of inna to the smitter and thus helps maintain the space-charge reduction.

This prediction that an additional 24-fold increase in power is contable in the costum diade over that actually optimistic, received increasing the cestum pressure is probably optimistic, The estemation has been made in this manner to order to indicate the patential edvantages in choosing the most favorable vaiue of the contum contenantion temperature. At this higher tomparange Eq. 19 permits the setimation of the cestum into mannthree path to be 1.6 mm. Since the electron mean-free path is undentially longer that the implication is that a diade spacing of 1 mm would be just as affective in the presence of cestum as a diade spacing of 102 micross, hereotisted with the correct density of 0.41 amp/emf. the chart on Fig. 11 permits the incation of the space-charge minimum to be colouinted as 14, 4 miction of the space-charge minimum to be colouinted as 14, 4 mic-

In the axiculations of this paper, electron energy steps are expressed in terms of their true values at the temperature involved. Therefore the fundamental equation obtained directly from the statistical analysis expresses the correct density in the followner form:

Tals is the Richardson type of squatton and cattles with it the number 110 instead of some empirically-determined constant that could be designated as is to indicate that it is the Richardson quantum found empirically to make the data fit for some set of otherrentens for which the Richardona work-function would be appropriate. Since "true" values of I are used in the analysis given here, the coefficient [20 is the only eprived as to det in it'rent asternation in which this the purpose is determine the formerstant of the coefficient for the the purpose is determine the solutions and which this the purpose is determine the

the transformation to a simple equation is given in Section 50 of "Thermionic Emission" and two metal equations may be obtained it on Eq. 31 to be applied over the antitler temperature ranges associated with ouch of these equations:

1000 1158"5 < T 4 2500°X 1000 1000 1000 1000 1000 1000 1000

Range 600°K < T < 1150°K

$$8-(5.04\phi + 0.76)\frac{1000}{T} \text{ amp/cm}^2 \quad (33)$$

$$\log_{10}I = 8.85 - (5.04\phi + 0.76)\frac{1000}{T} \quad (33a)$$



Fig. 16-Motive function for plasma diode.

The principal purpose of the above equations is to show the steps toward the writing of a simple equation by which the maximum temperature of the collector can be evaluated readily in terms of the available output volts V_0 and the energy step ϕ'' illustrated in Fig. 16 and the temperature of the electron emitter of the diode T_1 . The way this equation is written incorporates also the limitation that the electron current streaming from the collector toward the emitter shall be no more than 5 per cent of the electron current that flows in the opposite direction. This equation subject to these conditions and definitions permits the calculation of the maximum receiver temperature.

$$\max T_2 = 1000 \frac{5.04 (\phi''_1 - V_0) + 0.76}{0.65 + (5.04\phi' + 1.6) \frac{1000}{T_1}}$$
(34)

In the analysis just completed it was assumed that ϕ'' is 2.74 ev, V_O is 0.65, and T_1 is 1520° K. With these values substituted into Eq. 34, the maximum temperature of the collector is found to be 1040° K.



Flat. 16 Martice Junction for plasma diode.

The principal purpose of the above equations is to show the steps toward the writing of a simple equation by which the maximum strangeresture of the collectors can be evaluated readily in terms of the evaluable output volts Vo and the energy stop 42 filmutratad in Fig. 15 and the temperature of the electron emitter of the diode T₁. The way this equation is written incorporates also the biomitathed that the electron correct atteaming from the delicetor iterated the emitter shall be no more than 5 per cast of the electron current that the state of the opporte direction. This equation and the maximum readilities and definitions permits the calculation at the maximum readilities and definitions permits the calculation of the maximum readilities and definitions permits the calculation of the maximum readilities and definitions permits the calculation

In the analysis just completed it was assumed that θ_1^{α} is 2. 76 ev. Ye is 0. 65, and T_1 is 1520°K. With these values substituted into Eq. 34, the maximum isoperators of the collector is found to be 1040^{9} K.

Operation Considerations Related to Diodes Having High Work-Function Emitters

8 - 34

If the source of heat is one which lends itself to the use of a very high work-function emitter, then other considerations may be important. Under ordinary circumstances, it should be anticipated that the lower temperature at which the emitter can work, the more likely one is to have an efficient device. However, efficiency may not be the most important criterion. In fact, it could be that power per unit volume would be far more important than conversion efficiency. Under these circumstances, thought should be given to the operation of high temperature emitters.

Assume for this discussion that the emitter temperature is 2400°K and that it is realistic to make a diode of 100 micron spacing. Calculation shows that the space-charge minimum will coincide with the collector when the current density is 0.009 amp/cm². An emitter with an average work-function of 4. 4 ev would have an emission current available of 0.37 amp/cm². A high vacuum transducer would require a low work-function collector which could under favorable conditions have an average work-function of 2 ev and a V_R = 3.17. Under these conditions, the critical value of (V_R/V_T) is 15.3. This diode would have the maximum power available with a current received at the collector of 0.115 amp/cm². The power available to the external circuit would be 0.168 watts/cm². The question that may now be asked is: what improvement should be expected in this diode by the introduction of cesium, and what would be the most suitable cesium pressure as determined by the temperature of the liquid cesium?

The first effect of cesium if the collector temperature could be maintained at a sufficiently low value would be to reduce its work-function. Assume that the absorbed cesium would reduce the work-function to 1.4 ev. Such a change would have a very favorable influence on the power output. Secondly, all of the cesium atoms which would in their normal motion come in contact with the emitter would leave as ions. Very few of these ions would be lost to the collector since its surface would be 0.9 volts more positive than the emitter surface if the external surface conditions were maintained to hold the current at 0.115 amp/cm² in the absence of space-charge neutralization. Actually, as the cesium pressure increases, the ions will tend to neutralize space charge and the electron current achieve its full capability of 0.37 amp/cm². This current should remain constant as the output voltage is increased to 3 volts. The combination of these two effects would increase the available power a factor of 6.6, since the maximum power we would expect is:

$$0.37(4.4 - 1.4) = 1.1 \text{ watt/cm}^2$$

2

(35)

Operation Considerations Related to Diodes Having High Work-

(If the source of heat is one which lands itself to the dec.or a very light sorie-innerton smitter, then other considerations may be therefore that Under ordinary circomstances, it should be nullcipated that the lower temperature at which the antiter can work, the white likely one is to have an efficient device. However, eftrivisery may not be the most important criterion. In fact, it could be that power per unit volume would be far more important that converter of the lower that volume sould be far more important about the given to the operation of high temperature antiters.

Assumes for this discussion that the smither competential is ing. Calculation shows that the space-charge minimum will comcide with the collector when the space-charge minimum will coman emission certain available work-function of 4, 4 ev smuld have an unisation certain available of 0.37 amp/cm². A high vacuum traindness would require a line work-function of the vacuum of 2 ev and a Vg = 3, 17. Under these conditions, the artifical conditions of the scattable conditions inve an average work-function of 3 ev and a Vg = 3, 17. Under these conditions, the artifical power available with a current received at the collector of 0.115 and/cm². The power available to the external circuit would be and/cm². The question that the saternal circuit would be increased at the scattable to the external circuit would be and/cm². The question that the staternal circuit would be increased by the temperature of the inter the stated is what and contains, and what would be the most ratio of the terminal increased by the temperature of the inter stated is what conditions the states of the inter state of the state of the increased of the temperature of the interval increased is the temperature of the interval circuit would be and the terminal be the interval contained to the increased of the temperature of the interval circuit pressente increased by the temperature of the interval circuit pressente and the terminal by the temperature of the interval circuit pressente and the state of the interval contain pressente and the terminal contain the state of the interval circuit pressente and the terminal contained by the temperature of the interval circuit pressente and the state of the interval circuit circuit of the state of the interval circuit of the state of the terminal circuit of the state of the interval circuit of the state of the termin pressente of the termin termine of the termin termine of the termine of the state of the termine
be real interteent of contrast to value would be to redurn the work-function. Assume that the absorbed contum would redure the variation of a second between output, Secondly, all of the conlaverable influence on the power output, Secondly, all of the conlaverable influence on the power output, Secondly, all of the converts his contitlet would is their minical motion come in contact would be test to the collector since its evidence of these long in the absence of space charge neutralization. Acrually, as the confiltures were maintained to hold the current at the antical in the absence of space charge neutralization. Acrually, as the configure is the evidence current actions will tend to neutralize space in the absence of space charge neutralization. Acrually, as the configure is the evidence current actions will tend to neutralize space is the absence of space current actions will tend to neutralize space contings is intersaced to 3 value. The constitution of these topics the runt must dower we would extend to neutralize the sample working is intersaced to 3 value. The constitution of these two of the runt must dower we would extend to action of these two of the runt must dower we would extend to action of these two of the runt must dower we would extend to action of these two of the runt must dower we would extend to action of these two of the runt must dower we would extend to action of the of these two of the runt must dower we would extend to action of the of the sectors of the runt must dower we would expect is:

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13 54

Achievement of this power would depend on there being a negligible number of ions that are generated at the emitter and recombine at the collector. We may assume that the average energy associated with the moving electrons and also the moving ions will be 2 V_{T} (that is, 2 kT/q) and that if their energies are equal. their average velocities will be inversely proportional to the square root of their masses. This factor for cesium is close to 490. This figure will then be used to establish the order of magnitude of the desired cesium arrival rate if on the average every ion which leaves the cathode travels more or less unimpeded to the collector. The electron current of 0.37 amp/cm² corresponds to an emission rate of 2.3 x 10^{18} electrons per second for each square centimeter. If we assume that just the right number of ions are present to neutralize the space charge of the electrons, there will be no electric field and the average velocity of electrons in transit across the space may be computed to be 1.52 x 107 cm/sec. Since the electrons will travel unimpeded across this space, the density will be 1.51 x 10¹¹ electrons per cm³. An exactly equal ion density corresponds to an ion emission rate of 4.7 x 10¹⁵ ions per second for each square centimeter. Under these conditions the ion emission rate will be exactly equal to the atom arrival rate and the next question to be answered is the determination of the most suitable cesium condensation temperature.

Were it not for the fact that consideration must be given to the reduced density of atoms between the emitter and the collector, a condensation temperature of 330° K would give the required ion emission. The average temperature in the interelectrode space may be taken as about 1600° K. With this approximate value of the condensation temperature, Eq. 17 shows that the atom evaporation rate at the cesium surface should be increased 2. 2 over that calculated by Eq. 8. With this correction factor the theoretical value for the cesium condensation temperature becomes 340° K. At this temperature the mean-free path will be long compared with the spacing and therefore both the electrons and the ions should flow in an unimpeded manner from the emitter to the collector.

If the cesium condensation temperature is raised above the value 340°K then the arrival rate will be greater than that needed and the excess ion production will result in an ion space-charge sheath forming near the surface of the emitter. Such a sheath will inhibit the delivery of the ions to the plasma. It will also create an accelerating field for the electrons. This will increase the electron emission if the output voltage is reduced slightly to take advantage of the lowering of the electron work-function because of the accelerating field produced at the emitter by the ions. The fact that many of the ions that are produced are re-
Applies mamber of this power would append on there being a mpliphile at the collection. We may around that the emitter and seconation at the collection. We may around that the every second and being at the collection. We may around that it their every second of the a varage velocities will be inversely proportional to the square real of their masses. This factor for cestum is close to be which leaves the calinete travely more than the sverage every of the collector. The also around a rate of 0.37 and for the sverage every the collector. The also around the state of 0.37 and for the sverage every is and a use antiscing rate of 0.3 x 10⁻¹⁰ electrons per accord to the collector. The also around the state that here the right autoper the collector are also that a state of 0.37 and for the sverage every is an array of the state of 0.3 x 10⁻¹⁰ electrons per accord to the collector. The also around the state that here the right autoper the collector are also that also the state that here the right autoper the collector are also the state of 0.3 the state of the state of the form of the state of 0.4 and the state of 0.5 and the state of the state are the state of 0.5 are the state of the state of 0.5 and second to react a state of the state of 0.5 and second to also the state of the state of the state of 0.5 and second to a state of 0.5 are the state of the state of 0.5 and second to a state of 0.5 are the state of the state of 0.5 and second to a state of 0.5 are the state of the formation state and the state of the state of the state of the state of the most state of the most state of the state of the state of the state of the most state of the state of the state of the state of the most state of the sta

Were it not for the fact that consideration must be given to the reduced density of atoms between the emitter and the colleclor, a condensation temperature of 210°K would give the required the emission. The average temperature of 210°K would give the required appear may be taken as about 1500°K. With this approximate value of the condensation compatence, Eq. 17 anows that the storn the relation rate at the content of which this corrected 2.2 diver that calculated by Eq. 6. With this corrected de the compared with the spacing and threatons from the electrons one compared with the spacing and threatons from the electrons will be lore about flow in an unitable hold the local the time the long should flow in an unitable that the electrons will be lore about flow in an unitable distribute the electrons to be to the collector.

If the restore condenoted comparature is related above the withe 340°K these the errival rate will be prestor than that meded and the encess ton production will result in an ion space-charge will inhibit the delivery of the tore to the plasma. It will also draw an accelerating field for the solting is reduced slightly to the electron ennealed if the output voltage is reduced slightly to while alectron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the electron ennealed if the output voltage is reduced slightly to the set at the accelerating field produced at the animation be-

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turned to the emitter surface may also result in the establishing there of an average dipole moment favorable to a still further reduction of the work-function in spite of the high temperature. These two effects increase the emission capability of the cathode over the previously calculated value of 0.37 amp/cm². Without experimental experience it is difficult to determine the best cesium condensation temperature except to state that for temperatures less than 340°K, an insufficient number of ions will be available to neutralize the space-charge and as temperatures exceed this value, favorable results may come because of the reduction in the emitter work-function and the corresponding exponential increase in available current.

The cesium pressure called for by this discussion is much lower than that used by some experimenters. For example, V. C. Wilson⁴ experimented with high temperature emitters at relatively high cesium pressure. The two cesium temperatures he used were 534° K and 564° K. The use of the higher cesium pressure would result in the creation of an ion space charge sheath. The fact that an electron emission of 4 amp/cm² was observed sets the "effective" electron barrier at B" of Fig. 8 at 3 ev. Eq. 29 shows that any area of the hot surface with a work-function in the range 3 ev to 4.3 ev will deliver ions to help neutralize the electron space charge. The Wilson experiment would seem to indicate that work-function lowering actually takes place.

These thoughts are presented by way of illustration of the use of the equations presented here and the general ideas related to the behavior of a plasma diode as it might be used in conjunction with a high temperature, high work-function emitter. It is clear that many experiments should be performed before too much reliance is placed in these deductions since they depend on an extrapolation based on data not specifically applicable to present needs. Additional experimentally determined facts might come into prominence beyond those considered.

Concluding Remarks

Three principle objectives have guided the preparation of this report. The first was to discuss in some detail the physical principles that seem to be involved in the better understanding of the design and properties of a plasma diode heat-to-electricalpower transducer. The second objective was to make available an intricate set of empirical equations by which many answers to pertinent questions can be obtained numerically when desired. These equations are consistent with the experimental facts as they are know today. They depend very largely upon the studies of Taylor and Langmuir and some very recent measurements made by Robinson. The final objective has been to apply the ideas here to the experiments of Robinson and indicate by quantitative tained to the emitter contains may also redult in the establishing simple of an average dipole moment favorable to a still further multiched of the work-linection in spite of the alge temporature. These two effects increases the antiseton capability of the cathole develops previously calculated value of 0.37 mappent. Without develops the previously calculated value of 0.37 mappent. Without developer immedia experience it is difficult to determine the nest condimension the neutralized of the difficult to determine the nest condimension the neutralize of space-charge and an temperatures exercidicity to respect to a space-charge and an temperatures exercidicity with relax, favorable results may come because of the restanding the souther work-function and the correstions exdimension the two work-function and the correstions ex-

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These minarple objectives are guided for preparation of this report. The first was to discuss in some datali the physical principles that them to be avoired in the bears understanding of the design and properties of a plasma diode heat to sale tricalpower transfacer. The second objective was to make available as iniziants net of empirical equations by which many answers to pertinent questions can be obtained nomerically when desired. These equations can be obtained nomerically when desired, any are know today. They depend very largely open the studies and a physical second sets contained nomerically when desired, and a physical second sets contained nomerically when desired, and a physical test of and the second rest of the second rest set and the start indication of bolicative has been to apply the ideas calculation the results one might hope to obtain by the choice of a more favorable cesium condensation temperature than was actually used.

In the present report the detailed derivations involved in the development of the empirical equations have not been given. If the results found here are ultimately of real practical importance, the more interesting derivations can be prepared and made available as a supplement to this report. Twenty of the thirty-six equations used in this report may find direct application to other problems and are therefore summarized for quick reference in an appendix. ententation the results one might hope to obtain by the choice of a more favorable cestum confernation temperature than way ac-

surf in the present report the detailed derivations involved in the development of the empirical equations have not been given. If the results found here are ultimately of seal practical importances the more lateresting derivations can be prepared and made evailable as a supplement to this report. Twenty of the thirty-six equations used in this report may find direct application to other problems and are therefore summarized for quick reference in an somendix. Appendix

Selected equations from the text. Minimum temperature for surface ionization as a function of the atom evaporation rate at the cesium condensation surface:

$$T_{\min} = \frac{14,100}{27.56 - \log_{10}\mu_a}$$
(7)

Equation for evaporation rate of cesium:

$$\log_{10}\mu_a = 27.48 - \frac{3900}{T_{Cs}}$$
 (8)

$$\mu_{a} = 3 \times 10^{27} \times 10^{-7} \text{ T}_{\text{Cs}} \text{ atoms/cm}^{2} \qquad (9)$$
8980

$$\mu_a = 3 \times 10^{27} e^{\frac{T_{Cs}}{T_{Cs}}} atoms/cm^2$$
 (10)

Minimum temperature for surface ionization related to cesium temperature:

$$T_{m} = 3.6 T_{Cs}$$
 (11)

Ion evaporation rate for tungsten surface temperatures less than the minimum temperature calculated by Eq. 11:

$$\log_{10} v_{\rm p} = 54.16 - 1.113 \log_{10} \mu_{\rm a} - \frac{26,000}{\rm T}$$
 (12)

$$\nu_{\rm p} = \frac{1.45 \times 10^{54}}{\mu_{\rm a}^{1.113}} 10^{-\frac{26,000}{\rm T}}$$
 (13)

$$v_{\rm p} = \frac{1.45 \times 10^{54}}{\mu_{\rm a}^{1.113}} e^{-\frac{5.28}{V_{\rm T}}}$$
 (14)

The vapor concentration of cesium atoms in equilibrium with liquid cesium:

$$n_{Cs} = 2.7 \times 10^{23} e^{-\frac{8750}{T_{Cs}}} a toms/cm^3$$
 (15)

$$\log_{10} n_{\rm Cs} = 23.44 - \frac{3800}{T_{\rm Cs}}$$
(16)

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Salarted equations izon the text. Multimum temperature to: surface invitation as a function of the storn evaporation rate at the be elimit condimention surface!

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Minimum temperature for surface tonization related to cestion temperatures

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The vapor existentication of carbin stoms in equilibrium with liquid cosium:

and the second

Mean-free path of cesium ions in cesium vapor:

$$\log_{10} \lambda_{+} = \frac{3800}{T_{Cs}} - 9.7$$
 (19)

$$T_{Cs} = \frac{3800}{9.7 + \log_{10}\lambda_{+}}$$
(20)

Maximum power in a vacuum diode used for a plasma diode after the "effective" spacing is determined:

$$P_{\rm max} = 3.7 \times 10^{-6} V_{\rm T}^{1/2} \frac{V_{\rm R}^2}{w^2} \, {\rm watt/cm}^2$$
 (23)

Voltage output:

1

$$V_{O} = \frac{0.383 \left(\frac{V_{R}}{V_{T}} \right) V_{R}}{\frac{V_{R}}{1 + 0.31 \left(\frac{V_{R}}{V_{T}} \right)} 4/3}$$
(24)

Energy step ϕ_R related to current density and temperature:

$$b_{\rm R} = 2.3 V_{\rm T} \left[2.08 + 2 \log_{10} T - \log_{10} I_{\rm m} \right]$$
 (26)

Energy step ϕ_R related to ion surface work-function ϕ_b ; surface temperature; and cesium temperature:

$$\phi_{\rm R} = \frac{\phi_{\rm b}}{2} - 10.68 \, {\rm v_T} + 2.3 \, {\rm v_T} \, \log_{10} \, {\rm T} + \frac{4490}{{\rm T_{Cs}}} \, {\rm v_T}$$
 (29)

Simplified emission equation for the range 1150°K <T <2500°K:

$$\log_{10}I = 9.48 - (5.04 \phi + 1.6) \frac{1000}{T}$$
 (32a)

Range 600°K < T < 1150°K:

$$\log_{10} I = 8.85 - (5.04 \phi + 0.76) \frac{1000}{T}$$
 (33a)

Maximum temperature of the collector for 5 per cent return emission:

$$\max T_2 = 1000 \frac{5.04 (\phi'' - V_0) + 0.76}{0.65 + (5.04\phi' + 1.6)\frac{1000}{T_1}}$$
(34)

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Maximum power in a vacuum diode used for a plasma diede after Relificitive" spacing in determined:

Moltage sutput

Enorgy stop do related to current desuity and temperatures

$$v_{\rm R} = 2.3 V_{\rm T} \left[2.08 + 2 \log_{10} T - \log_{10} T_{\rm rel} \right]$$
 (26)

Energy step of related to ion surface work-function on surface temperatures and cestum temperatures

$$I_{II} = \frac{b}{2} - 10.68 \, V_{\rm T} + 2.3 \, V_{\rm T} \, \log_{10} \, T + \frac{4490}{7 \, G_{\rm S}} \, V_{\rm T} \quad (29)$$

Simplified entitation equation for the range 1150°K CT < 2500°K;

$$\log_{10} I = 9.48 - (3.044 + 1.6) \frac{1000}{T}$$
 (32a)

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Maximum temperature of the collector for 5 per cent return emiaatom

Acknowledgments

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Also the Thermo-Electron Engineering Corporation has contributed toward the support of this research and supplied significant experimental data.

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Befarences

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Physik, Springer-Verlag, Garmany, Val. 21, 1958. ... Taylor, J. D., and Lengmuir, L. Phys. Rev. 44, 423 (1953). ... Wilson, V. C., J. Appl. Flys. 30, 475 (1959).

Glossary of Symbols

"a"	Low work-function region as in Fig. 5
a - a'	Designations of emitter surface in Fig. 1
"b"	High work-function region as in Fig. 5
b - b'	Designations of collector surface as in Fig. 1
В	Designation of electron space-charge minimum or barrier
B"	Designation of electron space-charge minimum or barrier
	with cesium present
FL	Fermi level within emitter or collector
I	Current density when space-charge minimum is at collec-
m	tor Energy sten is d_ Used in Fig. 11
I	Current density obtained at maximum power as in Eq. 25
Tmax	Pandom current of ions at ionization surface. Same as
-р	arrival rate of ions as in Eq. 27
T.	Emission current density as used in Eq. 1
-1 k	Poltemannia constant used in Eq. 2 Value is 1.29 m
	10-23 in 1 / 1 is an 1 20 s $10-16$ and / 10
m	10^{-5} joure/deg or 1, 38 x 10 $^{-6}$ erg/deg.
M	Mass of an electron 9. 108 x 10 - gm or 9. 108 x 10 kg
101	Mass of an atom or ion. Atomic weight of cesium is
	132.9 gms/gm mole. Atoms/gm mole are 6.045 x 10 ⁻² .
	$M = 2.20 \times 10^{-22} \text{ gm or } 2.20 \times 10^{-25} \text{ kg.}$
"Cs	Concentration of cesium atom in atoms/cm ⁻
npo	Concentration of ions at ionization surface as in Eq. 27
"s	Concentration of cesium atoms in the space between the
	surfaces of the diode
"+B"	Concentration of ions at space-charge minimum B" as in
D	Fig. 8
F	Power per unit area delivered to the resistance as in Eq.
D	4
rmax	Maximum power as in Eq. 6
q	Electron charge as in Eq. 2. Value is 1.602 x 10 - cou-
D	lomb or 4. 803 x 10^{-10} statcoulomb
к <u>10</u>	Load resistance defined by Eq. 3
1	Emitter temperature where there is no need to specify
	further
Т	Emitter temperature as used in Eq. 1
max ^T 2	Maximum collector temperature which permits a "return"
	electron current of 5 per cent
T _C	Temperature of collector as in Eq. 17
TCa	Cesium condensation temperature
TE	Temperature of the emitter as in Eq. 17
Tm	Minimum temperature of a hot tungsten surface which is
	a function of cesium arrival rate as in Eqs. 7 and 11
Tmin	Minimum temperature of a hot tungsten surface which is
	a function of cesium arrival rate as in Eqs. 7 and 11
v	Incremental voltage in "negative" direction as in Eq. 4

Anosta m nest di et estati super supere superente antitati	
lectros current of 5 per cent	

m	Incremental voltage associated with maximum power as in Eq. 5
į	Ionization potential - value for cesium is 3.893 ev
0	A voltage defined as $\phi_1 = \phi_2$ as in Fig. 1
о ′р	Potential difference between the space-charge minimum and the potential of an electron at the surface of the col- lector
R	Potential applied to collector with respect to emitter when space-charge minimum coincides with collector
Т	Electron volt equivalent of temperature as defined in Eq. 2
a	Distance to potential minimum at B as in Fig. 7
, y, z	Direction in space between diode surface with x perpen- dicular to the surface
۷.	Diode spacing. Also used as in Fig. 11 for distance to potential minimum when current density I and tempera- ture T are related
	True work-function as in Eq. 31
	Work-function of low work-function region of Fig. 5
a	Work-function of high work-function region of Fig. 5
D	Average of high work-function area as shown in Fig. 16
11	Emitter true work-function as in Fig. 1
12	Collector true work-function as in Fig. 1
R	Energy step from the Fermi level (FL) of the emitter to the surface potential of an electron at the collector when space-charge minimum is there as in Figs. 12 and 15
ş •	Electron potential at space-charge minimum relative to the Fermi level as in Fig. 4
11	Energy at "hump" of motive diagram as in Fig. 7
,T	Energy at electron potential minimum at B as in Fig. 7
Γų.	Energy at "hump" of motive diagram as in Fig. 15. Ions present
£11	Electron potential at the space-charge minimum related
-	to the emitter Fermi level when cesium is present as in
	Fig. 8
2	True work-function of the collector with cesium present
[as in Fig. 7
λ_+	Mean-free path of an ion in cesium vapor
μ _a	Eq. 8
Vp	Ion emission rate in ions per sec for each cm
V7	Arrival rate of ions in number per second for a unit area
V_	Arrival rate of electrons in number per second for a unit
σ+	collision cross section for an ion in cesium vapor assumed to be 2×10^{-14} cm ² as in Eq. 18

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Electron potential at the space-charge minimum releved to the amitter Fermi level when cesium is present as in other 6

True work-function of the collector with costum present

Atom arrival rate in stoms per sec for each cm² as in

The amitesion rate in tons per sec for each cm

Arrival rate of ions in number per second for a unit area Arrival rate of electrons in number per second for a unit

Collision prose section for an los in crainin repor assumed





CESIUM PLASMA DIODE AS A

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HEAT-TO-ELECTRICAL-POWER TRANSDUCER

Professor Wayne B. Nottingham

Research Laboratory of Electronics Massachusetts Institute of Technology

May 1959

This work has been supported in part by the U. S. Army (Signal Corps), the U. S. Air Force (Office of Scientific Research, Air Research and Development Command), and the U. S. Navy (Office of Naval Research).

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ESTEM PLASMA DIODE AS A HEAT-TO-FLECTRICAL-POWER TRANSDUCER

Professor Vayne B. Nottingham Massachusetts Institute of Technology Cambridge, Massachusetts, 5.5.A.

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The new interest in the direct conversion of heat-to-electrical power has stimulated research in both the application of the high vacuum diode and the plasma diode to accomplish this purpose. The theory of the high vacuum diode is relatively simple and the experimental verification of the theory has been satisfactory. The plasma diode which depends on the ionization of cesium at a not surface cannot be worked out in all of its detail at present because of the tack of certain fundamental experimental data. It is possible to make use of published results of Taylor and Langmuir and a detailed analysis of recent thermitories studies to carry the understanding of the plasma diode far enough to take a direct comparison with experiment. This analysis first involves an understanding of the phenomenon of surface ionization. General properties of a plasma and space-charge considerations control the delivery of ions to neutralize electron space charge. When applied to the experimental data available, an interesting result comes as an important amplification. Essential to the theory of the high vacuum diode is the knowledge of the emitter temperature and the diode spacing. The electrical characteristics of the plasma diode have been found to be very closely duplicated by those of a high vacuum diode characterizer of all effective distance that is reduced from the actual diode spacing. This field supports the option that the efficiency of the plasma diode may be tremenuously improved over that of vacuum diodes of mactual casign.

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Glossary of Symbols

"a"	Low work-function region as in Fig. 5
a - a'	Designations of emitter surface in Fig. 1
"p"	High work-function region as in Fig. 5
b ~ b'	Designations of collector surface as in Fig. 1
В	Designation of electron space-charge minimum or barrier
Bu	Designation of electron space-charge minimum or barrier with cesium present
FL	Fermi level within emitter or collector
Im	Current density when space-charge minimum is at collector. Energy step is ϕ_R . Used in Fig. 11
Imax	Current density obtained at maximum power as in Eq. 25
Ip .	Random current of ions at ionization surface. Same as arrival rate of ions as in Eq. 27.
1	Emission current density as used in Eq. (1)
k	Boltzmann's constant used in Eq. (2) Value is 1.38 x 10 ⁻²³ joule/deg
	or 1.38 x 10 ⁻¹⁰ erg/deg.
m	Mass of an electron 9.108 x 10^{-28} gm or 9.108 x 10^{-31} kg
Μ	Mass of an atom or ion. Atomic weight of cesium is 132.9 gms/gm mole. Atoms/gm mole are 6.045 x 10^{23} . M = 2.20 x 10^{-22} gm or 2.20 x 10^{+25} kg.
ⁿ Cs	Concentration of cesium atom in atoms/cm ²
npo	Concentration of ions at ionization surface as in Eq. (27)
ns	Concentration of cesium atoms in the space between the surfaces of the diode
n _{+B'1}	Concentration of ions at space-charge minimum B" as in Fig. 8
Р	Power per unit area delivered to the resistance as in Eq. (4)
Pmax	Maximum power as in Eq. 6
q	Electron charge as in Eq. (2). Value is 1.602×10^{-19} coulomb or 4.803×10^{-10} stateculomb
R ₁₀	Load resistance defined by Eq. 3
T	Emitter temperature where there is no need to specify further
Tl	Emitter temperature as used in Eq. (1)
max ^T 2	Maximum collector temperature which permits a "return" electron current of 5 per cent
ТС	Temperature of collector as in Eq. (17)
TCs	Cesium condensation temperature
T_{E}	Temperature of the emitter as in Eq. 17
Tm	Minimum temperature of a hot tungsten surface which is a function of cesium arrival rate as in Eqs. (7) and (11)

Glossary of Symbols, contd.

Tmin	Minimum temperature of a hot tungsten surface which is a function of cesium arrival rate as in Eqs. (7) and (11)
v	Incremental voltage in "negative" direction as in Eq. 4
Vm	Incremental voltage associated with maximum power as in Eq. 5
V	Ionization potential - value for cesium is 3.893 ev
V	A voltage defined as $\phi_1 - \phi_2$ as in Fig. 1
VO	Output voltage generally
Vp	Potential difference between the space-charge minimum and the potential of an electron at the surface of the collector
V _R	Potential applied to collector with respect to emitter when space- charge minimum coincides with collector surface as in Fig. 15
VT	Electron volt equivalent of temperature as defined in Eq. (2)
xs	Distance to potential minimum at B as in Fig. 7.
x, y, z	Direction in space between diode surface with x perpendicular to the surface
w	Diode spacing. Also used as in Fig. 11 for distance to potential minimum when current density I and temperature T are related
ø	True work-function as in Eq. (31)
øa	Work-function of low work-function region of Fig. 5
ø _b	Work-function of high work-function region of Fig. 5
To be	Average of high work-function area as shown in Fig. 16
ø	Emitter true work-function as in Fig. 1
¢2	Collector true work-function as in Fig. 1
¢ _R	Energy step from the Fermi level (FL) of the emitter to the surface potential of an electron at the collector when space-charge minimum is there as in Figs. 12 and 15
φ' .	Electron potential at space-charge minimum relative to the Fermi level as in Fig. 4
6	Energy at "hump" of motive diagram as in Fig. 7
φ"	Energy at electron potential minimum at B as in Fig. 7
ϕ_{\pm}^{rr}	Energy at "hump" of motive diagram as in Fig. 15. lons present
\$` <u>`</u>	Electron potential at the space-charge minimum related to the emitter Fermi level when cesium is present as in Fig. 8
¢11	True work-function of the collector with cesium present as in Fig. 7
A.	Mean-free path of an ion in cesium vapor
p	Atom arrival rate in atoms per sec for each cm ² as in Eq. (8)
V D	lon emission rate in ions per sec for each cm ² .
VA	Arrival rate of ions in number per second for a unit area
	Arrival rate of electrons in number per second for a unit area
	Collision cross section for an ion in cesium vapor assumed to be 2×10^{-14} cm ² as in Eq. (18)

Cesium Plasma Diode As a Heat-to-Electrical-Power Transducer

Introduction

An analysis of the high vacuum diode as a heat-to-electrical-power transducer has been worked out in detail⁽¹⁾ based on theories presented in "Thermionic Emission" published some years ago⁽²⁾. In the high vacuum diode it is of the utmost importance to have the lowest possible work-function on the collector and to have the smallest practical spacing. It is anticipated that under these conditions the work-function of the emitter will be practically without influence so long as the space-charge minimum in front of the emitter is of the order of V_{TA} (the electron-volt equivalent of the temperature). Any further decrease in the emitter work-function will do neither good nor harm in controlling the usefulness of the device. In the plasma diode it is not so easy to generalize and since much of the most significant fundamental data relevant to the problem will not be available until additional research studies have been made. These remarks relevant to the plasma diode represent some of my own views on the subject in that they are being developed without the benefit of the experimental evidence needed.

In the high vacuum diode the understanding of the space charge is very important. It controls the properties of diodes that operate within the temperature limits set by available materials and the electron emission properties associated with them. The function of the positive ions in the plasma diode is to alter the effect of electron space charge. Even in the plasma diode there will be space charges near the boundaries of either the emitter or the collector or both.

Assume for the purpose of illustration that the emitter work-function is somewhat higher than the collector work-function and by some mechanism not specified for the moment exactly the right number of ions are available to reduce the space charge to zero. Assume furthermore that the spacing is sufficiently small in relation to the gas pressure so that the drop in potential over the plasma between the surface of the emitter and the collector can be neglected. This condition is represented diagramatically by Fig. 1. Here the <u>true</u> work-functions of the emitter and the collector are ϕ_1 and ϕ_2 . Note particularly that these are not the "Richardson" work-functions. The current emitted over the barrier ϕ_1 is given by the equation:

$$I_1 = 120 \times T_1^2 e^{-\frac{\phi_1}{\nabla_T}} amp/cm^2$$
 (1)

2.

In this equation T is the temperature of the emitter and $V_{\rm T}$ is its electron-volt equivalent defined by:

$$V_{\rm T} = \frac{kT}{q} = \frac{T}{11,600}$$
 (2)

The available power is the product I_1V_0 . The total resistance in the circuit from the receiving surface on the collector through the external load and to the emitting surface of the emitter may be expressed for a unit area as

$$R_{10} = \frac{V_0}{I_1}$$
(3)

If the total resistance is less than R_{10} , then the current around the circuit will remain constant and the output voltage decrease, thus giving a smaller available electrical power. If the load resistance is made greater than R_{10} , then the output voltage increases while at the same time the current decreases. Identify this increase in voltage by the symbol v. The following equation serves to relate these quantities for the calculation of maximum power.

$$P = I_1 e^{-\frac{v}{v_T}} (v_0 + v)$$
(4)

Equation 4 may be differentiated to obtain an expression for the deviation in the power as a function of v. A maximum of power output will be found when the differential (dP/dv) is zero and the value of v so determined is identified as v_{m} . The result is given as

$$v_{\rm m} = V_{\rm T} - V_{\rm o} = V_{\rm T} - (\phi_1 - \phi_2)$$
 (5)

The physical meaning of this equation may be considered in its relation to Fig. 1. If the work-function difference $(\phi_1 - \phi_2)$ is greater than V_T then v_m is zero or stated in other words maximum power is delivered to the external load when the resistance is chosen to satisfy Eq. 3 and the overall output voltage is exactly the difference between the work-functions. Under the circumstances in which the receiver work-function is actually greater than the emitter work-function, the power output is a maximum when the voltage available is V_T . This situation is illustrated by the diagram of Fig. 2 and the total available power is expressed by

$$P_{\text{max}} = 120 \times T^2 e^{-\frac{\phi_2 + V_T}{V_T}} V_T w/cm^2$$
(6)

In the range of work-function difference for which $(\phi_1 - \phi_2)$ is equal to or less than V_T even though ϕ_1 is greater than ϕ_2 , maximum power will occur with an available voltage of V_T and Eq. 6 applies.

These statements may be summarized as follows. For work-function differences greater V_T in which the emitter work-function is larger than the collector work-function, maximum power is available at an overall voltage level equal to the difference in the work-functions, whereas in all other cases the maximum power occurs with an available voltage of V_T .

It will be the purpose of the following sections to discuss the problem of ion production as well as the delivery to the plasma of the ions and the current flow expected in the presence of atoms and ions.

Ionization of Cesium at Heated Surfaces

The classic work on the ionization of cesium at heated tungsten surfaces was largely due to Langmuir and his collaborators. One of the latest in that series of researches was reported by Taylor and Langmuir⁽³⁾. This work serves as the basis of many of deductions made here. If the arrival rate of cesium atoms for each square centimeter of a heated tungsten surface is less than 10^{13} atoms per second (cesium condensation temperature 0° C), a tungsten filament at 970° K will have a neligible surface coverage of cesium atoms and every cesium atom that arrives will leave as a cesium ion. As the arrival rate increases to 10^{18} atoms /sec-cm², the minimum temperature for complete conversion of atoms to ions is approximately 1475° K.

This statement should not be attributed to Taylor and Langmuir but does depend on an analysis of their data which was made available in their Fig. 18. Since no other data are available, these are used to yield a relation between the atom arrival rate μ_a expressed in atoms per second for each square centimeter and the minimum temperature for which a negligible surface film will form on tungsten. At this temperature practically every atom that arrives will leave the surface as an ion. An empirical equation has been derived to relate this minimum temperature to the atom arrival rate and is

$$min = \frac{14,100}{27.56 - \log_{10}\mu_a}$$
(7)

At any given arrival rate, the production of ions is discontinuously reduced approximately a factor of 10 if the tungsten surface is at a temperature slightly below the minimum temperature given by Eq. 7.

The ideal gas laws are used to convert cesium vapor pressure data to atom arrival data. The following formula relates atom arrival to the temperature of the liquid cesium in equilibrium with its vapor.

$$\log_{10}\mu_{a} = 27.48 - \frac{3900}{T_{Cs}}$$
(8)

The corresponding formulae in the exponential form are given in Eqs. 9 and 10.

$$\mu_{a} = 3 \times 10^{27} \times 10^{-\frac{3900}{T_{Cs}}} \text{ atoms/cm}^{2}$$
 (9)

$$\mu_{\rm a} = 3 \times 10^{27} \, {\rm e}^{-\frac{8980}{T_{\rm Cs}}} \, {\rm atoms/cm}^2 \, (10)$$

It is an interesting fact that Eqs. 7 and 8 may be combined to yield a very simple relation between the temperature of the liquid cesium and the minimum temperature of the heated tungsten surface at which complete ionization takes place. This relation is:

$$T_m = 3.6 T_{CS}$$
 (11)

The fact that the minimum temperature at which all cesium atoms are converted to ions is linearly related to the temperature of the liquid cesium may not be a pure accident of numbers. In the broader sense of the word both the evaporation of atoms from the liquid and the evaporation from a tungsten surface may possibly involve atomic attractive forces that are not so different from each other. This would imply that their vibrational frequency before evaporation might be characterized by a force function not unlike that of a vibrating molecule. In the molecular case there is a dissociation energy whereas in the case of atomic evaporation there is the latent heat of evaporation which is dominated by a quantum state of vibrational activity which is the maximum that can be attained by the atom as it is on the border line between continued adherence to the surface and evaporation. If the equations of motion are not too dissimilar then the factor that relates these two critical temperatures could well be the ratio of the "activation" energies. Equation 8 implies an activation energy for evaporation from the liquid state that is not too far from 0.773 ev. Taylor and Langmuir deduce from their studies of cesium evaporation from tungsten that the heat of evaporation is 2.83 ev if the fraction of the surface coated is small. Note that the ratio (2.83/0.773) is 3.65 which is consistent with the empirical results presented in the form of Eq. 11.

Results of the Taylor-Langmuir experiments as they relate to the yield of ions from surfaces that have an appreciable fraction covered by adsorbed cesium atoms show an extremely small yield of ions. A detailed analysis of the experimental data available yields some interesting results. The equations to be presented fit quite well over the range of cesium pressures and tungsten surface temperatures studied by Taylor and Langmuir. The purpose in deriving empirical equations to represent their data is to permit computations to be made under conditions that involve considerable extrapolation into unexplored areas. The philosophy here is that estimates based on an extrapolation from existing data are better than pure guesses without a systematic relation establish facts. The ion production rate v_p expressed as the number of ions produced per second for each square centimeter area is expressed by the set of equations that follow;

$$\log_{10}\nu_{\rm p} \approx 54.16 - 1.113 \log_{10}\mu_{\rm a} - \frac{26,600}{\rm T}$$
 (12)

$$\nu_{\rm p} = \frac{1.45 \times 10^{54}}{\mu_{\rm a}^{1.113}} 10^{-\frac{26,600}{\rm T}}$$
(13)

$$v_{\rm p} = \frac{1.45 \times 10^{54}}{\mu_{\rm a}^{1.113}} e^{-\frac{5.28}{V_{\rm T}}}$$
 (14)

Attention may be directed specifically to the results shown as Eq. 13. The ion yield decreases rapidly with a decrease in the temperature of the surface for the range below the temperature T_m introduced in Eq. 7 and related to the liquid cesium temperature by Eq. 11. Equation 13 has no significance at temperatures higher than Tm since then the ion yield is precisely equal to the atom arrival rate μ_a . It is evident from this equation that at a fixed surface temperature T, the ion yield decreases almost linearly (1.113 power) with the atom arrival rate. Stated in another way this equation shows that the probability of ionization at a given surface temperature decreases with the 2.113 power of the atom arrival rate. The physical explanation for this result depends on the fact that at a given surface temperature the fraction of the surface covered by adsorbed cesium atoms increases as the rate of arrival of neutral atoms increases. This increase in surface coverage brings about a decrease in the average work-function of the surface. The probability that a cesium atom will evaporate as an ion instead of neutral atom is strongly influenced by the work-function of the surface. Since the ion yield decreases as the average work-function decreases, it is to be anticipated that a relation not unlike that of Eq. 13 might hold. The insertion of numbers into these equations and a comparison with the published data of Taylor and Langmuir may convince the reader that over the range of temperature and cesium arrival rate for which good data exist, the equations represent the observations. It is thought that the failure to represent the true facts over the ranges of the variables likely to be encountered in association with the plasma transducer problem will be less than an order of magnitude. that is a factor of ten. It is hoped that the error will be much less than this in many examples that are of practical interest.

Kinetics of Ions Formed at Hot Surfaces

The reader should be reminded that when drawings are made which show energy relations of electrons in diode structures, these drawings really relate to the "motive function" of an electron. That is, lines and energy levels apply to the <u>potential of an electron</u> in the space of interest. Figure 1 may be used as an example. We start at the Fermi level in the emitter and the line at - a represents the potential function of an electron in the neighborhood of the surface. The energy difference between the Fermi level and the surface potential at a is the true work-function ϕ_1 of the emitter. In this

energy diagram the surface of the emitter is joined to the surface of the collector by the line a-b and since that line is drawn horizontally it represents the potential energy of an electron in the field-free space between the emitter and the collector. The work-function of the collector is shown by ϕ_2 as the energy difference between the Fermi level in the collector and the potential energy of an electron at its surface at the point b. The misalignment of the Fermi level of the emitter with respect to that of the collector is indicated by V_o. This separation of Fermi levels can be maintained only by having some auxiliary and external source of power and may be measured directly by a voltmeter connected between the emitter and the collector electrodes. The kinetic energy of an electron in this diagram is represented by the fact that the electron is in an energy level which would exist in the diagram below the horizontal line a-b. The separation between the electronic energy level and the line a-b is a direct indication of the actual kinetic energy of the electron associated with the motion across the space from a to b. This direction is taken as the x direction whereas the y and z directions are taken perpendicular to this one and therefore parallel to the planes of the emitter and the collector. We can show in this diagram only the kinetic energy associated with the motion in the x direction. It is not suitable to try to show the kinetic energy associated with the other directions in this one-dimensional diagram. Energy levels do not exist for electrons in the space between the electrodes that would be represented by electron levels above the a-b line. Such levels do exist within the conductors but not outside of them.

This same potential diagram applies equally well to ions that might be in the space between a and b. Specifically an ion at rest would be represented as being on an energy level coincident with the line a-b, whereas one which is moving in the x direction with some kinetic energy would be occupying an energy level in this dongram above the line a-b. No positiveion energy levels exist that would be represented by states drawn below the line a-b. These remarks are made to anticipate the discussion with reference to the energy distribution of ions created at a hot surface. One of the few sets of measurements on the ion energy distribution that exists in the literature is that of Fig. 16 of Taylor and Langmuir. Their data are reproduced as Fig. 3. The plot shows the ion current received at a coaxial collector as a function of the applied voltage with the emitter temperature

7.

held constant and the rate of arrival of neutral atoms established by a constant bath temperature of 275°K. The critical temperature for this rate of arrival of atoms is 990°K and therefore since the measurements were made at 980°K it was probable that the ion yield was less than 10 per cent of the atom arrival rate. Under this condition the average work-function of the emitter was very close to 3.4 volts. Other evidence would indicate that the work-function of the collector was very close to 2 volts. Therefore under these circumstances, the contact difference in potential was close to 1.4 volts. This fact is exhibited reasonably well by the data of Fig. 3. Under the conditions of this experiment, the heated tungsten surface undoubtedly had considerable nonuniformity in work-function, and also space-charge effects reduce the ion current at zero field. It may be assumed that these two factors account for the relatively poor saturation of the ion current. The evidence seems to be satisfactorily clear that the application of an ion retarding voltage of a fraction of a volt is sufficient to inhibit the flow of ions from the hot tungsten surface over to the collecting electrode. The slope of the semi-log plot is in agreement with the temperature of 980[°]K.

A Generalized Discussion of the Simultaneous Emission of Electrons and the Creation of Ions at a Hot Tungsten Surface

In Fig. 4 the emitter work-function ϕ_1 is assumed to be uniform. The collector work-function is ϕ_2 ; the Fermi level of the collector is V_0 more negative than that of the emitter. Electrons are being emitted from the surface a-a' and those that impinge on the surface from inside the metal at an energy level ϕ' with respect to the Fermi level have a chance of escaping across the space-charge barrier at B. If the electron has an excess energy V_T as it passes the barrier, then its energy state is represented by the dot-dash line of Fig. 4. Cesium ions will evaporate from the emitter surface in an appreciable number if the work-function ϕ_1 is high enough and the temperature suitable. An ion which originates at the emitter surface with practically no kinetic energy associated with its motion in the x direction would find itself excelerated by the electrostatic field created by the electron space charge and acquire kinetic energy so that as it passes through the region B it will have acquired a maximum of kinetic energy represented by the vertical distance between the solid potential line and the dotted line of

the diagram. If the ion evaporates from the surface with an initial kinetic energy of V_T , its energy level will be that of the dash-plus line. In either case the ion will be accelerated across the space, impinge on the collector with considerable energy, and probably absorb an electron from it and evaporate off as a neutral atom. It is presumed that the collector will be at a higher temperature than the liquid cesium surface somewhere within the tube envelope and therefore maintain a surface coverage of less than a monolayer. As the pressure of the cesium is increased, the production rate of ions may increase or decrease depending on the temperature of the heated surface and the rate of arrival of cesium atoms.

This discussion indicates that if the cathode has a uniform workfunction structure, ions may be produced at the energy level a or above and will not be as effective in neutralizing space charge as they would be if they could become trapped in the electronic space-charge potential minimum at B. As the cesium pressure is increased, there will be a greater and greater probability that the cesium ion will encounter a neutral cesium atom in such a way as to deliver energy to the atom and thus find itself in an energy level below the surface potential of the collector shown in the diagram at b.

The interaction between the neutral cesium and the ionized cesium may follow either one of two mechanisms. The cesium ion may collide with the cesium atom with an energy-sharing and momentum-conserving collision. The subsequent products then would be a slower-moving ion which might then become trapped, and a faster moving neutral atom. An alternate mechanism which also could have a good probability of occurring would be that the fast-moving ion would come into the neighborhood of a slow-moving cesium atom, absorb the electron from the atom, and continue on its way as a <u>neutral atom</u> with a relatively high kinetic energy. The ion thus created would be a slow-moving ion and therefore lie close to the electronic motive function and be trapped. Either of these processes would accomplish the desired result, namely, that of altering the energy level of the ion to bring it into a state that is below the energy level of the most negative surface. In the example shown in Fig. 4 this is the energy level at b.

As the cesium pressure is increased, the probability of such energylosing collisions increases in direct proportion to the concentration of cesium atoms in the space between the two electrodes. It may therefore be of some interest to have equations by which this concentration may be estimated with reasonable accuracy. These equations in turn can be combined with an estimated "cross-section" associated with the energylosing transition to try to determine the fraction of the ions produced that find their way into the space-charge minimum. Finally in the steady state situation as the space-charge minimum is reduced, the rate of arrival of ions into the plasma will equal their rate of loss. If the ion concentration builds up to be practically equal to the electron concentration then the main space-charge field will be wiped out and the only fields that will remain will be space-charge fields near one or the other of the two electrodes or both and the "drift" field needed to carry the electrons across the space from the neighborhood of the emitter space-charge sheath to the surface of the collector.

Atom Concentration in the Space Between the Emitter and the Collector

In order to calculate an ion mean-free path it is first necessary to have an approximate formula for determining the atom density in the immediate neighborhood of liquid cesium in equilibrium with its vapor at a temperature T_{CS} . This concentration is given by:

$$n_{Cs} = 2.7 \times 10^{23} e^{-\frac{8750}{T_{Cs}}} atoms/cm^3$$
 (15)

A useful form of this equation for calculation purposes is:

$$\log_{10} n_{\rm Cs} \approx 23.44 - \frac{3800}{T_{\rm Cs}}$$
 (16)

The fact that the exponents of Eq. 10 and Eq. 15 are different is not an error but results from the inclusion of a temperature coefficient term into the exponent. Although the above two equations serve to give the density of cesium atoms in equilibrium with the liquid, a correction should be used to relate the estimated temperature in the space between the emitter and the collector to the temperature at the cesium liquid surface.

A suitable form of this correction term is given as:

$$n_s = n_{Cs} \left(\frac{2 T_{Cs}}{T_E + T_C}\right)^{1/2}$$
 (17)

This equation takes this form on the assumption that the effective temperature in the diode space may be taken as the average of the emitter temperature T_E and the collector temperature T_C . To give some idea of the magnitude of this correction, assume for example that the emitter temperatube is 1600°K and the collector temperature is 900°K when the cesium temperature is 500°K. The correction factor is then 0.63.

In order to estimate the mean-free path of an ion it is necessary to know the effective cross-section for an energy-losing collision. This quantity is undoubtedly energy-dependent and therefore any statement concerning its value should preferably be backed by experimental data not known accurately at present. For the purposes at hand, the assumption will be made that the cross-section for energy-losing collisions is 2×10^{-14} cm². This assumption is the equivalent of stating that if a fast-moving ion comes close enough to a slow-moving atom for the center-to-center distance to be 8×10^{-8} cm, there will be a high probability that an exchange of some sort will take place between the two in a manner to leave as a product a slower-moving ion. If the cross-section is represented by σ_4 , and the density of atoms by n_8 , then the best estimate for the mean-free path for the ions is given by:

$$\ddot{h}_{+} = \frac{1}{n_{s}\sigma_{+}} = \frac{5 \times 10^{13}}{n_{s}} \text{ cm}$$
 (18)

Equations 16, 17, and 18 may be combined for numerical calculations. Since the correction term in Eq. 17 is hardly great enough to be compared with the uncertainty in the collision cross-section, an equation can be written which neglects this factor and serves as a quick means of estimating the ion mean-free path in terms of the cesium-condensation temperature. The equation is:

$$\log_{10} \lambda_{+} = \frac{3800}{T_{Cs}} - 9.7$$
 (19)

A second useful forn, of this equation serves to determine the condensation temperature needed to approach a desired mean-free path. This equation

$$T_{Cs} = \frac{3800}{9.7 + \log_{10} \lambda_{+}}$$
(20)

This equation yields the result that approximately 1 mm mean-free path will be associated with the condensation temperature of 437[°]K and onetenth of a millimeter will be the approximate mean-free path at 493[°]K.

If these calculations and estimations are valid, they may be helpful to the designer of a practical heat-to-electrical-power transducer that operates according to the plasma principle. It has been pointed $out^{(1)}$ that the high vacuum transducer must have a very small spacing in order to operate with satisfactory efficiency. The conclusion that one would draw from this discussion is that such a small spacing could work as a definite disadvantage in the plasma transducer.

For illustration purposes, assume a spacing of 0.5 cm for a diode and a cesium pressure adjusted so that the ion-free path would be approximately half this distance or 2.5 mm. The cesium temperature would be 418°K. Equation 11 is used to estimate the minimum temperature of the cathode for moderately efficient ion production. This temperature is $T = 1500^{\circ} K$ and is a reasonable one for a dispenser-type cathode. If its average workfunction is approximately 2.5 ev, then the available electron emission would be about 1 amp /cm². Assume that a space-charge sheath near the surface of the emitter added an additional 0.4 volt step to make the effective value of ϕ ' shown in Fig. 4 equal to 2.9 ev. This would reduce the available electron emission a factor of 20 and bring it to 0.05 amp/cm^2 . This current density would be 25,000 times the current density that would have been available from the same cathode in a high vacuum diode of this spacing when the space-charge minimum coincided with the collector. Again with this cathode operating at this temperature, the current density of 0.05 amp.cm² implies that the location of the space-charge minimum, would be approximately 30 microns from the emitter. The point in mentioning these figures is to lead the way toward an evaluation of the production rate of ions needed to hold the space-charge minimum at this point and give a very small potential difference between the minimum point at B and the electron collector surface at b. The next section will attempt to evaluate these factors.

Ion and Electron Evaporation from a Nonuniform Cathode

The motive diagram shown in Fig. 4 is a one-dimensional diagram suitable for an emitter and a collector, each of which has a uniform surface work-function. In many practical examples of emitters this situation does not represent the facts. Specifically for pure tungsten the variation of workfunction even without the adsorption of films may range from 4.3 to 5.3 ev. Adsorbed films may result in still wider differences. Details concerning dispenser cathodes are very uncertain. Specifically one may picture a work-function structure of a dispenser cathode as one in which there are many islands or wells of strong electron emission to be found at crystal boundaries between the sintered crystals of which the structure is made. Each of the individual pieces of the powdered tungsten used in this fabrication may exhibit considerable range in work-function. In order to illustrate this point, the sketch in Fig. 5 has been produced and represents a completely hypothetical situation which may not differ too much from reality to be worth considering. The lines on the diagram represent imaginary crystal boundaries between the solid tungsten crystalites or sintered powder particles and the shading is related to the thermionic emission. Regions that are white represent strong electron emission and regions that are dark represent high work-function areas of weak electron emission. The scale used on this figure implies that each of the individual particles of tungsten that were sintered together to make a porous block had an average linear dimension of approximately 10 microns. The activation material is assumed to have migrated out between the tungsten particles and activated them locally. The higher the temperature that the cathode is operated, the more likely a situation of this kind exists.

It is important for this discussion to attempt to represent in a twodimensional diagram a motive function to be associated with this situation. It is quite evident that it is impossible to draw an exact representation but Fig. 6 may help to bring out the ideas that are involved.

In Fig. 5 one of the strongly emitting regions is identified as the "a" region, while a neighboring dark region is identified as the "b" region. The work-function of the "a" region is taken to be ϕ_a and the "b" region ϕ_b .

These work-function steps are shown in Fig. 6. If the a and b regions are of comparable size, then the motive function becomes something close to the average at a distance comparable to the average dimension of the patches of high work-function and low work-function area. This is illustrated by Fig. 6 by the fact that one line starts at ϕ_a and the other line starts at ϕ_b and they come together at a distance just outside the emitter comparable with the size of the individual patches involved. If the required potential is applied, shown as $V_{\rm O}$, and the work-function of the collector is ϕ_2 , the motive function the rest of the way across the diode has no slope and therefore corresponds to the zero field condition. If the emitter is heated sufficiently to cause a strong electron emission, then the motive function will take on a form similar to that shown in Fig. 7.

A word description of Fig. 7 may be in order. The dravature of the motive function indicates the existence of space charge. The minimum in the motive function found at B establishes the minimum electron energy within the interior of the emitter for which electrons can escape from the emitter to the collector. The value of this energy is shown as ϕ_{\perp}^{1} . Thus any electron emitted from the high work-function area $\phi_{\rm b}$ is accelerated into the space and moves over to the collector. It is to be expected that there will be a gradation in work-function from ϕ_a to ϕ_b close to the boundaries of the activated area. It is impossible to show in this diagram that additional detail, and therefore only the extremes of the motive function are illustrated Note that in this figure there is an energy level indicated at ϕ_+^* which represents a peak in the motive function. Any positive ions generated at the surface will have to traverse this peak in order to find themselves in the space-charge region near B. This quantity ϕ'_{+} is very important because of the fact that if it is less than 3.9 ev then the difference $(3.9 - \phi_{\pm}^{*})/V_{T}$ is related exponentially to the probability that an ion produced at the surface of the emitter will be able to pass into a region between the emitter and the collector. It is only here that it can be at all effective in reducing space charge.

The next problem to be considered in this qualitative manner is the influence of cesium vapor introduced at a moderately low density. Equation 13 indicates that at a cesium temperature of 390°K, the approximate mean-free path for cesium ions will be 1 centimeter. Furthermore, the relation

14.
given as Eq. 9 indicates that the minimum temperature for a pure tungsten surface to remain, on the average, in a state for which good ionization can take place will be 1410° K. It follows from this that a dispenser cathode operating at 1500° K will not be expected to adsorb an appreciable coverage of cesium. The low work-function areas will be very poor absorbers in any case, and they will also be very poor ionizers. The most efficient ionization will take place over those regions of the cathode for which the work-function is greater than 3.9 ev. Figure 8 attempts to illustrate in a qualitative manner the various influences which the presence of cesium is likely to have if the cesium pressure is controlled by a temperature T_{CS} equal to 392° K, and the emitter temperature is maintained close to 1500° K.

In Fig. 8 the dotted lines are a superposition of Fig. 7 on Fig. 8 so that it will be easier to see a comparison of the two. Note that ϕ_{a} and $\phi_{\rm b}$ are the same whereas ϕ_2 shows a measurable decrease to ϕ_2^{**} . This decrease is the result of the adsorption on the collector of a film of cesium which in all probability will reduce the work-function of the collector by 0.4 ev or more. If no other change took place as a result of the cesium, this would be a distinct advantage. The new work-function is designated by ϕ''_2 . In the drawing of Fig. 8, it is assumed that some of the ions produced at the hot emitter surface will find their way into the neighborhood of the potential minimum at B which in turn acts as an ion trap. In other words once that an ion is caught at an energy level lower in the diagram of Fig. 7 than ϕ_{k}^{*} , it will remain in that area more or less indefinintely since recombination between ions and free electrons is such an improbable event that the ion will remain trapped in the potential minimum for a very long time. As additional ions are trapped there, the potential minimum will rise. This is illustrated schematically in Fig. 8 in that the potential minimum changes from B to B". This change in the potential minimum results in a corresponding change in the value of the limiting electron energy needed to transfer current from the emitter to the collector. The new level is at ϕ^{**} . An objectionable change, from the point of view of being able to deliver ions to the space-charge minimum, is that indicated by the rise in the level diagram associated with ϕ_{\pm}^{**} . Thus the rise to B'' because of the trapped ions results in a change of the motive function which inhibits the delivery of additional ions. Finally a balance takes place at

which the delivery rate of ions is exactly equal to the loss rate. This condition more or less inevitably gives a rise in the electron minimum from B to $B^{\prime\prime}$. This change results in a distinct gain in efficiency of the unit as a heat-to-electrical-power transducer.

It will be assumed for the present that if the transducer is working under the most favorable conditions the voltage output V_O added to the receiver work-function ϕ_2^{*1} will actually be less than the energy difference from the Fermi level of the emitter to the "hump" in the potential function shown as ϕ_{+}^{*1} in Fig. 8. In those circumstances the loss of ions from the space-charge region will be back to the hot emitter and not to the collector. If the problem were as simple as this then the density of ions at B" could be related to the ionization potential V, by:

$$\frac{n_{\pm B^{11}}}{n_{S}} \approx \frac{1}{4} e^{-\frac{V_{i} - \phi_{-}^{12}}{V_{T}}}$$
(21)

In this equation V_i is the ionization potential of cesium of 3.9 volts; n_s is the density of atoms in immediate neighborhood of the ionization surface, and the factor (1/4) is a guess made up of a combination of two facts. In the use of an equation of the form of Eq. 21 a factor of 1/2 is usually introduced as a so-called statistical weight and an additional factor of 1/2 is being introduced because of the fact that only part of the cathode is capable of producing ions. Once they are produced and caught in the potential minimum, the entire region is available for their occupation. This equation cannot be said to be exact but is offered here as a reasonable guess.

An additional fact needs to be considered which is that the ion production process will be characterized by the temperature T of the emitter, whereas the temperature that characterizes the distribution in energy of the ions that are trapped can very well be a lower temperature. This lower temperature could approach that of the neutral cesium vapor outside of the emitter-collector region for experimental tubes in which the spacing between the emitter and collector is not considerably smaller than the diameter of these surfaces. On the other hand, if the spacing is small compared to the diameter, then the characteristic temperature for the ions in the trap should be assumed to be approximately the mean temperature of the emitter and the collector.

In spite of the fact that the discussion applies to the conditions under which the mean-free path is large compared with the spacing, the ion may nevertheless come to thermal equilibrium with the atoms in the space because of the fact that it can oscillate back and forth many times and can therefore have a total distance of travel during its lifetime in the potential minimum much longer than the mean-free path. This detail can be considered to be a refinement which acts in the favorable direction from the point of view of the making of a practical and effective transducer.

Influence of Cesium Pressure in Association with a Nonuniform Emitter

Under the circumstances illustrated in Fig. 8 an increase in cesium pressure will increase the rate of arrival of cesium atoms at the emitter. This increase in arrival rate will result in more adsorption of cesium on the high work-function areas. Once the cesium is adsorbed there, these areas will no longer be very effective at producing ions. The effect to be anticipated then will be a raising of the limiting level ϕ_{ϕ}^{ii} . This change will work to disadvantage in that it makes it more difficult for the ions that are produced to find their way to the region marked B". The lack of a suitable ion density atB" will result in a lowering of this level or an increase in the value of ϕ^{ii} . Thus it is to be anticipated that other things being equal, the increase in cesium pressure will first result in a raising of the potential minimum for electrons from B toward B" with an increase in cesium pressure toward its optimum but additional cesium pressure will result in a decrease in the available current for the transducer. The important point is to try to establish the optimum pressure and this may be possible only by experiment. The theory as so far carried out indicates that an optimum is likely.

Loss of Positive Ions to the Collector

As the output voltage V_O is increased at the expense of some decrease in electron current, the difference in potential between the potential minimum at B' and the surface of the collector at b will

decrease. At the critical condition expressed by:

$$V_{\rm O} + \phi_2^{ii} = \phi_4^{ii}$$
 (22)

ions will begin to escape to the collector to the same extent that they escape to the emitter. If V_O is made still larger, then the principal loss of ions will be at the collector surface and this rate of loss must be supplied by the ions which are able to pass over the ion barrier at ϕ_{+}^{**} . As V_O is made larger, it will be slightly easier for ions to escape from the emitter. This increase in yield may not be sufficient to maintain the desired trapped ion density.

Under the conditions shown in Fig. 8 there is a difference in potential between the space-charge minimum at B^{**} and the surface of the collector which is numerically equal to

$$\phi_{-}^{i_1} - (\nabla_{\phi_{-}} + \phi_{2}^{i_1}) = \nabla_{p}.$$
 (22a)

This potential difference does not represent a loss of energy by the electrons because of the presence of the neutral cesium atoms, but is simply a difference needed to satisfy the space-charge relations. The reader must be reminded that the situation in this part of the plasma discharge is an entirely different one from that found in self-sustained low voltage arcs, because there the difference in potential along the plasma column is one that is determined by the rate at which energy must be put into the system in order to maintain the excitation and ionization of the plasma. In the transducer, no ionization whatsoever takes place in the space since all of the ions are produced at the heated emitter surface unless some auxiliary electrode is introduced. For the present discussion it is assumed that the only two electrodes in this diode are the nonuniform emitter and the uniform collector.

An Interpretation of Data Taken on An Experimental Diode

A diode was constructed for study by Mr. Thomas Robinson of the Thermo-Electron Engineering Corporation which had two dispensertype cathodes, each 3 mm in diameter separated from each other a distance of 0.68 mm. One of these dispensers was heated to 1520[°]K and before cesium was admitted to the tube, a current voltage characteristic was obtained over the range of applied voltage from zero to -2.2 volts with the receiving electrode negative with respect to the emitter. These data were plotted as shown in Fig. 9 and compared with the "master curve"⁽²⁾. The solid line of this figure is the master curve and the index of that curve establishes the value of (V_R/V_T) of 10.4 and a corresponding value of V_R of 1.37. These numbers combine in the formulae given here as Eqs. 16 and 17 permit the calculation of the maximum power available from this diode and the voltage output at which maximum power occurs.

$$P_{\max} = 3.7 \times 10^{-6} V_{T}^{1/2} \frac{V_{R}^{2}}{w^{2}} \text{ watt/cm}^{2}$$
(23)
$$V_{O} = \frac{0.383 \left(\frac{V_{R}}{V_{T}}\right) V_{R}}{\frac{V_{C}}{1+0.31} \left(\frac{V_{R}}{V_{T}}\right)^{4/3}}$$
(24)

In Eq. 16 the distance w is expressed in centimeters for the calculation of the maximum power available in watts/cm². The insertion of the figures mentioned gives a predicted $P_{max} = 5.5 \times 10^{-4}$ watts/cm² and the voltage output at the maximum power is 0.683. The current at maximum power is given by:

$$I_{max} = I_{m} \left[1 + 0.31 \left(\frac{V_{R}}{V_{T}} \right)^{\frac{4}{3}} \right]$$
 (25)

For the present experiment I max * 7.96 I ...

Robinson measured the power delivered to the load in his experiment as a function of the output voltage and obtained the curve. designated "without cesium" of Fig. 10 It is clear that the maximum power was correctly calculated by theory and the voltage output at maximum power was correct as shown by the circle on that graph. Later cesium was admitted to the tube and the available power again measured as a function of the voltage. This result is also shown in Fig. 10 and it is very evident that the favorable action of the cesium increased the power a factor of 10. Before the details concerning this second experiment are discussed, a few additional computations should be made relative to the high vacuum experiment. A calculation chart, shown here as Fig. 11, shows that with this operating temperature and spacing, a current density of 100 microamperes per square centimeter should have been expected in terms of the temperature-spacing relation for the critical current density I_m which flows to the collector with a space-charge minimum coinciding with it. This situation is illustrated by the dotted lines of Fig. 12.

The actual value of $\phi_{\rm R}$ applicable to this experiment may be calculated by:

$$\phi_{\rm R} = 2.3 V_{\rm T} \left[2.08 + 2 \log_{10} {\rm T} - \log_{10} {\rm I}_{\rm m} \right]$$
 (26)

The value of ϕ_R is 3.73 ev. The fact that the observed current voltage characteristic follows the "master curve" so well, as is illustrated by Fig. 9, indicates that the inhomogeneity of the collector is relatively small but does seem to be present, and furthermore, such inhomogeneity as may exist at the emitter probably represents a small part of the area. It will become evident as the calculation proceeds that it will be desriable to invoke the concept that some inhomogeneity does exist and that potential functions not unlike those shown in Fig. 7 and 8 will be involved as a step in the analysis to explain the increased power shown by the curve in Fig. 10 in the presence of cesium. The numerical data mentioned are summarized in Fig. 12.

The basic data upon which the remaining part of this analysis depends are illustrated in Fig. 13. The two curves on this figure show the current-voltage relations as observed with and without the cesium. The liquid cesium temperature was 316° K and this according to Eq. 9 gives an arrival rate at the emitter of 1.4×10^{15} atoms per second for each square centimeter. The estimated collector temperature was 780° K. A sufficient coating of cesium was adsorbed on the collector to reduce its work-function by 0.45 volts as indicated by the horizontal shift in the retarding potential range when one compares the two curves. This yields a collector work-function of 1.9 volts. If the entire curve had shifted horizontally only, then the change in power output would have been due only to the lowering of the work-function of the receiver. The new curve is not one obtained by a parallel shift.

The cesium data when plotted as in Fig. 14 can again be reasonably well represented by the "master" space-charge curve for electrons. The . main difference on analysis, however, is that the current under the critical condition of zero space-charge at the collector is one which would have been associated with a shorter distance than the actual one. The chart on Fig. 11 permits a quick calculation of this distance to be 0.23 mm. It is to be noted by reference to Fig. 12 that the new condition. in the presence of some space-charge neutralization from cesium atoms. is practically as though a diode had been created with the collector located precisely at the potential minimum illustrated in Fig. 12 for the condition of maximum power. This result suggests the drawing of the potential distribution as shown in Fig. 15. The number of electrons that cross the boundary at B per second for a unit area is 5.6 x 10¹⁵. This current would correspond to a density of electrons of 4.6 x 10⁸ electrons per cubic centimeter. This calculation is based on the estimated average velocity of a Maxwellian group of electrons characterized by the temperature 1520° K to be 1.2 x 10^{7} centimeters per second.

With no more data than we have at present, it is altogether reasonable to assume that with an arrival rate of neutral atoms at the heated surface, in the neighborhood of high work-function territory, of 1.4×10^{15} atoms per second for each square centimeter the density of ions right at the surface will be 1.25×10^{11} ions per cc. This calculation depends on the assumption that very close to the high work-function area, the "random current" of ions given by the equation

$$I_{p} \approx n_{po} \left(\frac{kT}{2\pi M}\right)^{1/2} (ions/sec)/cm^{2}$$
 (27)

Under this condition ion production is exactly equal to ion annihilation and the production rate depends on the atom arrival rate. In Eq. 20, I_p is the random ion current expressed in ions arriving at the surface per second for each square centimeter. The density n_{po} is taken to be the ion density in the immediate neighborhood of the surface. The ion mass is M.

21.

The experimental data permits the calculation of the energy difference between the Fermi level of the emitter and the limiting barrier B to be 3.47 ev as shown in Fig. 15. If the density of ions there is taken to be equal to the density of electrons, the energy difference between B and the average surface at which ions are produce I can be approximately 0.61 ev. Under this condition, the effective surface potential will be close to 4.1 ev. Figure 15 has been prepared on the assumption that a surface for ionization does, in fact, exist at 4.1 ev away from the Fermi level of the emitter. On the basis of present knowledge with regard to these surfaces, any ionization surface with a work-function greater than 3.5 ev could deliver ions to the region at B with approximately the same efficiency. When the work-function is less than 3.9, then many of the neutral atoms that arrive at the surface are likely to leave as neutral atoms and therefore the ion production will not be as great as it would be if the work-function wer: higher. Thus, as the work-function increases, the effectiveness of the surface as an ion producer increases but the fraction of those ions p.cduced that can find their way over the ion barrier identified here as ϕ^{*} is reduced by an exponential function of the type exp - $(\delta_{\rm b} - \delta_{\pm}^{\rm in})/V_{\rm T}$.

Since the data shown in Fig. 14 fit the idealized master curve within experimental error, the numbers derived from it may be used to compute the maximum power to be expected from the device. The value of (V_R/V_T) for this curve is 11.8. The corresponding value of V_R is 1.53 ev. Equations 16 and 17 may be used to compute the maximum power and the voltage output at maximum power. The results thus obtained are $P_{max} = 6.15 \times 10^{-3}$ watts per cm² and the voltage output is 0.73 v. These calculated results are represented by the cross with the circle in Fig. 10 and agree well with experiment. The electron current density at maximum power is 8.4×10^{-3} amp/cm⁴.

Determination of the Optimum Cesium Temperature

It is impossible to predict with confidence the optimum cesium temperature because of the lack of needed experimentally determined data applicable to this problem. This section will, therefore, have to depend on the making of a few simple assumptions and if these hypothese are proven wrong, then the predictions based on them will certainly be in error.

The first assumption is that the zero field condition illustrated by Fig. 15 is determined by the equality of the positive ion and the electron densities. For equality, the arrival rate of ions and electrons must be related by:

$$\left(\frac{\nu_{-}}{\nu_{+}}\right)_{\text{at B}} \approx \left(\frac{M}{m}\right)^{1/2}$$
 (28)

In this equation M is the mass of an ion and m is the mass of an electron. The relations represented here imply that both ions and electrons leave the region by going to the collector and since the velocities are inversely proportional to the square root of the mass ratio the ion current will be correspondingly lower for the zero space-charge condition. In order to use this assumption in a numerical calculation, the "effective" average work-function of the ionization region must be known. The experiment described in the previous section gave a value as $\tilde{\phi}_{\rm b} = 4.1$. The equation which will relate the important quantities is the following

$$\phi_{\rm R} = \frac{\phi_{\rm b}}{2} - 10.68 V_{\rm T} + 2.3 V_{\rm T} \log_{10} T + \frac{4490}{T_{\rm Cs}} V_{\rm T}$$
 (29)

The numerical validity of this equation may be tested by inserting into it the values associated with the experiment described in the previous section. When this is done the calculated value of $\phi_{\rm R}$ is 3.47 ev on the assumption that $\overline{\phi}_{\rm h}$ is 4.1.

In order to determine the optimum value of T_{CS} , use is first made of the relation shown as Eq.9. The implication here is that unless some other factor interferes, the best choice of the cesium temperature will be the highest that will result in effective ionization on a tungsten surface. Certain interfering factors will be discussed later in this section.

According to Eq. 9, the maximum cesium temperature is 425° K for an emitter temperature of 1520° K. These two figures are supplemented by the assumption that the previously determined value of ϕ_b of 4.1 is suitable. The predicted value of ϕ_p at this higher condensation

temperature of cesium is then 3.0 ev. This new value represents a reduction in $\phi_{\rm R}$ of 0.47 and a corresponding increase in electron current delivered to the collector by a factor of 36. The current density expected is 3.2 x 10⁻² amp/cm². The chart on Fig. 11 may now be used to determine that the effective spacing of the diode in the presence of this increased cesium pressure will be 39 microns.

At the lower cesium pressure the average work-function of the collector was found to be $\phi_2 = 1.94$ ev. There is no way to know for sure than an increase in cesium pressure will decrease this average work-function still more but for the purpose of illustration at least, it will be assumed that the increase in pressure will reduce the work-function to 1.70. The predicted value of $V_{\rm R}$ is then:

$$V_R = \phi_R - \phi_2 = 3.00 - 1.70 = 1.30$$
 (30)

The corresponding value of (V_R/V_T) is 10.

The next assumption is that having established the equivalent spacing of a vacuum diode which would have the same current density as the cesium diode the current voltage characteristics will follow the vacuum diode curve associated with this reduced spacing. The new spacing for this calculation is the one given as 39 microns. Equations 16 and 17 may be used to determine the predicted maximum power output and corresponding voltage output. The values obtained are $P_{max} = 0.15 \text{ w/cm}^2$ and V_O is 0.65. The current dansity is 0.23 amp/cm². The corresponding value for ϕ''_{1} is 2.74 ev. It is implied in these calculations that the true work-function of the emitter ϕ_a is less than 2.6 ev. The chief advantage in having a smaller value of ϕ_a for the electron emitting portion of the emitter is its influence on the value of ϕ^{**}_{\pm} which is the hump in the diagram of Figs. 15 and 16 that inhibits the loss of ions to the emitter and thus helps maintain the space-charge reduction.

This prediction that an additional 24-fold increase in power is available in the cesium diode over that actually obtained as a result of increasing the cesium pressure is probably optimistic. The calculation has been made in this manner in order to indicate the potential advantages in chosing the most favorable value of the cesium condensation temperature. At this higher temperature Eq. 13 permits the estimation of the cesium ion mean-free path to be 1.8 mm. Since the electron mean-free path is undoubtedly

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longer than this, the implication is that a diode spacing of 1 mm would be just as effective in the presence of cesium as a diode spacing of 100 microns. Associated with the current density of 0.23 amp/cm^2 , the chart on Fig. 11 permits the location of the space-charge minimum to be calculated as 14.4 microns.

In the calculations of this paper, electron energy steps are expressed in terms of their true values at the temperature involved. Therefore the fundamental equation obtained directly from the statistical analysis expresses the current density in the following form:

$$I = 120 T^2 e^{-\frac{\phi}{V_T}} amp/cm^2$$
 (31)

This is the Richardson type of equation and carries with it the number 120 instead of some empirically-determined constant that could be designated as A_R to indicate that it is the Richardson constant found empirically to make the data fit for some set of observations for which the Richardson work-function would be appropriate. Since "true" values of ϕ are used in the analysis given here, the coefficient 120 is the only correct one to use.

For calculations in which it is the purpose to determine the temperature at which a certain emission density will be obtained, Eq. 31 is not the most convenient one to use. The theory behind the transformation to a simpler equation is given in Section 50 of "Thermionic Emission" and two useful equations may be obtained from Eq. 31 to be applied over the emitter temperature ranges associated with each of these equations:

$$1150^{\circ} K < T < 2500^{\circ} K$$

I = 3 x 10^{9-(5.04\phi + 1.6)} $\frac{1000}{T}$ amp/cm² (32)

$$\log_{10}I = 9.48 - (5.04\phi + 1.6)\frac{1000}{T}$$
 (32a)

Range 600° K < T < 1150 $^{\circ}$ K

Range

$$8 - (5.04 \phi + 0.76) \frac{1000}{T} \text{ amp/cm}^2$$
(33)

$$\log_{10} I = 8.85 - (5.04 \phi + 0.76) \frac{1000}{T}$$
(33a)

25.

The principal purpose of the above equations is to show the steps toward the writing of a simple equation by which the maximum temperature of the collector can be evaluated readily in terms of the available output volts V_Q and the energy step ϕ''_1 illustrated in Fig. 16 and the temperature of the electron emitter of the diode T_1 . The way this equation is written incorporates also the limitation that the electron current streaming from the collector toward the emitter shall be no more than 5 per cent of the electron current that flows in the opposite direction. This equation subject to these conditions and definitions permits the calculation of the maximum receiver temperature.

$$\max_{D} T_{2} = 1000 \frac{5.04 (\phi_{-}^{\dagger} - V_{O}) + 0.76}{0.65 + (5.04 \phi_{-}^{\dagger} + 1.6) \frac{1000}{T_{1}}}$$
(34)

In the analysis just completed it was assumed that ϕ_{1}^{11} is 2.74 ev, V_{O} is 0.65, and T_{1} is 1520^OK. With these values substituted into Eq. 34, the maximum temperature of the collector is found to be 1040^OK.

Operation Considerations Related to Diodes Having High Work-Function Emitters

If the source of heat is one which lends itself to the use of a very high work-function emitter, then other considerations may be important. Under ordinary circumstances, it should be anticipated that the lower temperature at which the emitter can work, the more likely one is to have an efficient device. However, efficiency may not be the most important criterion. In fact, it could be that power per unit volume would be far more important than conversion efficiency. Under these circumstances, thought should be given to the operation of high temperature emitters.

Assume for this discussion that the emitter temperature is 2400° K and that it is realistic to make a diode of 100 micron spacing. Calculation shows that the space-charge minimum will coincide with the collector when the current density is 0.009 amp/cm². An emitter with an average work-function of 4.4 ev would have an emission current available of 0.37 amp/cm². A high vacuum transducer would require a low work-function collector which could under favorable conditions have an average work-function of 2 ev and a $V_R \approx 3.17$. Under these conditions, the critical value of (V_R/V_T) is 15.3. This diode would have the maximum power available with a current received

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at the collector of 0.115 amp/cm². The power available to the external circuit would be 0.168 watts/cm². The question that may now be asked is: what improvement should be expected in this diode by the introduction of cesium, and what would be the most suitable cesium pressure as determined by the temperature of the liquid cesium?

The first effect of cesium if the collector temperature could be maintained at a sufficiently low value would be to deduce its work-function. Assume that the absorbed cesium would reduce the work-function to 1.4 ev. Such a change would have a very favorable influence on the power output. Secondly, all of the cesium atoms which would in their normal motion come in contact with the emitter would leave as ions. Very few of these ions would be lost to the collector since its surface would be 0.9 volts more positive than the emitter surface if the external surface conditions were maintained to hold the current at 0.115 amp /cm² in the absence of space-charge neutralization. Actually, as the cesium pressure increases, the ions will tend to neutralize space charge and the electron current achieve its full capability of 0.37 amp/cm². This current should remain constant as the output voltage is increased to 3volts. The combination of these two effects would increase the available power a factor of 6.6, since the maximum power we would expect is:

$$0.37 (4.4 - 1.4) = 1.1 \text{ watt/cm}^2$$
 (35)

Achievement of this power would depend on there being a negligible number of ions that are generated at the emitter and recombine at the collector. We may assume that the average energy associated with the moving electrons and also the moving ions will be 2 V_T (that is, 2 kT/q) and that if their energies are equal, their average velocities will be inversely proportional to the square root of their masses. This factor for cesium is close to 490. This figure will then be used to establish the order of magnitude of the desired cesium arrival rate if on the average every ion which leaves the cathode travels more or less unimpeded to the collector. The electron current of 0.37 amp.cm² corresponds to an emission rate of 2.3 x 10¹⁸ electrons per second for each square centimeter. If we assume that just the right number of ions are present to neutralize the space charge of the electrons, there will be no electric field and the average velocity of electrons in transit across the space may be computed to be 1.52 x 10⁷ cm/sec. Since the electrons

will travel unimpeded across this space, the density will be 1.51×10^{11} electrons per cm³. An exactly equal ion density corresponds to an ion emission rate of 4.7×10^{15} ions per second for each square centimeter. Under these conditions the ion emission rate will be exactly equal to the atom arrival rate and the next question to be answered is the determination of the most suitable cesium condensation temperature.

Were it not for the fact that consideration must be given to the reduced density of atoms between the emitter and the collector, a condensation temperature of 330°K would give the required ion emission. The average temperature in the interelectrode space may be taken as about 1600°K. With this approximate value of the condensation temperature, Eq. 17 shows that the atom evaporation rate at the cesium surface should be increased 2.2 over that calculated by Eq. 8. With this correction factor the theoretical value for the cesium condensation temperature becomes 340°K. At this temperature the mean-free path will be long compared with the spacing and therefore both the electrons and the ions should flow in an unimpeded manner from the emitter to the collector.

If the cesium condensation temperature is raised above the value 340°K then the arrival rate will be greater than that needed and the excess ion production will result in an ion space-charge sheath forming near the surface of the emitter. Such a sheath will inhibit the delivery of the ions to the plasma. It will also create an accelerating field for the electrons. This will increase the electron emission if the output voltage is reduced slightly to take advantage of the lowering of the electron work-function because of the accelerating field produced at the emitter by the ions. The fact that many of the ions that are produced are returned to the emitter surface may also result in the establishing there of an average dipole moment favorable to a still further reduction of the work-function in spite of the high temperature. These two effects increase the emission capability of the cathode over the previously calculated value of 0.37 amp/cm². Without experimental experience it is difficult to determine the best cesium condensation temperature except to state that for temperatures less than 340°, an insufficient number of ions will be available to neutralize the space-charge and as temperatures exceed this value, favorable results may come because of the reduction in the emitter work-function and the corresponding exponential increase in available current.

The cesium pressure called for by this discussion is much lower than that used by some experimenters. For example, V. C. Wilson⁽⁴⁾ experimented with high temperature emitters at relatively high cesium pressure. The two cesium temperatures he used were 534° K and 564° K. The use of the higher cesium pressure would result in the creation of an ion space charge sheath. The fact that an electron emission of 4 amp/cm² was observed sets the "effective" electron barrier at B" of Fig. 8 at 3 ev. Equation 29 shows that any area of the hot surface with a work-function in the range 3 ev to 4.3 ev will deliver ions to help neutralize the electron space charge. The Wilson experiment would seem to indicate that work-function lowering actually takes place.

These thoughts are presented by way of illustration of the use of the equations presented here and the general ideas related to the behavior of a plasma diode as it might be used in conjunction with a high temperature, high work-function emitter. It is clear that many experiments should be performed before too much reliance is placed in these deductions since they depend on an extrapolation based on data not specifically applicable to present needs. Additional experimentally determined facts might come into prominence beyond those considered.

Concluding Remarks

Three principle objectives have guided the preparation of this report. The first was to discuss in some detail the physical principles that seem to be involved in the better understanding of the design and properties of a plasma diode heat-to-electrical-power transducer. The second objective was to make available an intricate set of empirical equations by which many answers to pertinent questions can be obtained numerically when desired. These equations are consistent with the experimental facts as they are known today. They depend very largely upon the studies of Taylor and Langmuir and some very recent measurements made by Robinson. The final objective has been to apply the ideas here to the experiments of Robinson and indicate by quantitative calculation the results that one might hope to obtain by the choice of a more favorable cesium condensation temperature than was actually used.

29.

In the present report the detailed derivations involved in the development of the empirical equations have not been given. If the results found here are ultimately of real practical importance, the more interesting derivations can be prepared and made available as a supplement to this report. Twenty of the thirty-six equations used in this report may find direct application to other problems and are therefore summarized for quick reference in an appendix.

Appendix

Selected Equations From the Text

Minimum temperature for surface ionization as a function of the atom evaporation rate at the cesium condensation surface:

$$\Gamma_{\min} = \frac{14,100}{27.56 - \log_{10} \mu_{a}}$$
(7)

Equation for evaporation rate of cesium:

$$\log_{10}\mu_{a} \approx 27.48 - \frac{3900}{T_{Cs}}$$
 (8)

$$\mu_{\rm a} = 3 \times 10^{27} \times 10^{-\frac{3900}{\rm T_{Cs}}} \text{ atoms/cm}^2$$
 (9)

$$\mu_{\rm a} = 3 \times 10^{27} \, {\rm e}^{-\frac{8980}{{\rm T}_{\rm CS}}} \, {\rm atoms/cm}^2$$
 (10)

Minimum temperature for surface ionization related to cesium temperature

$$T_{\rm m} = 3.6 T_{\rm Cs}$$
 (11)

Ion evaporation rate for tungsten surface temperatures less than the minimum temperature calculated by Eq. 11

$$\log_{10} \nu_{\rm p} = 54.16 - 1.113 \log_{10} \mu_{\rm a} - \frac{26,600}{\rm T}$$
 (12)

$$v_{\rm p} = \frac{1.45 \times 10^{54}}{p_{\rm a}^{1.113}} 10^{-\frac{26,600}{T}}$$
 (13)

$$v_{\rm p} = \frac{1.45 \times 10^{54}}{\mu_{\rm a}^{1.113}} e^{-\frac{5.28}{V_{\rm T}}}$$
 (14)

The vapor concentration of cesium atoms in equilibrium with liquid cesium

$$n_{Cs} = 2.7 \times 10^{23} e^{-\frac{8750}{T_{Cs}}} atoms/cm^3$$
 (15)

$$\log_{10} n_{\rm Cs} = 23.44 - \frac{3800}{T_{\rm Cs}}$$
 (16)

Mean-free path of cesium ions in cesium vapor

$$\log_{10}\lambda_{+} = \frac{3800}{T_{Cs}} - 9.7$$
 (19)

$$T_{Cs} = \frac{3800}{9.7 + \log_{10} \lambda_{+}}$$
(20)

Maximum power in a vacuum diode used for a plasma diode after the "effective" spacing is determined.

$$P_{max} \approx 3.7 \times 10^{-6} V_T^{1/2} \frac{V_R^2}{w^2} watt/cm^2$$
 (23)

Voltage output

$$V_{\rm O} = \frac{0.383 \ (\frac{V_{\rm R}}{V_{\rm T}}) \ V_{\rm R}}{\frac{V_{\rm R}}{1 + 0.31 \ (\frac{V_{\rm R}}{V_{\rm T}})}}$$
(24)

Energy step $\boldsymbol{\phi}_{\mathrm{R}}$ related to current density and temperature

$$\phi_{\rm R} = 2.3 V_{\rm T} \left[2.08 + 2 \log_{10} T - \log_{10} I_{\rm m} \right]$$
 (26)

Energy step ϕ_R related to ion surface work-function ϕ_b ; surface temperature; and cesium temperature

$$b_{\rm R} = \frac{\phi_{\rm b}}{2} - 10.68 V_{\rm T} + 2.3 V_{\rm T} \log_{10} T + \frac{4490}{T_{\rm Cs}} V_{\rm T}$$
 (29)

Simplified emission equation for the range $1150^{\circ}K < T < 2500^{\circ}K$

$$\log_{10}I = 9.48 - (5.04 \phi + 1.6) \frac{1000}{T}$$
 (32a)

Range 600° K < T < 1150°K

$$\log_{10} I = 8.85 - (5.04 \phi + 0.76) \frac{1000}{T}$$
(33a)

Maximum temperature of the collector for 5 per cent return emission

$$\max_{T_2} T_2 = 1000 \frac{5.04 (\phi_1^{**} - V_0) + 0.76}{0.65 + (5.04 \phi_1^{*} + 1.6) \frac{1000}{T_1}}$$
(34)

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18.





FIG.2

PLASMA DIODE WITH HIGH COLLECTOR WORK-FUNCTION



Ionization rate as a function of applied volts observed by Taylor and Langmuir.



Fig. 4 Motive curve with electron space charge.





Hypothetical electron emission distribution over the surface of a very hot dispenser cathode.





EMITTER - NO SPACE CHARGE - ZERO FIELD



FIG. 7 MOTIVE CURVE FOR A NON-UNIFORM EMITTER WITH ELECTRON SPACE CHARGE





Motive functions plasma diode compared with vacuum diode.

Zero-field - - - (plasma) 00000 (vacuum) Max power _____ (plasma) 00000 (vacuum)



Experimental results and comparison with space-charge theory for vacuum diode. Data from Robinson of TEE.

Fig. 9









Fig. 12 Motive curve in experimental high-vacuum diode.





Experimental results and comparison with space-charge theory for plasma diode. (Vacuum diode for comparison). Data from Robinson of TEE.



