Measurements of Plasma Parameters in a Simulated Thermionic Converter

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Cesium-filled thermionic energy converters are being considered as candidate electrical energy sources in future spacecraft requiring tens to hundreds of kilowatts of electric power. The high operating temperatures necessary for a large specific power and high efficiency inevitably impose stringent constraints on the converter fabrication to achieve the desired reliability of the power system. The converter physics for reducing operating temperatures and cesium plasma losses are being studied to achieve high reliability without sacrificing the power performance of the converters. Various cesium parameters which affect the converter performance are: (1) electron temperatures, (2) plasma ion densities, and (3) electric potential profiles. These were investigated using a Langmuir probe in a simulated converter. The parameters were measured in different cesium discharge modes.

Introduction

Cesium-filled thermionic energy converters are being considered as candidate electrical energy sources in future spacecraft requiring tens to hundreds of kilowatts of electric power. The advantage of the thermionic converter over other direct energy conversion devices is its high conversion efficiency, which in turn reduces the required fuel inventory. The conversion efficiency, which is typically larger than 15%, stems mainly from an operating temperature of nearly 2000 K at an emitter electrode where the primary heat is received. The high operating temperature also results in a reduced radiator area for heat rejection, which is an additional advantage. Conversely, the requirements for high temperatures add stringent constraints to the materials and the fabrications of these converters which must have high reliability.

To increase the reliability and to relax the engineering constraints so that the practical converters can be more readily fabricated, a reduction of operating temperatures is being considered. An investigation of a new mode of operation or a new improved converter design is essential to meet the high reliability and performance of a low-temperature converter. To achieve this goal the converter physics must be re-examined in two areas: electrode surface physics and plasma physics.

In this article results of recent investigations of a cesium plasma using a Langmuir probe in a simulated thermionic converter are presented. The results include: (1) electron temperatures, (2) plasma ion densities, and (3) electric potential profiles in various discharge modes.

Test Vehicle

The diode used for probing the cesium plasma is a simulated thermionic energy converter with parallel plane electrode geometry. This device differs from a practical converter in that it has: (1) a sapphire window, (2) a large interelectrode distance (≅5.2 mm), and (3) a movable Langmuir probe. The 1-mm-diam probe wire, similar to that of Bullis (Reference 1), protrudes through a hole in the collector at its center. A micrometer mechanism makes it possible to move the probe across the entire interelectrode spacing between the collector and the emitter. The active area of the probe (0.0078 cm^2) is parallel to the collector. The active area of the collector is 1.27 cm^2; hence, the probe occupies 1/163 of the current-collecting area of the diode. The probe area is the exposed cross section of a tantalum wire. The cylindrical side of the probe is insulated by tantalum oxide, 0.005 cm thick, formed directly on the wire by a thermal oxidation process. The probe assembly is attached to the tube envelope through stainless steel bellows. The probe may be moved by a micrometer screw with respect to the tube envelope where the collector is mounted.

During the measurements, the diode envelope was heated by electric heating tapes. The cesium reservoir was kept at least 50°C below the tube envelope temperature so that the cesium pressure could be determined by the cesium reservoir temperature.

Measurements

The plasma parameters were measured with a circuit (Figure 1) consisting of: (1) the diode loop for driving it as a cesium gas discharge tube, and (2) the probe loop for measuring the probe current flowing in the probe–collector circuit through a variable probe bias. The probe characteristics were displayed on an X–Y recorder as the probe potential was swept between −6 V and +1 V with respect to the collector. A family of characteristic curves was obtained for different locations of the probe, and each family was taken for different discharge modes of the diode. Depending upon the diode current, the conduction occurred in four different modes of cesium discharge: (1) extinguished mode, (2) anode glow mode, (3) ball-of-fire mode, and (4) plasma mode. The first two modes occur at low currents before the cesium vapor breaks down and the remaining modes, which are accompanied by the characteristic plasma column in the interelectrode space, occur thereafter. The diode operations were further defined by measuring the emitter temperature T_E and the cesium reservoir temperature T_R. The emitter temperature was measured through a sapphire window using an optical pyrometer at the blackbody hole in the emitter.

The location of the probe tip was measured from the plane of the collector by noting the turns of the micrometer screw required to protrude the probe into the interelectrode space. Thus, the probe tip is flush with the collector surface, showing no protrusion, when $d = 0$, and the tip is 1.04 mm from the collector when $d = 1$; at $d \cong 5$ the tip comes in contact with the emitter. From the measured probe characteristics, the temperatures of electrons, plasma ion densities, and the potential profiles in the interelectrode gap were determined.

Also, the visual observations of the cesium discharge are incorporated with the analysis to obtain comprehensive interpretations of these results.

Results

Diode Volt-Ampere Curves

To investigate various modes of cesium discharge, the diode was operated at relatively low temperatures at which the diode exhibits all modes, depending upon the magnitude of current. A volt-ampere curve shown in Figure 2 was obtained with $T_E = 1173$ K and $T_R = 404$ K. This curve exhibits a break at a voltage where the cesium vapor ignites. The volt-ampere curve is divided into two regions: the lower-current unignited region, and the higher-current ignited region. Within the unignited region, the cesium discharge occurs in two modes, i.e., the extinguished mode and the anode glow mode, depending upon the diode current. The anode glow

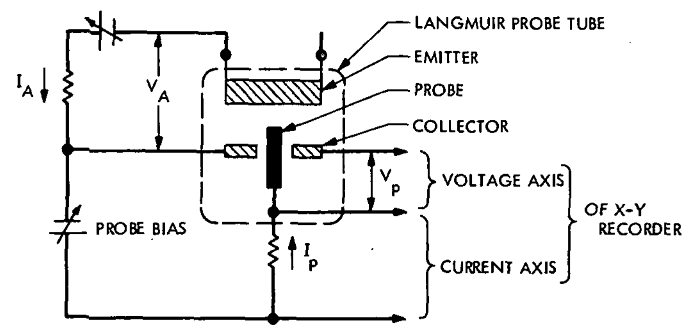

Figure 1. Schematic circuit diagram

mode is accompanied by a rapid increase of the diode current as a result of an increased electron-space-charge neutralization by those ions generated in the anode glow. As the applied voltage increases, the energy supplied to the stream of electrons becomes sufficiently large to cause a propagation of visible glow (ionized zone) toward the emitter which in turn results in the cesium ignition.

In an ignited condition the voltage drop in the plasma, which is in contact with the collector, becomes small since the plasma has nearly zero space charge. Consequently, the diode becomes equivalent to a diode having its virtual collector at the edge of the ball-shaped plasma. The emitter and plasma are separated by a thin dark space. Current conduction occurs with the interelectrode gap partially filled with a ball-of-fire plasma (Reference 2) at the magnitude of current shown at (3) in Figure 2. As the current

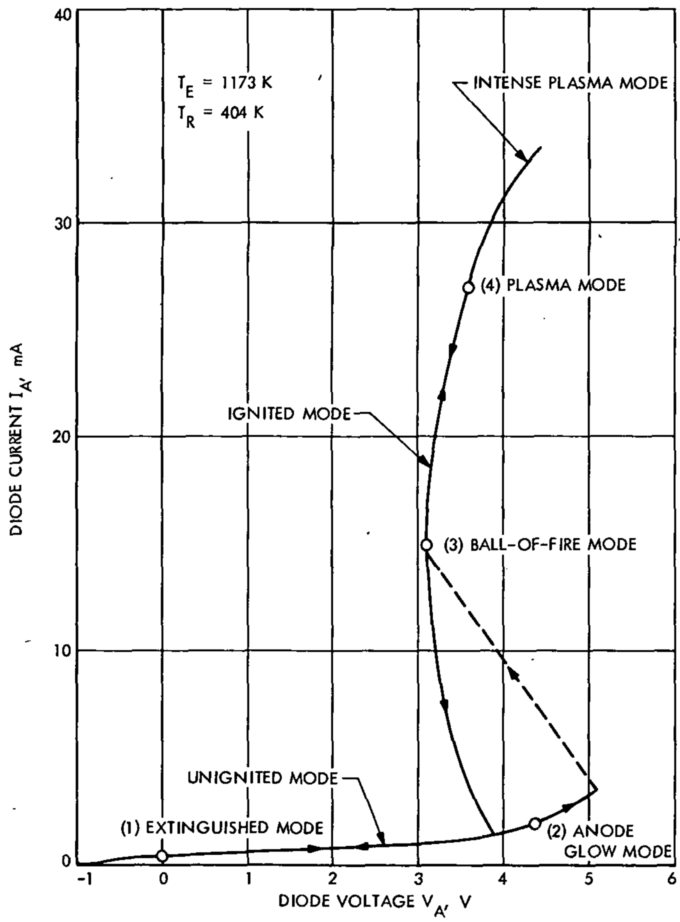

Figure 2. Diode volt-ampere curve

increases further, the plasma merely spreads to a larger area, maintaining the current density constant. The voltage across the diode remains practically constant between point (3) and (4) in the volt-ampere curve. This region is, therefore, similar to that in a normal glow discharge (Reference 3) in inert gases at low pressures. Further increase of diode current requires an increase in the diode voltage to produce an intense plasma. The plasma mode, which occurs between the ball-of-fire mode and an intense-plasma mode, is identified as the maximum power point in practical converters. Similar observations were made by Hansen (Reference 4) in a thermionic converter having an interelectrode spacing of approximately 1 mm.

The probe characteristics, showing the functional dependence of probe current on the probe voltage with respect to the collector, were also measured at four different operating points associated with four different discharge modes. A typical result is shown in Figure 3, where the positive current indicates that the net current to the probe is an electron current, and the negative current indicates that the probe is collecting more ion current than electron current, and/or the probe is emitting electrons. An increased electron emission from the probe, because of an increased heating from the hot emitter, becomes more evident when the probe is located closer to the emitter. The middle part of the probe curve is predominantly prescribed by the thermalized group of electrons as is shown in the semi-log plots (Figure 4).

In the following, the analysis of the probe characteristics obtained with the diode operating in the plasma mode by applying the existing probe theory (Reference 5) is given.

Analysis of Volt-Ampere Curves

Since the probe current I_p is a sum of the electron current I_e arriving at the probe tip, the ion current $-I_i$ contributed by both the plasma ions and surface-generated ions, and the current $-I_b$ by electrons that are emitted back into the emitter from the probe tip, I_p is given by

$$I_p = I_e - I_i - I_b \qquad (1)$$

Referring to the electron energy diagram of the diode shown in Figure 5, the current I_b is given by

$$I_b = I_{b0} \exp\ [e(\phi_p - V_p - \phi_E - V_A)/kT_p], \text{ for } \phi_p - V_p \leqslant \phi_E + V_A$$

and (2)

$$I_b = I_{b0}, \text{ for } \phi_p - V_p \geqslant \phi_E + V_A$$

where I_{b0} is the saturated electron emission from the probe tip at temperature T_p at which its work function is ϕ_p, and V_p is the probe voltage with respect to the collector voltage.

The ion current is saturated for all values of V_p larger than that satisfying the following:

$$-V_p + \phi_p = V_s \tag{3}$$

where V_s is the potential of the interelectrode space at the probe tip.

The electron current I_e is given by

$$I_e = I_{es} \exp\ [-e(\phi_p - V_p - V_s)/kT_e], \text{ for } \phi_p - V_p \geqslant V_s \tag{4}$$

where T_e is the electron temperature.

In this equation, a Boltzman distribution that would occur in fully thermalized plasmas is tacitly assumed. The electron saturation current I_{es} was not observable during this measurement because of a local discharge at the probe tip.

In general, then,

$$I_p = I_{es} \exp\ [-e(\phi_p - V_p - V_s)/kT_e] - I_i - I_b, \text{ for } \phi_p - V_p \geqslant V_s \tag{5}$$

Therefore,

$$I_{es} \exp\ [-e(\phi_p - V_p - V_s)/kT_e] = I_p + I_i + I_b \tag{6}$$

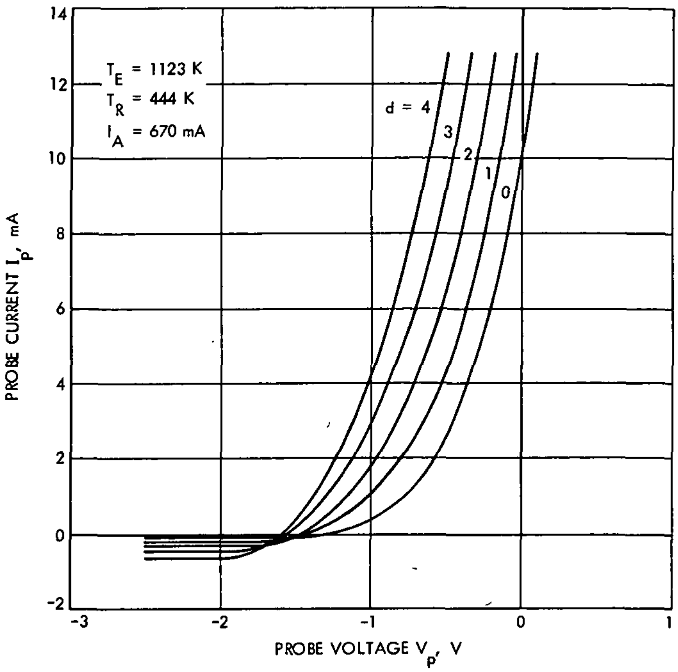

Figure 3. Probe characteristics

Thus, the logarithm of the quantity $I_p + I_i + I_b$, equaling the electron current I_e, should have a linear relationship shown below with the probe voltage V_p:

$$\ln(I_p + I_i + I_b) = \ln(I_e)$$

$$= \left[-\frac{e(\phi_p - V_s)}{kT_e}\right]\left[\frac{eV_p}{kT_e}\right] + \text{constant} \qquad (7)$$

Curves shown in Figure 4 for three different values of T_R with T_E = 1123 K indicate that the logarithm of electron current is linearly dependent upon the probe voltage V_p except for values where the local breakdown or the back emission from the probe disturbs the probe current. From the slope of the curve, which is proportional to e/kT_e, the electron temperature T_e was determined.

The electron temperature T_e was practically independent of distance d (Figure 6) and varied between 17,000 and 3000 K for cesium reservoir temperatures between 404 and 444 K. Observed functional dependence did not agree with other published results (References 1 and 6), which were obtained at higher cesium temperatures or with diodes with smaller gaps.

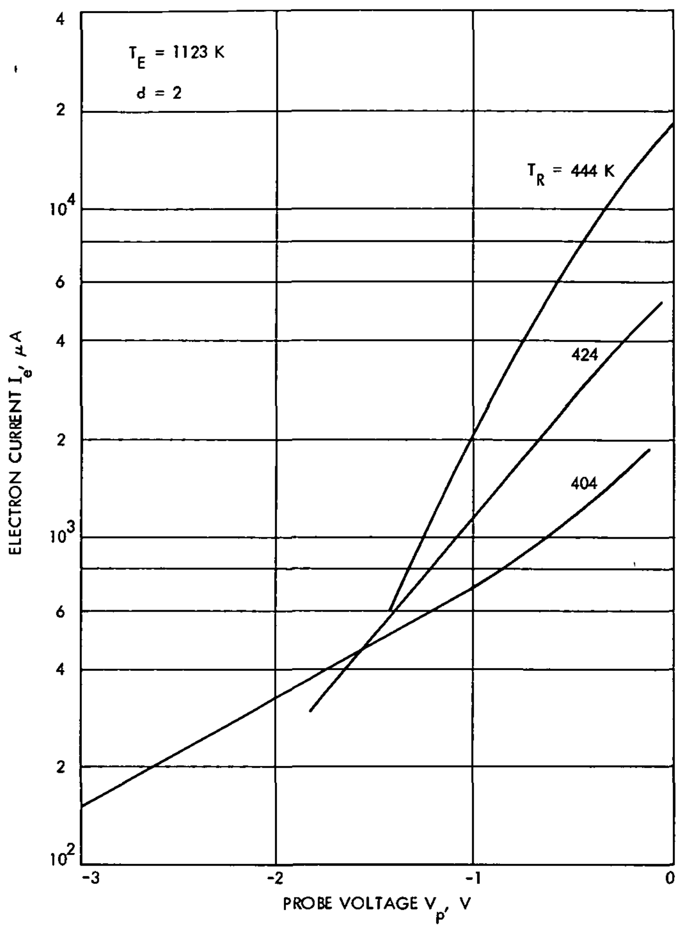

Figure 4. Electron current versus probe voltage

The difference appears to be caused by the fact that the current conduction is drift-dominated in the present work in contrast to the diffusion-dominated conduction in others, in which electrons cool off toward the collector. It may be concluded that the cesium discharge at relatively low pressures and low electrode temperatures is more similar to a glow discharge in inert gases than to a cesium discharge in an ignited thermionic energy converter.

The plasma ion densities were determined from the negative-saturation values of the probe characteristics. In this calculation the probe back-emission I_b was graphically subtracted from the negative saturation to obtain the ion current component I_i. The results obtained at $T_E = 1178$ K, for the ion density N_i, are shown in Figure 7 in semi-log curves. The ion densities increase toward the emitter (larger d), and it varies exponentially

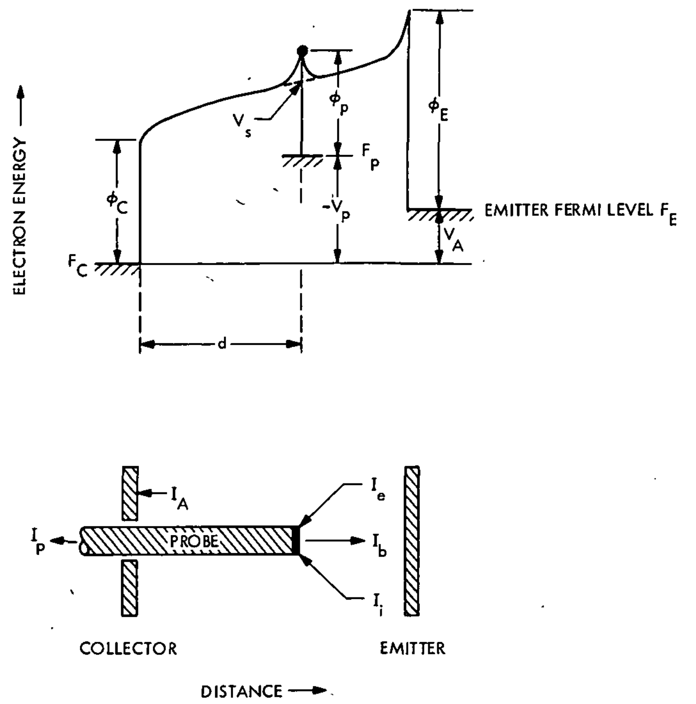

Figure 5. Electron energy diagram

as expected (Reference 7). The ion density, which was of the order of 10% of the cesium gas density, increased with the cesium reservoir temperature T_R.

Lastly, the electric potential profiles in the diode for four different modes of operation will be discussed. The electric potential of the interelectrode space was determined as the probe voltage at which the probe current equaled 1/163 (probe area/collector area) of the diode current. This method was used since the current flow was drift-dominated in this diode in which an LTE (local-thermodynamic-equilibrium) plasma did not exist. The electric potential determined by this method is plotted as a function of distance in Figure 8, after normalizing the potential to zero volts at $d = 0$ (collector). The correction required for this normalization was approximately 0.35 V and is equal to the work function difference between the collector and the probe.

These results show that the negative space potential increases monotonically from the collector toward the emitter, except in the extinguished mode. It should be pointed out that points at the emitter ($d \cong 5$) are the calculated values from $\phi_E - \phi_C + V_A$ (Figure 5) and that the dashed lines between these points and the last measured points at $d = 4.75$ are extrapolations.

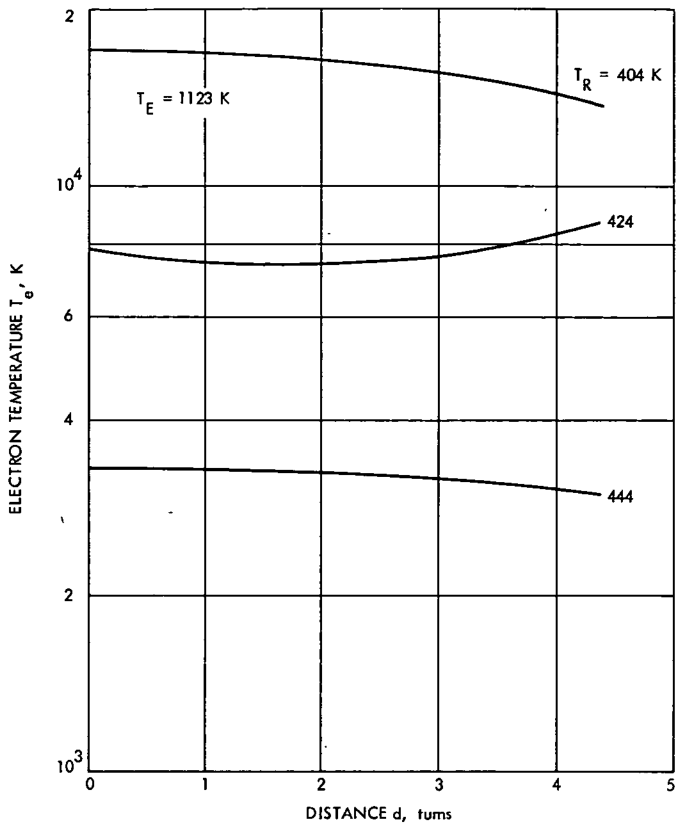

Figure 6. Electron temperature versus probe location

In the extinguished mode the electric potential profile is typical for a negative space-charge-dominated conduction, and the current flow is limited by the negative emitter sheath. As the applied voltage to the collector increases to approximately 5 V, a faint glow appears on the anode indicating a local cesium discharge. In this anode glow the plasma drop is small, as shown in Figure 8 for $d < 1$.

The electric potential profile in a ball-of-fire mode shows a formation of the plasma region being connected to the ion-rich emitter sheath for $4.75 < d < 5.0$. In the plasma mode the profile remains basically the same as that in the ball-of-fire mode since the plasma merely spreads to a larger area from the center of the diode where the probe is located. In both cases the emitter sheath drop is approximately 2 V and the average electric field in the plasma is 4 V/cm.

Conclusions

The probe measurements were made in a simulated thermionic energy converter having an interelectrode spacing of 0.52 cm. The emitter

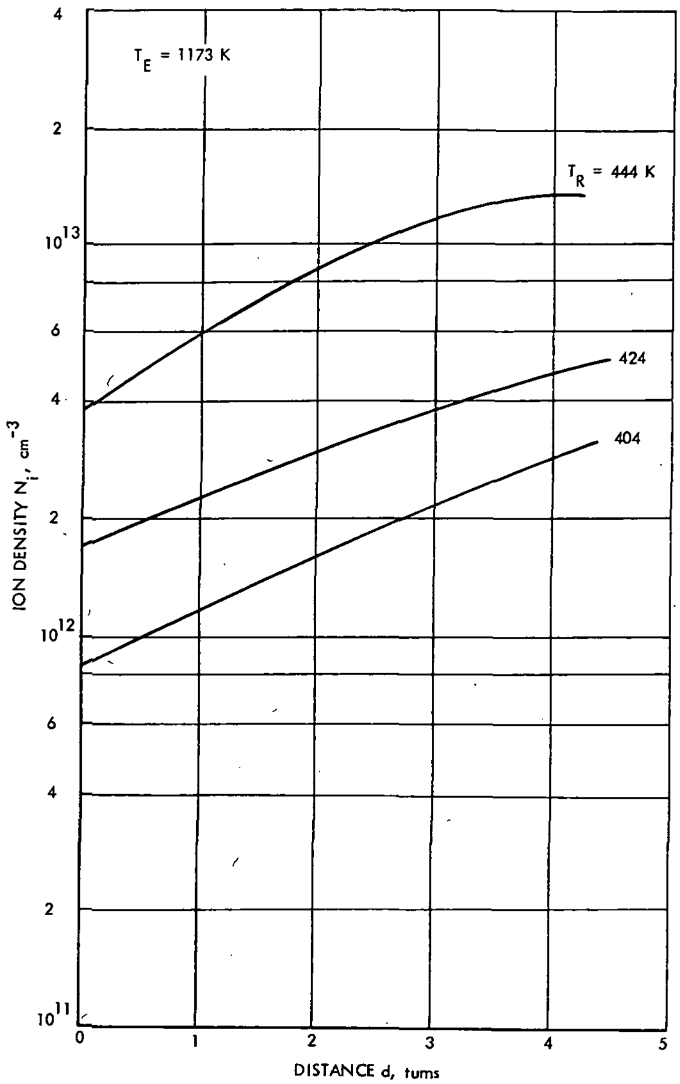

Figure 7. Plasma ion density versus probe location

temperatures were 1123, 1173, and 1223 K, and the cesium reservoir temperatures were 404, 424, and 444 K. The probe, having its active area faced toward the emitter, is axially movable across the entire space between the collector and the emitter. The plasma parameters, including (1) electron temperature, (2) plasma ion densities, and (3) electric potential profiles, were determined in various modes of cesium discharge in the diode.

The electron temperature varied between 17,000 and 3000 K for cesium reservoir temperatures between 404 and 444 K. The higher than expected temperature was a result of low cesium pressure at which the current conduction was drift-dominated.

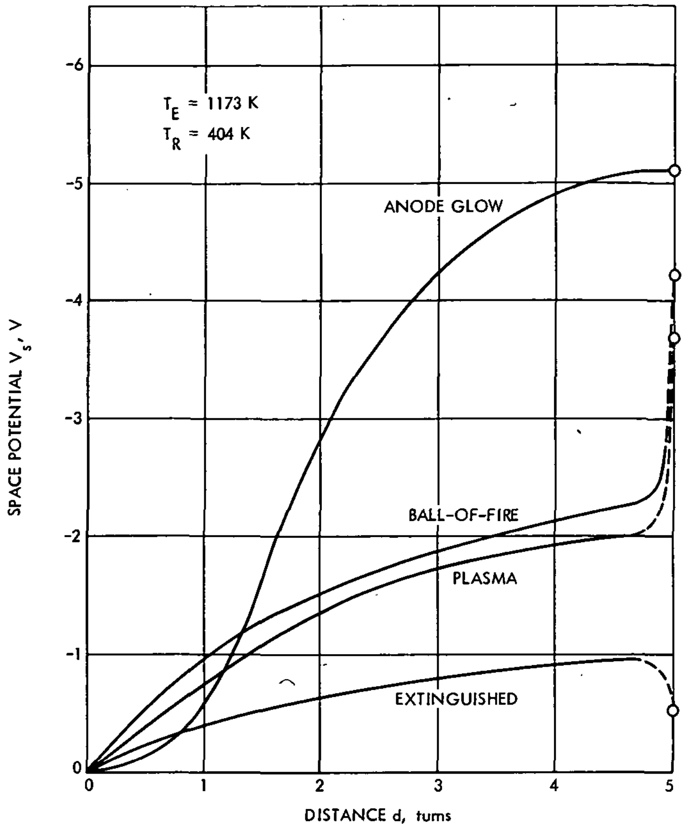

Figure 8. Space electric potential profile

The ion plasma densities were in a range between $10^{13}/cm^3$ and $10^{12}/cm^3$. The magnitude as well as the functional dependence of densities on the location in space was as expected.

The potential profile was obtained in four modes of discharge for the first time in a cesium thermionic diode. The result showed clearly a region of anode glow having a small plasma drop adjacent the collector. The similarity in potential profiles between the ball-of-fire mode and the plasma mode was established; the difference between these two modes mainly lies in the size of the plasma and not the intensity.

The conclusion was extended further to the power performance of practical converters. The maximum output power would be obtained at the transition between the ball-of-fire and the intense plasma mode operation of the converter and the maximum efficiency would be achieved in the unignited mode.

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