Experimental Study of Plasma Contactor Phenomena

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Results illustrating variations in plasma properties near hollow cathode plasma contactors (for use with electrodynamic tethers and in other charge control applications) are presented. Emphasis is placed on describing results obtained when the plasma contactor is collecting electrons from a simulated ionospheric plasma. Two important results include 1) the observation of a double layer located between the plasma generated by the contactor and the simulated ionospheric plasma and 2) enhanced effectiveness of the electron collection process when the ionization rate within the plasma adjacent to the contactor is increased.

Nomenclature

e = electron charge, 1.6×10^{-19} C
J_{CE} = contactor electron emission current, A
J_{CD} = contactor discharge current, A
J_{p+} = ion current produced near the plasma contactor by electrons streaming from the ambient plasma, A
J_{SD} = simulator discharge current, A
j_0 = normalized current parameter in the model for a spherical double layer (from Ref. 18)
k = Boltzmann constant, 1.38×10^{-23} J/K
m_e = electron mass, 9.1×10^{-31} kg
m_+ = xenon ion mass, kg
$\dot{m}_c$ = contactor flow rate, standard cm^3/min (sccm), (xenon)
$\dot{m}_s$ = simulator flow rate, standard cm^3/min (sccm), (xenon)
n_0 = simulated ionospheric plasma density, m^{-3}
n_i = ion density of the plasma associated with the contactor, measured near the double layer boundary, m^{-3}
P_0 = pressure in vacuum facility measured far from contactor and simulator devices, Torr
r_i = radius of plasma associated with the contactor (assumes spherical geometry with contactor at origin), m
r_0 = radius measured from the contactor to the ambient plasma (assumes spherical geometry), m
T_0 = neutral atom temperature measured far from contactor and simulator devices, K
T_c = temperature of neutral atoms flowing from contactor hollow cathode, K
T_{e0} = temperature of electrons in the simulated ionospheric plasma, eV
T_{ei} = temperature of electrons in the plasma associated with the contactor, eV
V_B = bias voltage, V
V_P = potential of simulated ionospheric plasma measured far from the vacuum tank walls, V
V_{CD} = contactor discharge voltage, V
V_{SD} = simulator discharge voltage, V
V_{SH} = double layer potential drop, V
α = normalized current ratio from a model of a spherical double layer (from Ref. 18)
ϵ_0 = permittivity of free space (8.85×10^{-12} F/m)
η = normalized sheath potential drop ($eV_{SH}/k\ T_{ei}$)
λ_D = Debye length $\sqrt{(\epsilon_0 e T_e/e^2 m_e)}$, m
γ = constant used to calculate the Bohn current density of ions approaching a double layer boundary from a contactor plasma (assumed equal to 0.3)

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Introduction

OBJECTS placed in a space plasma collect and emit charged particles and they can accumulate net electrical charge. Because the capacitance of a typical spacecraft surface is small, this net charge accumulation can cause the potential of these surfaces to change rapidly and dramatically. A

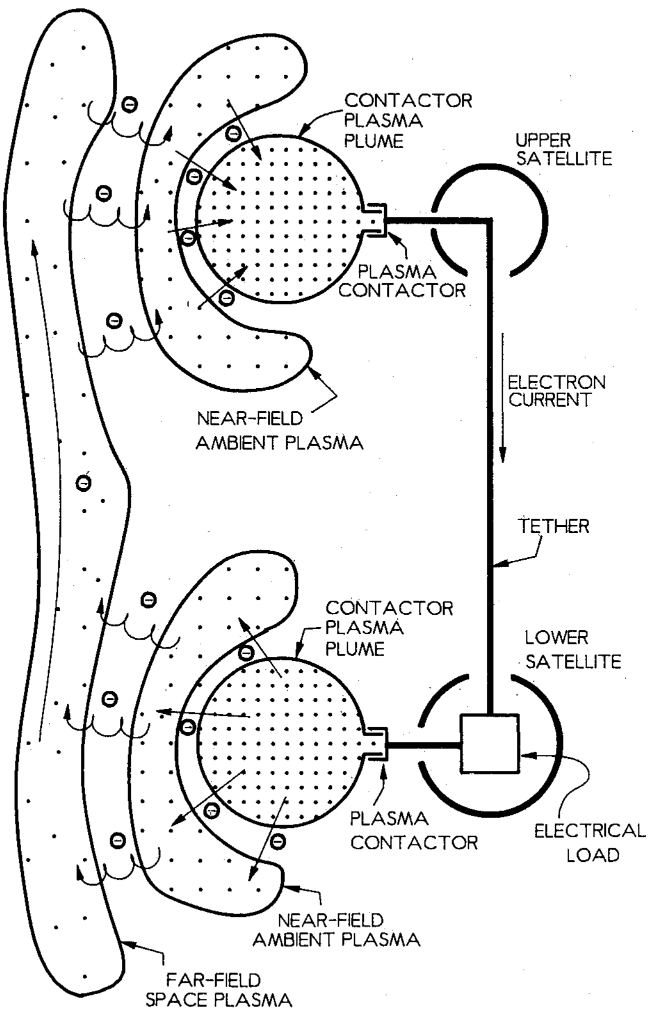

Fig. 1 Conceptualized electrodynamic tether circuit.

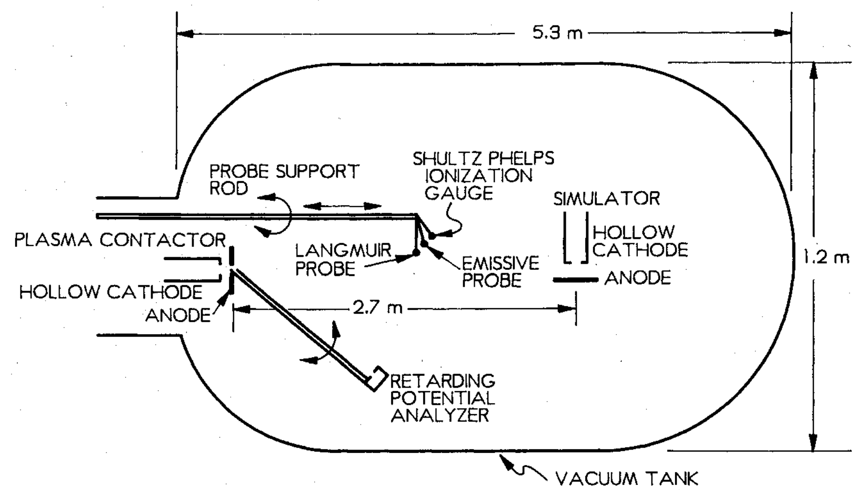

Fig. 2 Mechanical schematic diagram.

plasma contactor serves to prevent this problem by providing low-impedance electrical connections between spacecraft surfaces and a space plasma. It can prevent both gross spacecraft charging[1] and differential charging[2] of isolated spacecraft surfaces. It can also serve to establish a firm reference potential (local space plasma potential) so the bias on an instrument will be known.

In all of these applications, the contactor enables the achievement of mission objectives by preventing detrimental charging effects. However, these are applications in which the contactor is required to handle currents that are typically small and it can conduct them without substantial voltage differences developing. On the other hand, plasma contactors are also needed as elements in circuits associated with electrodynamic tethers[3] where large currents must be conducted and larger voltage differences can develop.

An electrodynamic tether system includes two spacecraft connected by a long conductive wire or tether in the manner suggested in Fig. 1. When oriented properly, the tether will cut geomagnetic field lines as it moves in orbit and will induce a voltage difference between its two ends. In order to take advantage of this voltage difference for power generation purposes, a return path for the current flowing through the tether and an electrical load must be provided. Figure 1 illustrates a route for this return path through a space plasma via plasma plumes that serve as electrical brushes or space plasma contactors. As the figure suggests, it might be possible to separate the overall plasma contacting process into near- and far-field processes. The near-field process is assumed to reflect effects associated with current conduction between adjacent, static plasmas. The far-field process, on the other hand, is assumed to include effects associated with relative motion between two plasmas, as well as current flow through the geoscale plasma. The experiments that are discussed in this paper will address phenomena occurring in the near-field region.

An electrodynamic tether will generate power efficiently provided the load impedance is large compared to the sum of the impedances associated with the tether, the space plasma, and the contactors (one collecting electrons and the other emitting them). Hence, an important characteristic of a plasma contactor is that it exhibits a low voltage drop to ambient plasma at typical operational currents. Electrons are identified as the principal carriers of this current in Fig. 1 (because they are less massive and therefore more mobile than ions), but it should be recognized that ions are also present, and they flow in a direction generally opposite to that of the electrons. Although the ions do not conduct substantial current, it will be shown that they play an important role in determining the contractor-to-ambient plasma potential difference.

Hollow Cathode Devices

A review of the desirable characteristics of a plasma contactor (e.g., reliability, simplicity, low expellant flow rates and power demands, as well as low impedance coupling capability) has suggested a hollow cathode discharge is well-suited to the plasma contacting application.[4,5] Such a device consists of a small diameter (of order 1 cm) refractory metal tube that is electron-beam welded to a thoriated tungsten plate containing an orifice that is typically 1 mm in diameter. Located within and electrically connected to the tube is a low work function insert from which electrons are emitted. An anode, biased positive of the hollow cathode and located immediately downstream of the orifice plate, collects a fraction of the electrons being drawn through the cathode orifice. The remaining fraction can be drawn into the plasma plume which emanates from the cathode and contacts an ambient plasma electrically.

The hollow cathode discharge is initiated by flowing xenon through the cathode tube and orifice, applying power to the cathode heater to raise the insert temperature to thermionic emission levels, and applying a bias on the anode that can range, depending on insert temperature, from a few hundred to several thousand volts. Once the insert begins to emit electrons, a dense plasma is formed within the cathode, and a discharge is established between this plasma and the anode through the orifice. A detailed study of a hollow cathode has been provided by Siegfried and Wilbur.[6]

Apparatus and Procedures

In order to study the plasma contacting process, the apparatus shown schematically in Figs. 2 and 3 was constructed. Physically, this apparatus consists of two hollow cathode devices. One is shown at the right of each figure and is labeled "simulator." It is used to generate a simulated space plasma (the ambient plasma). The other hollow cathode, shown on the left and labeled "contactor," is used to generate the contactor plasma plume. The contactor and the contactor plasma plume are biased relative to the ambient plasma to induce current flow. Also shown are the power supplies and instrumentation needed to sustain and measure the characteristics of the plasmas produced. The simulator and contactor hollow cathodes are separated by 2.7 m and are located within a 1.2-m-diam by 5.3-m-long vacuum chamber. They both utilize cathodes with 6.4-mm-diam tubes and inserts that were fabricated by rolling 0.013-mm-thick tantalum foils into the shape of a hollow cylinder and treating them with Chemical R-500. [Chemical R-500 is a double carbonate ($BaCO_3$, $SrCO_3$), low work function mixture that has been made by J. T. Baker Co., but it is no longer in production.]

For these tests, the orifice in the simulator cathode was 0.38 mm in diameter and its anode was a solid 3-cm-diam, 0.25-

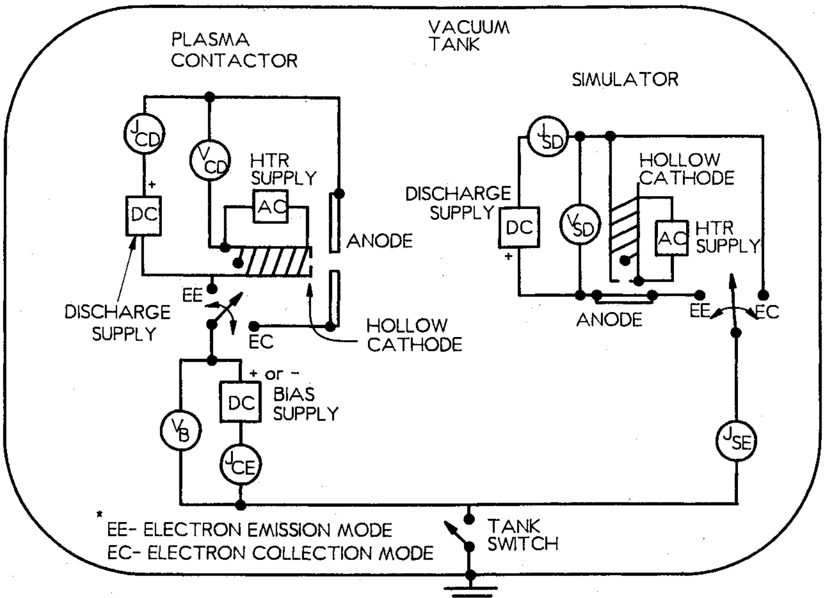

Fig. 3 Electrical system schematic.

mm-thick tantalum plate oriented parallel to the orifice plate and separated from it by a distance that could be varied from 1 to 5 mm. The orifice in the contactor cathode was 0.76 mm in diameter. Its anode was a 12-cm-diam stainless steel plate with an on-centerline, 1-cm-diam tantalum insert having a 5-mm-diam orifice in it. The anode plate, insert, and orifice were all located concentric with the contactor cathode centerline on a plane ~2 mm downstream of the cathode orifice plate.

Typical tests were conducted by heating the contactor and simulator cathodes to about 1300 K, establishing high expellant (xenon) flow rates through them, and initiating an arc discharge between the anode and cathode at each device. Next, the desired contactor and simulator flow rates and discharge current levels were established; the contactor was biased relative to the simulator using the bias power supply; and voltage, current, and probing instrument data were collected. The voltages and currents measured during typical tests are designated by the symbols shown within the circles in Fig. 3; they include the contactor and simulator discharge currents and voltages, the bias voltage between the contactor and simulator, and the contactor and simulator electron emission currents.

The experimental apparatus contains three switches. The two shown at the contactor and simulator are positioned at either the "EE" or "EC" position depending on whether the contactor is biased negative of the simulator and therefore Emitting Electrons (EE) or biased positive and therefore Collecting Electrons (EC). It is necessary to position these switches properly for each contactor operating mode to assure that intentional limitations imposed on the discharge current levels do not result in unintentional limitations being imposed on the electron emission or collection currents.[7] The tank bias switch shown in Fig. 3 was installed so the vacuum tank could be allowed to float relative to the contactor/simulator system or be connected to the simulator. Tests conducted to investigate the effects of changes in the position of this switch on plasma and performance data have suggested that it has no significant effect on a contactor collecting electrons. On the other hand, when the contactor is emitting electrons and the switch is closed, most of the electron current is drawn to the tank walls. Opening this switch during contactor electron emission tests, however, forced most of the electron emission current to flow to the simulator. Tests described in this study were generally conducted with the tank bias switch closed. Any data collected with this switch open will be identified specifically.

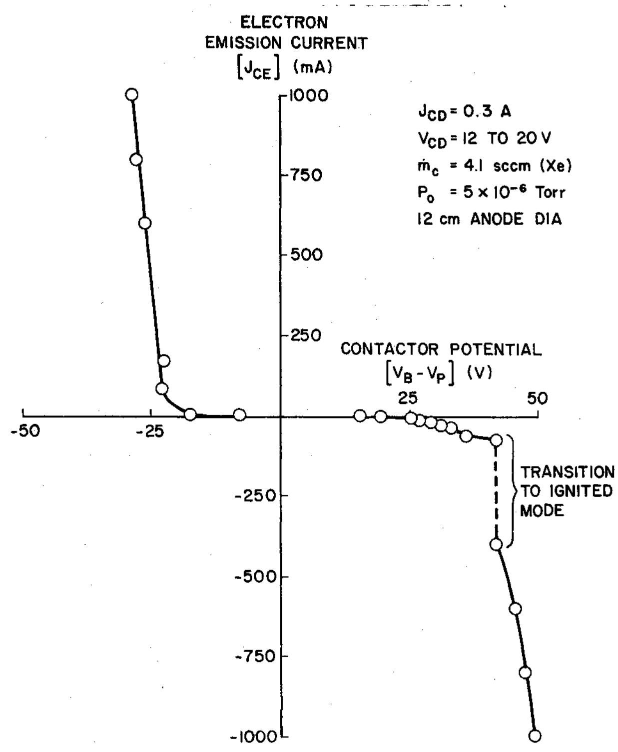

Fig. 4 Typical plasma contactor performance curve.

The plasma environment produced between the contactor and the simulator was probed using the various instruments shown in Fig. 2. They include an emissive probe,[8] a Langmuir probe,[9] a Shultz-Phelps nude pressure gauge,[10] and a retarding potential analyzer.[11]

Results

The typical data in Fig. 4 show the electron current emitted as a function of the voltage difference between the plasma contactor and the ambient plasma. These particular data correspond to a contactor discharge current of 0.3 A and an expellant flow rate of 4.1 sccm of xenon. Under these conditions the pressure in the vacuum tank was 5×10^{-6} Torr, and the contactor discharge voltage varied over the range from 12 to 20 V as the electron emission current was varied from +1 A to −1 A. The data of Fig. 4 show the contactor potential remains near −25 V when the contactor is emitting electrons (second quadrant) and that the contactor potential rises to about 50 V when the contactor is collecting electrons (i.e., for negative emission currents in the fourth quadrant).

The curve in the fourth quadrant of Fig. 4 shows that the electron collection current increases rather suddenly at a potential difference of about 40 V where the "transition to ignited mode" operation is identified. The onset of this transition is accompanied by the appearance of a bright luminous glow that typically extends several centimeters from the contactor and is somewhat spherical in shape. This luminosity is caused by the de-excitation of xenon atoms that have been excited by electrons being drawn (streaming) toward the contactor. It is presumed that some ionization is also induced along with these excitation reactions.

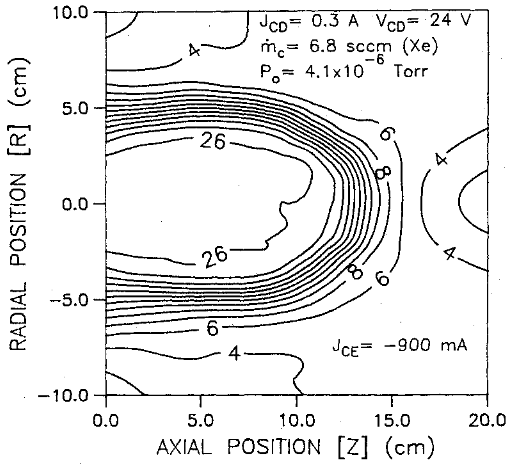

Fig. 5 Typical potential variation near a contactor collecting electrons.

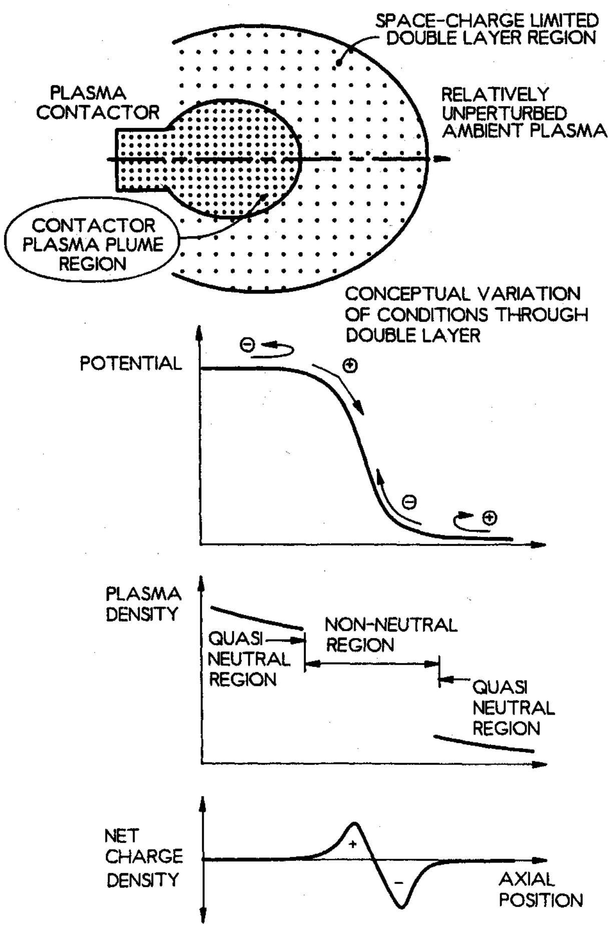

Fig. 6 Conceptual model of the near-field electron collection process.

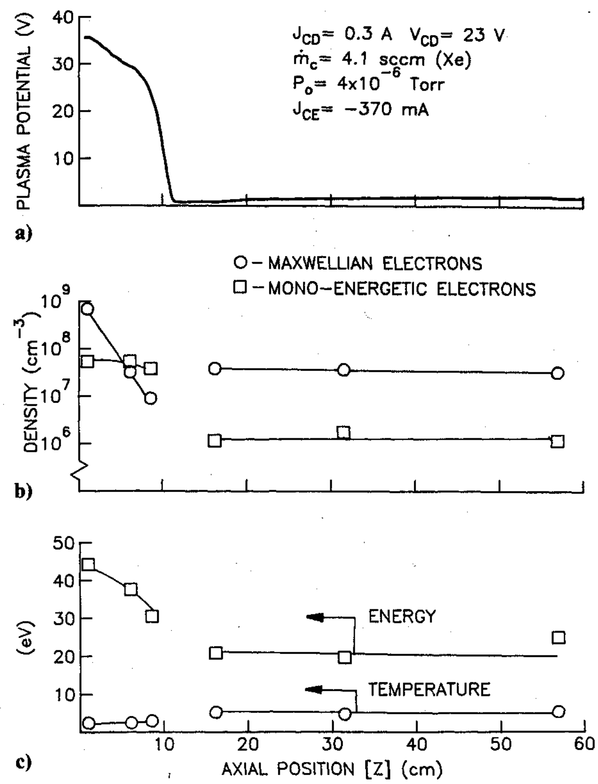

Fig. 7 Typical plasma property profiles measured along the centerline—electron collection mode.

Electron Collection

When plasma potentials are measured throughout the region immediately downstream of a contactor collecting electrons, data like those shown in Fig. 5 are obtained. This figure shows two regions of relatively uniform potential plasma separated by a region in which the potential gradients are large. Since neither magnetic field nor collision-induced impedances are present in the region where the potential changes rapidly, this must be a double layer region,[12] i.e., one in which charged particle acceleration occurs and induces charge separation.

On the basis of the typical data of Fig. 5, one can propose the model of the near-field electron collection process suggested by Fig. 6. This model involves a relatively higher density plume of quasineutral plasma in the region immediately adjacent to the contactor separated from a lower density quasineutral ambient plasma by a double layer (or double sheath). As the centerline plasma potential profile in this figure suggests, electrons and ions counterflow through the double layer. Specifically, electrons from the ambient plasma are drawn toward the contactor plasma plume, and ions from this plume are drawn toward the ambient plasma. On the other hand, ions from the ambient plasma and electrons from the contactor plume are both reflected at the double layer boundaries. The ion and electron currents that can be drawn through the double layer region are limited by the space-charge effects suggested by the net accumulations of positive and negative charge shown, respectively, upstream and downstream of the double layer midpoint in the bottom sketch of Fig. 6. Hershkowitz[13] has provided a comprehensive review of double layers and their related phenomena, and the reader is referred to this work for more information on this subject.

When plasma properties are measured along the vacuum tank/contactor centerline, data such as those shown in Fig. 7 are obtained. These results suggest plasma conditions do vary in a way that is consistent with the model of Fig. 6. Figures 7b and 7c indicate the high density and ambient plasmas both contain monoenergetic (or primary) and Maxwellian electron groups. They show that the Maxwellian temperature and density and the primary energy and density all remain constant at about 6 eV, 4×10^7 cm^{-3}, 20 eV and 1×10^6 cm^{-3}, respectively, in the ambient plasma region for this case where 370 mA of electrons are being collected.

In experiments conducted after the one corresponding to Fig. 7, the relative noise level in the ambient plasma was measured. This was accomplished by measuring the rms fluctuation in the current flowing to the Langmuir probe when it was held at plasma potential and comparing it to the time-averaged value. This ratio was observed to vary from 0.14 to 0.6 depending on the simulator operating conditions. These values suggest that the ambient plasma was noisy, and according to Crawford,[14] this noise could cause errors in the plasma properties that were determined from time-averaged Langmuir probe traces. Specifically, overestimates of the plasma density by factors of 2 or more are likely. The Langmuir probe traces were measured using an ammeter (bandwidth 0 to ~100 Hz) that fed a mechanical X-Y recorder (bandwidth 0 to ~20 Hz), which also received the probe potential signal. This combination of low-pass ammeter and mechanical recorder effectively filtered the higher frequency noise from the Langmuir probe signal. Density data such as those shown in Fig. 7 could be reproduced within a factor of 2 from one experiment to the next. Similar noise levels (about 0.2) have been reported by Guyot and Hollenstein[15] in experiments investigating double layer phenomena that included plasma density data. In view of this work and the level of reproducibility in the present experiments, it is suggested that the relative values of plasma density can be used to understand trends observed with changing contactor conditions, and that absolute densities are accurate at the order of magnitude level.

The energy of the primary electrons in the ambient plasma (Fig. 7c) is on the order of the simulator cathode-to-ambient plasma potential difference. This suggests that these electrons are ones that have been accelerated into the ambient plasma from a plasma generated near the simulator hollow cathode and have had few energy-degrading collisions. It should be noted that the ratio of primary-to-Maxwellian electrons in the ambient plasma is small (usually less than 5% as in the case of the data of Fig. 7). The data of Fig. 7b show the density of the Maxwellian electrons upstream of the double layer drops rapidly with distance from the contactor cathode. In fact, the Maxwellian density and temperature were nearly immeasurable (at contactor plasma plume locations very near the double layer boundary) because the primary electron signal to the Langmuir probe nearly overwhelmed the Maxwellian one. The data of Fig. 7c show the primary electron density upstream of the double layer is about two orders of magnitude greater than that downstream. The primary electron density upstream of the double layer is also seen to increase slightly as the distance from the contactor decreases, probably because these electrons are being concentrated as they stream radially inward toward the cathode. Finally, it should be noted that the energy of the primary electrons in the region upstream of the double layer (35 to 45 V) is roughly equal to the double layer potential drop (V_{SH}). This suggests that the primary electrons found in the high density plume are indeed those that have been accelerated across the double layer from the Maxwellian electron group in the ambient plasma. This result also supports the proposed physical model of the electron collection process.

Theoretical Model of Electron Collection

Conversion of the basic physical model of near-field electron collection into a quantitative model requires that the unknowns of the problem (double layer location and voltage drop, for example) be expressed mathematically in terms of such known or controllable parameters and variables as the current being collected and the ambient and contactor plume plasma densities and temperatures. An elementary theoretical model of the electron collection process has been developed and verified using experimental results obtained in the laboratory.[16] The essential features of this model reflect the observations that 1) the surface area of the downstream boundary of the double layer is determined by the electron current being collected and by the random electron current density in the ambient plasma, 2) the surface area of the upstream boundary of the double layer is determined by the space charge-limited ion current that must flow across the double layer at a current density defined by the Bohm condition for a stable sheath,[17] and 3) the voltage drop across the double layer is determined by the requirement that ions and electrons flow across the double layer at their space-charge-limited levels.[18] These essential features can be invoked to develop the following mathematical model, which is summarized from Ref. 16.

If it is assumed that electron collection is spherically symmetric and that it occurs over a full 4π sr solid angle, then the first condition identified in the previous paragraph requires that the outer radius of the double layer (r_0) be given by

$$r_0 = \left[\frac{|J_{CE}|}{e\, n_0} \sqrt{\frac{m_e}{8\pi\, k\, T_{e0}}} \right]^{1/2} \tag{1}$$

Imposition of the second condition for the same case leads to the following expression for the inner radius of the double layer

$$r_i = \left[\frac{J_+}{4\pi e\, n_i\, \gamma} \sqrt{\frac{m_+}{k\, T_{ei}}} \right]^{1/2} \tag{2}$$

In Eq. (2), γ is a pre-sheath correction parameter that is projected to have a value of 0.3 based on laboratory tests.[16]

Imposition of the third condition yields the voltage drop (V_{SH}) that develops across the double layer

$$V_{SH} = \left[\frac{|J_{CE}|}{4\pi\, \epsilon_0\, j_0} \left(\frac{m_e}{2e}\right)^{1/2} \right]^{2/3} \tag{3}$$

In this equation, j_0 is a parameter that depends on r_i/r_0 and is determined by the solution to the spherical space-charge-limited, double layer problem.[18]

Effects of Ion Current on Electron Collection Behavior

In order for the simple model expressed in the preceding equations to be valid, the contactor plume should be spherical, and the ion and electron currents should both be flowing at their space-charge-limited values. This means that the ion

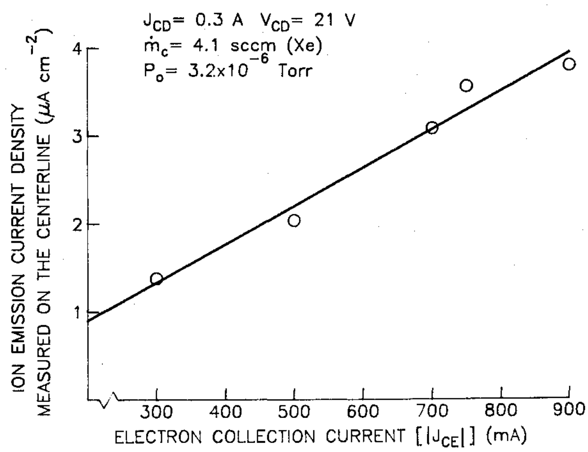

Fig. 8 Effect of electron collection current on ion emission current density measurements.

current flowing from the contactor plume to the ambient plasma would be given by

$$J_+ = \frac{|J_{CE}|}{\alpha}\sqrt{\frac{m_e}{m_+}} \tag{4}$$

where α is a parameter (dependent upon radius ratio) determined from the solution of the space-charge current flow problem.[18] Equation (4) is commonly referred to as the Langmuir condition (when $\alpha = 1$) and is actually valid only at high double layer voltage drop/electron temperature ratios (η).[13] The correction due to finite temperatures tends to increase J_+ above the value given by Eq. (4) but does not change the functional relationships significantly at the high values of η for our experiments.

Figure 8 shows the effect of changes in the ion current density flowing across a typical double layer as a function of the electron current being collected through it. These measurements were made with the retarding potential analyzer positioned on the tank centerline under conditions where the double layer radius ratio and the double layer potential drop did not change significantly as collection current was varied. This figure demonstrates that the measured functional relationship between the ion and electron currents (linear) is in good agreement with Eq. (4). Measurement of the azimuthal variation in the ion current density through a typical double layer using the retarding potential analyzer and integration of the resulting profile yields a total ion collection current that agrees qualitatively with the prediction of Eq. (4) [measured ion emission currents were typically 2 to 3 times greater than those predicted by Eq. (4)]. These results are considered to be a verification that ion and electron currents flowing through the double layer are space-charge-limited.

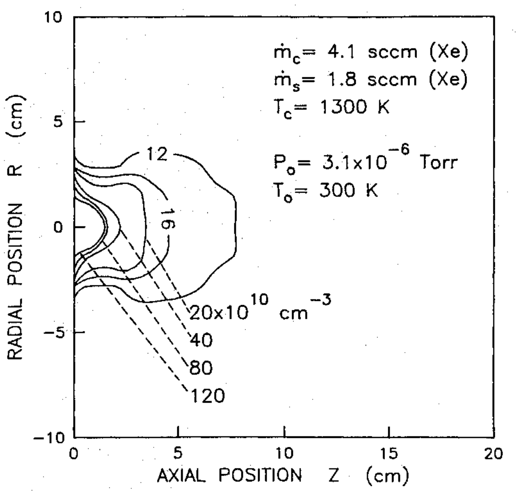

Fig. 9 Typical variation in neutral atom density.

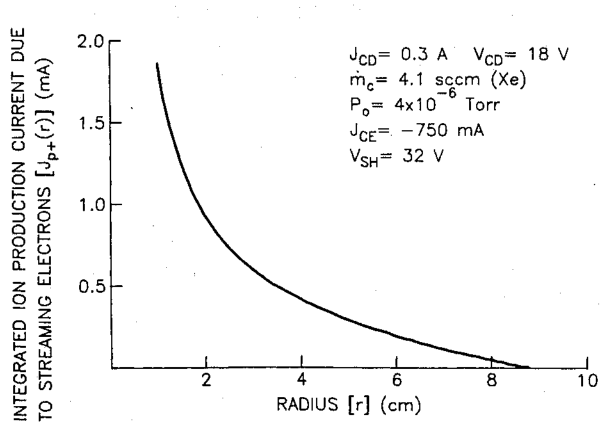

Fig. 10 Prediction of ion production by streaming electrons.[16]

Ignited Mode Electron Collection

The rather sudden increase in electron collection current shown in the data of Fig. 4 that is accompanied by luminosity in the high density plume region is an important phenomenon. When this transition into the ignited mode of electron collection occurs, the slope of the current/voltage characteristic becomes more negative, and smaller double layer voltage drops are required at a given electron collection current. It is believed that this occurs because electrons being collected acquire sufficient energy on passing through the double layer so they can excite and ionize expellant atoms coming through the cathode orifice. The excitation would be expected to cause the observed increase in contactor plume luminosity, and the ionization would be expected to cause an increase in the ion current leaving the plume. This would in turn be expected to cause the observed increase in electron collection current [see Eq. (4)].

In order to assure that sufficient excitation and ionization reactions do occur to induce "ignited mode" operation, it is necessary to determine if the neutral atom density is sufficient to yield a reasonable electron-atom inelastic collision frequency. The equal-density contour plot of Fig. 9 shows the axial and radial variation in xenon atom density determined from measured pressures immediately downstream of the contactor at typical contactor and simulator flow conditions. These data have been computed on the basis of pressure measurements by applying the perfect gas equation and assuming that the xenon flowing from the contactor is at 1300 K and the background gas is in equilibrium with the vacuum chamber wall at a temperature of 300 K. Figure 9 suggests that the density drops from a high value at the contactor orifice to background levels at distances several centimeters from it. Using data such as those shown in Fig. 9, typical ion production rates due to electrons streaming toward the contactor cathode can be computed.[16,19] A typical result obtained from such calculations is shown in Fig. 10 in the form of a plot of integrated ion production rate by electrons that have streamed from the outer radius of the double layer to the radius values indicated on the horizontal axis. The calculations have been made using experimentally measured double layer voltage drops (V_{SH}), double layer radii, etc. The curve indicates that the ion production rate increases dramatically as the streaming electrons approach the contactor orifice ($r \to 0$) because the xenon density and the streaming electron density are highest there. The space-charge-limited ion current associated with the operating conditions of Fig. 9 is about 2 mA, and Fig. 10 indicates that this amount of ion current is produced by the streaming electrons as they travel from the inner radius of the double layer to a radial location of about 1 cm. Hence it is suggested that ion production induced by streaming electrons alone could be sufficient to assure low voltage operation of a contactor collecting electrons without including any ions produced in the hollow cathode-to-anode discharge. It is noted in this regard that discharge-produced ions are generated sufficiently close to the cathode so they can recombine on hollow cathode or anode surfaces more readily than ions produced by streaming electrons. It is considered likely that essentially all ions produced within a few Debye shielding lengths of the cathode by either mechanism would be lost to the cathode.

It is noted that the discharge current of a contactor may be reduced to zero without inducing a significant change in the double layer voltage drop once the contactor is collecting electrons stably in the ignited mode. This observation also supports the hypothesis of substantial ion production by streaming electrons.

Electron Emission Mode of Operation

Each contactor used on an electrodynamic tether will probably be designed as both an electron emitter and an electron collector. Since hollow cathode contactor operation has been demonstrated in space in the electron emission mode at relatively high current levels,[20,21] this mode has been considered less problematic. As a result the early efforts at plasma probing and modeling the plasma contacting processes have focused on the less well-understood electron collection mode of contacting. Data showing typical double layer voltage drops have been measured in the laboratory, however, and these results (as those in Fig. 4) suggest that the double layer voltage drops are lower for the electron emission mode than for the electron collection mode.

Figure 11 shows typical plasma potential maps measured for a contactor emitting electrons at a current level of 1.25 A. These maps differ from those for a contactor collecting electrons because they show no uniform plasma potential region adjacent to the contactor. Because such a region is not apparent, it has not been possible to apply the simple double layer model to this case, even though electrons and ions would be expected to counterflow at their space-charge-limited levels in the electron emission mode just as they appear to in the electron collection mode.

As the electron emission current level is reduced, the associated potential profiles begin to show increased structure like that in Fig. 12, where potentials rise from zero in the ambient plasma to about 3 V before they drop below -5 V at the contactor orifice. In this lower current case, the potential hump suggests a net positive space-charge accumulation develops, presumably because electrons streaming from the cathode with substantial kinetic energies ionize neutral atoms and leave behind slow-moving ions. The reason that a potential hump should develop at low emission current levels (Fig. 11) and not at high ones (Fig. 12) is not apparent. However, a careful analysis of the data has suggested the hump probably develops to an even greater extent at the higher current levels, but the emissive probe does not measure it properly. This measurement error can be understood by recognizing that an emissive probe, which is being held at a relatively high but constant temperature so it will emit electrons, measures a floating potential that is close to the true plasma potential when it is in a low density plasma. As it is moved into more dense plasmas, however, it floats at potentials that drop progressively further below the true potential of the plasma. This occurs because the thermal current of electrons flowing to the emissive probe from progressively more dense plasma eventually exceeds the thermionic emission capability of the probe. It is noted that the data of Fig. 12 were collected for the case where the tank switch (Fig. 4) was open because this produced a more dramatic potential hump.

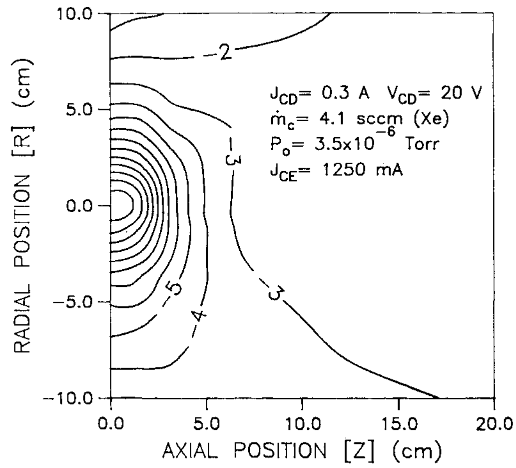

Fig. 11 Typical potential variation near a contactor emitting electrons at a high current level.

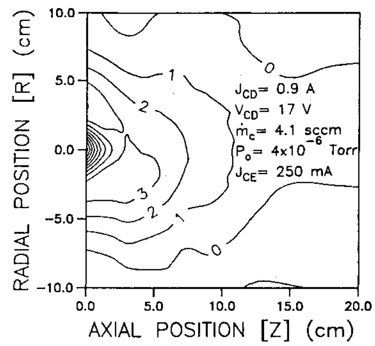

Fig. 12 Typical potential variation near a contactor emitting electrons at a low current level.

Extending Laboratory Results to Space

It should be recognized that an ideal experimental simulation of the in-space plasma contacting process would involve similarity of not only the current levels and contactor hardware involved but also the space environment. Complete simulation of this environment implies 1) similar ambient ionic/atomic species concentrations, 2) similar ambient plasma density and temperature levels, 3) similar magnetic field intensity and relative contactor/magnetic field velocity conditions, and 4) an ambient plasma that is not perturbed by vacuum chamber walls or other apparatus during the conduct of the tests. In the present study these conditions have in general not been met.

Specifically, no attempt has been made to simulate the ionic and atomic species of space; rather, the background gas in the tests is principally xenon coming from the contactor and simulator. Further, it has been found that electrons being emitted or collected by the contactor and simulator collide with the background gas and produce ions at a rate that has a far greater influence on the ambient plasma density and temperature than does the simulator discharge current and voltage. As a result, ambient plasma densities used in the tests are substantially greater than those expected during the conduct of space tests. This high plasma density has the beneficial effect, however, of preventing the contactor plasma plume/double layer from extending to and interacting with the vacuum chamber walls. If the tests had been conducted at the low densities of space, an unreasonably large vacuum chamber would have been required to prevent these interactions from occurring.

Although some effects of changes in magnetic field strength on the plasma contacting process have been examined[7] and found to have a negligible influence on laboratory test results, the effects of magnetic field strength and relative motion at space plasma density conditions are not reflected in any test results. If a near-field plasma moving at low Earth orbital velocity with a spacecraft exists, then the results apply directly. If not, they still provide insight into important plasma phenomena. It is suggested, therefore, on the basis of the review of the differences between the laboratory and space plasma experiments just discussed that results obtained from space tests may differ substantially from those measured in laboratory tests. The laboratory results can, however, be used to identify phenomena that will probably be important in space, and they can serve to calibrate numerical models of the contacting process[22-24] that can reflect the effects of magnetic fields, spacecraft motion, and accurate ionospheric properties.

Conclusions

Hollow cathode-based plasma contactors represent an effective means of preventing various types of spacecraft-charging problems. The near-field plasma contacting process associated with electron collection can be described using three distinct regions in which different plasma properties and particle acceleration phenomena prevail. These are a contactor plasma plume region that is immediately adjacent to the contactor, a double layer region, and a near-field ambient plasma region. Beyond these regions, it is presumed the effects of motion of the near-field plasma relative to the ionospheric plasma and the magnetic field within it become important.

Ions and electrons counterflow through the collisionless double layer to conduct current between the contactor and near-field ambient plasmas biased relative to each other. The outer boundary of this double layer is located such that its surface area is sufficient to collect the electron current being drawn from an ambient plasma characterized by a prescribed random electron current density. The inner boundary of the double layer is located such that its surface area is sufficient to supply an ion current at a rate that will satisfy the Bohm criterion. The bulk of the voltage drop associated with the near-field electron collection process develops between these two boundaries of the double layer. This voltage difference establishes itself at a value that will assure both the ion and electron currents flow at their space-charge-limited values.

Electron collection is most efficient when the contactor is operating in the "ignited mode." In this operating mode, electrons streaming from the ambient plasma through the double layer and into the high density plume excite and ionize expellant gas coming from the contactor hollow cathode. Once operation in this mode develops, it is possible to sustain the electron collection process without supplying power from the hollow cathode discharge supply.

Although operation in the electron emission mode is not considered to be a limiting problem for hollow cathode-based plasma contactors, interesting phenomena have been observed. One noteworthy feature of electron emission operation is the presence of a positive potential hill just downstream of the contactor cathode.

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