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Probe Measurements of a Cesium Plasma in a Simulated Thermionic Energy Converter

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PREFACE

The work described in this report was performed by the Guidance and Control Division of the Jet Propulsion Laboratory.

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ABSTRACT

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.

I. INTRODUCTION

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.

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.

II. 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 D, which is 5.2 mm and 2.1 mm during the measurements for cesium temperatures up to 444°K and to 533°K respectively, and (3) a movable Langmuir probe. The 1-mm-diam probe wire, similar to that of Bullis (Ref. 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 1.25 cm^2; hence, the probe occupies 1/160 of the current-collecting area of the diode. The probe area is the exposed cross section of a tantalum wire. For a case with D = 5.2 mm, the cylindrical side of the probe was insulated by tantalum oxide, 0.005 cm thick, formed directly on the wire by a thermal oxidation process. In contrast, the probe was insulated with a layer of plasma-sprayed alumina for a case with D = 2.1 mm. The probe assembly is attached to the tube envelope through stainless steel bellows and 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°K below the tube envelope temperature so that the cesium pressure could be determined by the cesium reservoir temperature.

III. MEASUREMENTS

The plasma parameters were measured with a circuit (Fig. 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. 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.

IV. RESULTS

To investigate various modes of cesium discharge, the diode was initially operated at relatively low temperatures at which the diode exhibits all modes, depending upon the magnitude of current. A volt-ampere curve shown in Fig. 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 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 net space charge in the plasma is nearly zero. 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 (Ref. 2) at the magnitude of current shown at (3) in Fig. 2. As the current 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 (Ref. 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 (Ref. 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 Fig. 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 semilog plots (Fig. 4).

Curves shown in Fig. 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 (Fig. 5) and varied between 17,000 and 3000°K for cesium reservoir temperatures between 404 and 444°K. At higher cesium temperatures the electron temperature decreased to as low as 2.1 times that of the emitter temperature; for example, T_e = 2572°K when T_E = 1273°K with D = 2.1 mm. Observed functional dependence did not agree with other published results (Refs. 1 and 5), which were obtained at higher cesium temperatures or with diodes with smaller gaps. The difference at low cesium temperature case 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 (Fig. 6). The results obtained at T_E = 1173°K, for the ion density N_i, are shown in Fig. 7 in semi-log curves. The ion densities increase toward the emitter (larger d), and it varies exponentially as expected (Ref. 6). 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 1/160 (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 Fig. 8, after normalizing the potential to zero volts at d = 0 (collector). The correction required for this normalization was approximately 0.35 V, which can be considered as the work function difference between the collector and the probe. For comparison, the electric potential profiles are also shown in Fig. 9 at higher cesium temperatures. The space potentials in the ignited mode here were determined differently from the previous case by determining the break in probe characteristics where the electron current saturated.

V. CONCLUSION

The electron temperature varied between 17,000 and 3000°K for cesium reservoir temperatures between 404 and 444°K. The temperature higher than expected was a result of low cesium pressures at which the current conduction was drift-dominated. However, the electron temperatures as low as 2572°K were recorded when T_E = 1273°K with higher cesium temperature at 533°K. The current conduction was diffusion-dominated in this case.

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. 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.

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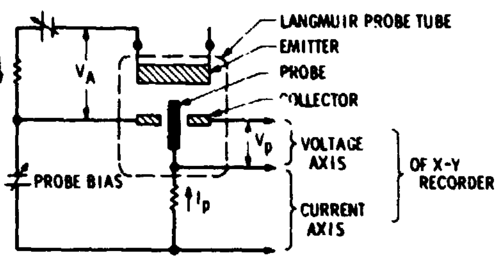

Fig. 1. Schematic circuit diagram

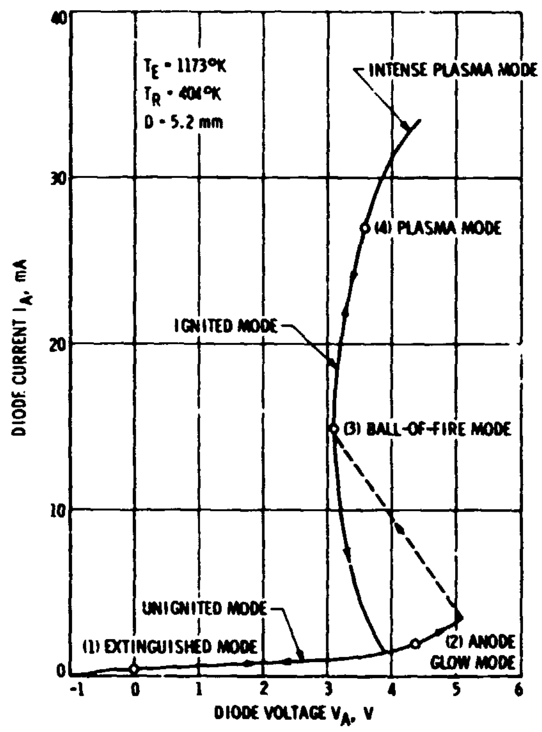

Fig. 2. Diode volt-ampere curve

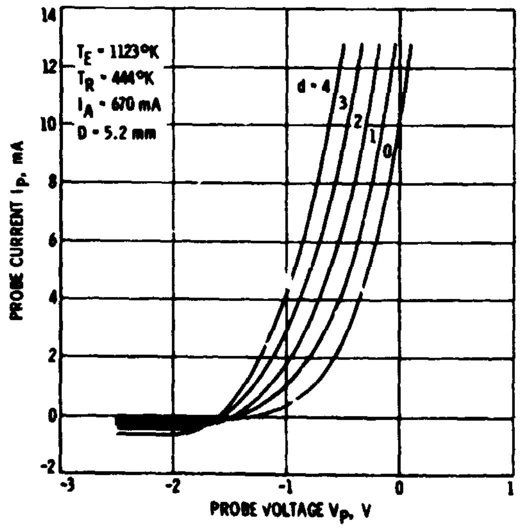

Fig. 3. Probe characteristics

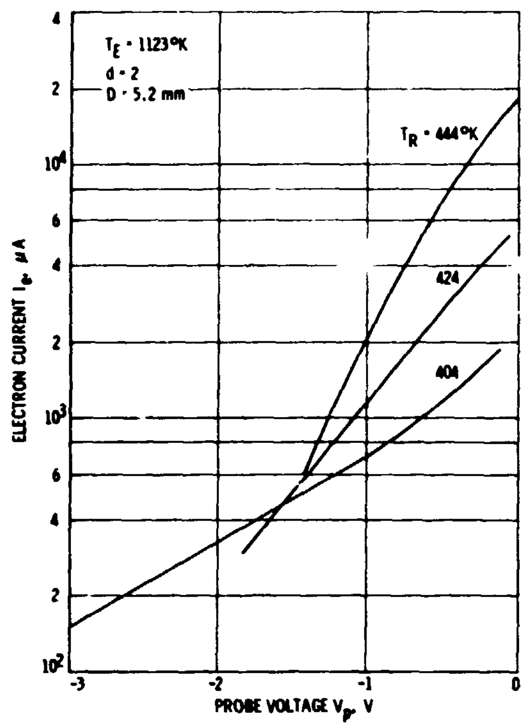

Fig. 4. Electron current versus probe voltage

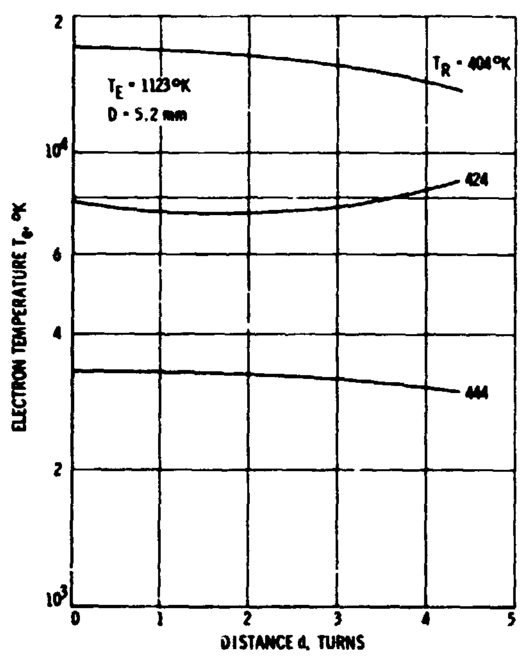

Fig. 5. Electron temperature versus probe location

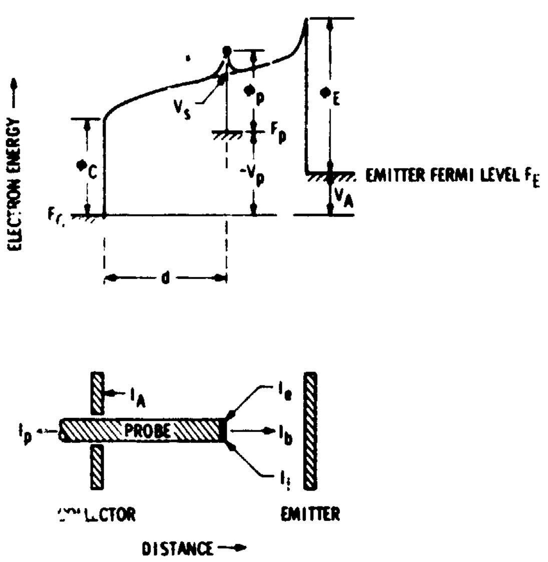

Fig. 6. Electron energy diagram

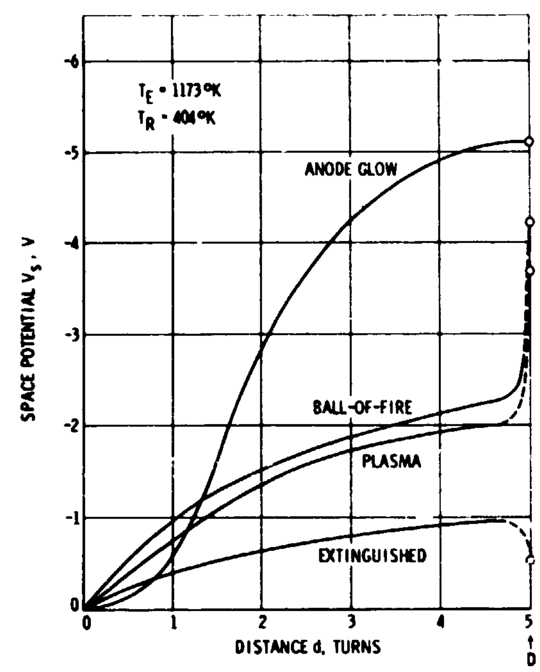

Fig. 8. Space electric potential profile, D = 5.2 mm

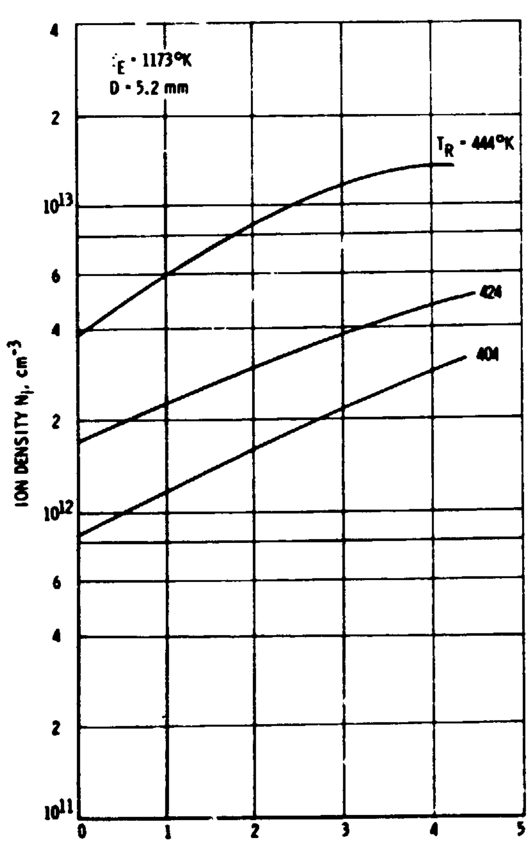

Fig. 7. Plasma ion density versus probe location

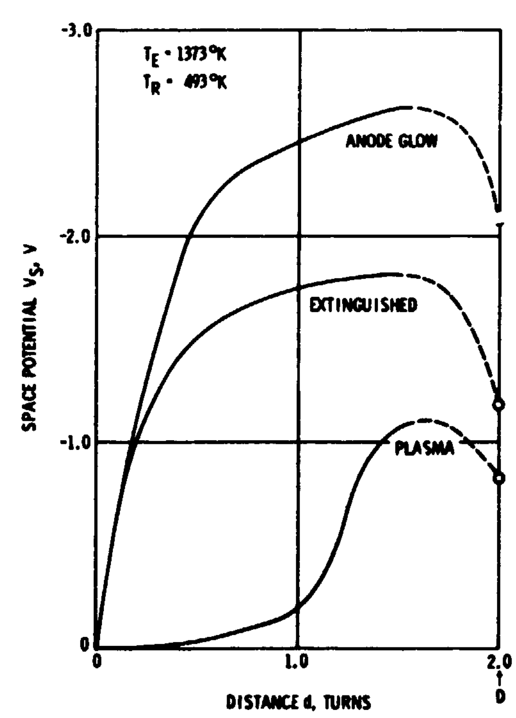

Fig. 9. Space electric potential profile, D = 2.1 mm

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