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LABORATORY EXPERIMENTS ON PLASMA CONTACTORS

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Abstract. Experimental results describing the operation of hollow cathode plasma contactors collecting and emitting electrons from and to an ambient plasma at current levels of order one ampere are presented. The voltage drops induced between a contactor and an ambient plasma are shown to be a few tens of volts at such current levels. The development of a double sheath and the production of substantial numbers of ions by electrons streaming across it are associated with the electron collection process. The development of a complex potential structure including a high potential hill just downstream of the cathode orifice is shown to characterize a typical contactor emitting electrons.

Introduction

Objects placed in a space plasma collect and emit charged particles at variable rates and, consequently, 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 such a surface to change rapidly and dramatically. A space plasma contactor serves to prevent this problem by providing low impedance electrical connections 1) between spacecraft surfaces and space plasma thereby preventing gross spacecraft charging (Purvis and Bartlett, 1980) and 2) between adjacent spacecraft surfaces that are isolated from each other thereby preventing differential charging (Olsen, et al., 1981). A contactor could also serve to establish a firm reference potential (local space plasma potential) for space-based instruments.

Effective spacecraft charging control is realized when the voltage differences associated with gross and differential charging are minimal over the full range of environmental conditions in which the spacecraft could find itself. A hollow cathode appears to be a device that can be used to achieve such control in both positive and negative spacecraft charging environments. The purpose of this paper will be to review the operating principles of a hollow cathode, to describe laboratory experiments conducted to demonstrate how hollow cathodes couple to ambient plasmas and to suggest, based on test results, mechanisms by which a hollow cathode and possibly other discharge plasma devices effect spacecraft charging control.

Background

Hollow Cathode Devices

A review of the desirable characteristics of a plasma contactor (e.g. reliability, simplicity, low expellant and power demands and low coupling impedance) has suggested that a hollow cathode discharge is attractive compared to other contactor alternatives (Wilbur, 1986). Key features of a hollow cathode and the mechanisms by which it produces a discharge are illustrated in Fig. 1. The cathode itself consists of a small diameter (of order 1 cm) refractory metal tube that is electron-beam welded to a refractory metal (typically thoriated tungsten) orifice

plate. 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 it, collects a fraction of the electrons being drawn through the cathode orifice. The remaining fraction can be drawn into plasma plumes that can contact an ambient plasma and couple adjacent isolated surfaces to prevent charging events.

The hollow cathode discharge is generally initiated by flowing an expellant gas such as xenon through the cathode tube and orifice, applying power to the 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 the anode voltage drops into the ten volt range. At this point a dense plasma develops within the cathode and a discharge is established between this plasma and the anode through the orifice. A detailed study of a hollow cathode (Siegfried and Wilbur, 1984) has suggested that the following physical processes illustrated in Fig. 1 are active:

1. Primary electrons emitted from the insert surface via a field-enhanced, thermionic emission process are accelerated into the cathode interior plasma through a sheath at the insert surface,
2. These electrons acquire sufficient energy as they pass through the sheath so they can ionize neutral atoms present in the hollow cathode interior through multistep, inelastic collision processes.
3. Both electrons that originate at the insert surface and those resulting from ionization are generally unable to reach the insert surface from the plasma because of the adverse potential gradient at the cathode interior plasma/insert interface. Consequently, they must leave the cathode interior plasma through the orifice at a rate equal to their supply rate.
4. Ions created within the cathode, on the other hand, generally will not go through the orifice because of the adverse potential they see between the cathode interior plasma and the plasma downstream of the orifice. They instead bombard cathode interior surfaces heating them and, in the case of the insert, helping to maintain its temperature at the level needed to sustain electron emission.
5. As ions reach the wall surfaces they recombine and then re-enter the cathode interior plasma as neutral atoms. Neutral atoms must leave the cathode interior through the orifice at their supply rate.
6. As electrons pass through the orifice they are accelerated through a potential difference that gives them the energy needed to ionize some of the neutral atoms that are also passing through the orifice.
7. The ions and electrons downstream of the orifice form the plasma structure needed to facilitate the plasma contacting process. These particles are eventually lost by either going to nearby surfaces (e.g. the anode or cathode) where they can recombine or by being drawn into the plasma downstream of the cathode from where they can flow to the ambient plasma or other spacecraft surfaces.

Phenomenological Description of the Contacting Process

The physical phenomena observed in ground-based experiments of hollow cathode plasma contactors exchanging current with a simulated ambient plasma can be described using axial plasma potential profiles. The generalized plots of Fig. 2 show potential structures measured around contactors collecting and emitting electrons from and to a simulated ambient plasma at current levels of the order of 1 A. As Fig. 2a indicates, a contactor that is positive of an ambient plasma collects electrons through a double sheath and a quasi-neutral collector plume. Most of the potential difference associated with this process develops across the double sheath through which ions and electrons counterflow to conduct the current. While electrons are the principal charge carriers in the process, ions play the critical role of reducing the current-limiting effect of electron space charge.

The small potential dip shown separating the ambient plasma and the collector double sheath in Fig. 2a is interesting although its effect on contactor performance may not be significant. Such dips are frequently observed in plasma contactor tests and they have been observed and modeled by other researchers under somewhat different conditions (Langmuir and Compton, 1931). Their results suggest that this dip occurs (and as a result the electron and ion currents counterflowing through the double-sheath are enhanced) because the ambient plasma Maxwellian electron population have a non-zero temperature and they therefore approach the sheath with non-zero velocities.

When a contactor is biased negative of an ambient space plasma, it emits electrons and the general potential structure shown in Fig. 2b develops. The potential hump immediately adjacent to the emitter double sheath appears to evolve because electrons being drawn from the emitter induce substantial ionization of the neutral atoms which are also flowing through the cathode orifice and have a high density close it. Because electrons ejected from typical ionization events have substantial kinetic energies they tend to escape the ionization zone quickly leaving behind an overabundance of relatively massive, low energy and therefore slow-moving ions (Langmuir, 1929). In the region downstream of the peak where the potential drops, forces develop that decelerate the electrons and accelerate the ions. Further downstream, the potential flattens and a non-Maxwellian plasma composed of relatively low density, nearly monoenergetic electrons and ions which have an unknown energy distribution are observed. The required electron emission current is conducted through this region via a plasma expansion (streaming) process to the surrounding ambient plasma. Measurements have suggested the potential rise across the emitter double sheath may range as high as several tens of volts depending upon the emitter operating conditions. The intermediate double sheath shown in Fig. 2a seems to facilitate accommodation of the streaming and ambient plasmas. In laboratory tests it is believed it may stabilize at a location that is influenced by tank wall interactions.

One should note that it is contactor potential (collector potential in Fig. 2a for electron collection and emitter potential in Fig. 2b for electron emission) that determines contactor efficiency. The variation in this potential with electron collection or emission current and the way in which it can be controlled are, therefore, important.

Experimental Apparatus and Procedures

In order to study the plasma contacting process experimentally, the apparatus shown schematically in Figs. 3 and 4 has been constructed.

Physically, this apparatus consists of two hollow cathode devices, one (shown at the right of each figure and labeled "simulator"), which is used to generate a simulated ambient plasma, and the other (shown at the left and labeled "contactor"), which is used to generate a contactor plasma. To conduct experiments, the contactor is biased relative to the simulated ambient plasma to induce current flow between these plasmas. 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 dia. by 5.3 m long vacuum chamber. They both utilize cathodes with 6.4 mm dia. orifice plates and electron emission inserts that were fabricated by rolling 0.013 mm thick tantalum foils to form multi-layer hollow cylinders which were then treated with Chemical R-500*.

The orifice in the simulator cathode is 0.38 mm in diameter and its anode is a solid 3.0 cm dia., 0.25 mm thick tantalum plate oriented parallel to the orifice plate and separated from it by a distance that can be varied from 1 to 5 mm. The orifice in the contactor cathode is, on the other hand, 0.76 mm in dia. Its anode is a flat stainless steel plate with a 1 cm dia. tantalum insert having a 5 mm dia. orifice in it (Fig. 1). The anode plate and insert are located ~2 mm downstream of the cathode orifice and the anode and cathode centerlines are colinear. The anode outside diameter was varied during the tests, but the data presented here were all obtained using a 12 cm diameter anode unless noted otherwise.

Typical tests were conducted by heating the contactor and simulator cathodes to temperatures where significant thermionic electron emission could occur (~1300 K), establishing high expellant (xenon) flowrates through them, and biasing their anodes positive using the discharge supplies to initiate cathode-to-anode discharges at each device. Next, the desired contactor and simulator flowrates ($\dot{m}_c$ and $\dot{m}_s$) and discharge current levels (J_{CD} and J_{SD}) were established; the contactor was biased relative to the simulator using the bias power supply shown in Fig. 3; 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 (J_{CD}, J_{SD}, V_{CD} and V_{SD}), the bias voltage between the contactor and simulator (V_B) and the contactor and simulator electron emission currents (J_{CE} and J_{SE}).

The two switches shown at the contactor and simulator in Fig. 4 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). Williams (1988) has shown it is necessary to position these switches properly for each operating mode to assure that intentional limitations imposed on the discharge current levels (J_{CD} and J_{SD}) do not result in unintentional limitations being imposed on the contactor or simulator electron emission currents.

*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 is no longer produced.

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 connected to the simulator, most of the electron current is drawn to the tank. When the switch is open and the tank is floating, most of this electron emission current must flow to the simulator. Electron currents emitted with the switch open were, therefore, found to induce higher bias voltages and current flow/plasma density patterns that tended to be concentrated along the tank centerline rather than being distributed uniformly in the tank. This occurred because all of the emitted electrons were being forced into collection at the simulator and this distorted the current flow patterns away from the spherical symmetry that would be expected in space. In order to conduct tests that were considered to be more representative of those expected in space, tests described herein were generally conducted with the tank bias switch connected to the simulator. Any data collected with this switch open will be identified specifically.

The plasma environment produced between the contactor and the simulator was probed using the various instruments shown in Fig. 4. These instruments, the function they serve and the physical volume in which they can be used are:

Emissive Probe - This sensor and the associated circuitry system, which are similar to those used by Aston and Wilbur (1981), yield plasma potential data directly. The sensor can be swept axially downstream from the contactor to the simulator and/or radially along an arc that extends from the tank/contactor centerline out to a radius of ~30 cm. Probe output voltage (i.e. plasma potential) and position are recorded simultaneously on an X-Y recorder to assure well-correlated values of the data.

Langmuir Probe - The sensor used on this probe is a 3.2 mm dia stainless steel sphere that can be moved conveniently into any position occupied by the emissive probe. Probe current/voltage characteristic curves recorded at these positions are analyzed using a two-electron-group model (Beattie, 1975) that is assumed to describe plasmas such as these. This analysis yields the density and temperature of a Maxwellian electron group and the density and energy of a primary (or mono-energetic) electron group. This analysis is aided by inputing plasma potential data determined using the emissive probe at each location where Langmuir probe data are collected. The circuitry together with additional detail about the numerical procedures used to obtain plasma information have been described by Laupa (1986).

Shultz-Phelps Ionization Gauge - This commercially available pressure gauge was modified by removing the glass enclosure around the sensor so perturbations to static pressure measurements that could have been induced by gas flows through the contactor, would be minimized and so its spatial resolution would be improved. The probe was used to measure ambient pressure distributions over the same region swept by the emissive and Langmuir probes. Neutral atom density distributions were computed from these data by applying the perfect gas state equation and assuming the ambient gas was in equilibrium with the vacuum tank walls at a temperature of 300 K. Because gauge readouts from this device are inaccurate when a plasma is present, the measurements were made only when the cathodes were at operating temperatures and flowrates and the plasma discharges were extinguished.

Retarding Potential Analyzer - The sensor on this instrument was designed so it could be swept through an 18 cm radius arc that passed through the tank centerline and was centered at the contactor cathode orifice. In the course of moving through this arc its aperture remained sighted on the cathode orifice. It was biased so it repelled both electrons and low energy ions and therefore sensed the azimuthal current density profile of high energy ions flowing across the sheath.

Test Results

When a typical hollow cathode plasma contactor is biased relative to an ambient plasma and the voltage difference between it and the ambient plasma in contact with it (defined as the collector or emitter potential in Fig. 2) is measured as a function of the electron current being emitted, data like those shown in Fig. 5 are obtained. These particular data were obtained at a contactor discharge current (J_{CD}) of 0.3 A and an expellant flowrate ($\dot{m}_c$) of 4.1 standard cubic centimeters per second (sccm) of xenon. Under these conditions the ambient neutral gas pressure (P_o) in the vacuum tank was 5 x 10^{-6} Torr and the contactor discharge voltage (V_{CD}) varied over the range from 12 to 20 V as the electron emission current (J_{CE}) was varied from +1000 mA to -1000 mA. The contactor potential plotted on the horizontal axis in this figure is the difference between the contactor anode or cathode potential (V_B) and the ambient plasma potential (V_p) sensed by an emissive probe located ~1 m downstream of the contactor. The data of Fig. 5 show the contactor potential remains near -25 V when substantial electron currents are being emitted (second quadrant) and that it rises to about 50 V for substantial electron collection currents (i.e. for negative emission currents in the fourth quadrant).

The curve in the fourth quadrant of Fig. 5 shows that the magnitude of the electron collection current increases rather suddenly at a potential difference of ~40 V where the "transition to ignited mode" operation is identified. This transition is generally observed as contactor bias potential is being increased. Its occurrence is accompanied by the appearance of a bright luminous glow that typically extends several centimeters from the contactor and is frequently somewhat spherical in shape. It is believed that this luminosity is caused by the de-excitation of xenon atoms that have been excited by electrons being drawn (streaming) from the ambient plasma toward the contactor and that ionization is also induced by these electrons.

Electron Collection

When plasma potentials are measured throughout the region immediately downstream of a contactor collecting electrons, data like those shown in Fig. 6 are obtained. This figure includes both a raised potential map, which shows the structure of the plasma field around the contactor qualitatively and an equipotential contour map from which quantitative information about the potentials can be obtained. These two plots show the plasma field consists of two relatively uniform potential plasma regions separated by a region of large potential gradient. Since neither magnetic field nor collisionally induced impedances are expected in the region where the potential changes rapidly, this must be a sheath region (Langmuir, 1929), i.e. one in which charged-particle acceleration is occurring.

On the basis of the typical data of Fig. 6 one can propose the model of electron collection suggested by Fig. 7. This model shows a relatively higher density plume of quasi-neutral plasma in the region immediately adjacent to the contactor which is separated from a lower density quasi-neutral ambient plasma by a double-sheath (or double-layer). As the centerline plasma potential profile in this figure suggests electrons from the ambient plasma are drawn toward the contactor 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 sheath. The ion and electron currents that can be drawn through the double-sheath 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 sheath midpoint in the bottom sketch of Fig. 7.

When plasma properties are measured along the vacuum tank/contactor centerline through a typical double-sheath, data like those shown in Fig. 8 are obtained. These results suggest plasma conditions do vary in a way that is consistent with the model of Fig. 7 (note that the zero voltage for the plots of Figs. 6 and 7 is the ambient plasma potential, while that for Fig. 8a is the simulator cathode potential). Figures 8b and c indicate the plume and ambient plasmas are both composed of primary (mono-energetic) and Maxwellian electron groups. They show the Maxwellian temperature and density and the primary energy and density all remain constant at about 6 eV, 4×10^{7} cm^{-3}, 40 eV and 3×10^{6} cm^{-3} respectively, in the ambient plasma region for this case where ~370 mA of electrons are being collected.

It is noted that the energy of the primary electrons in the ambient plasma (Fig. 8c) is approximately equal to the simulator cathode-to-ambient plasma potential difference. This suggests that these electrons are ones that have been accelerated into the ambient plasma from the simulator hollow cathode and have had few energy-degrading collisions. It is noted that the ratio of primary-to-Maxwellian electrons in the ambient plasma is generally not large (usually less than 10% as in the case of the data of Fig. 8). The data of Fig. 8b show the density of the Maxwellian electrons upstream of the double-sheath drops rapidly with distance from the contactor cathode. The floor symbol drawn on Fig. 8b upstream of the double-sheath location indicates that the Maxwellian density and temperature were not measurable at this location because the primary electron signal to the Langmuir probe overwhelmed the Maxwellian one. The data of Fig. 8c show the primary electron density upstream of the sheath is more than an order of magnitude greater than that downstream. The primary electron density upstream of the sheath is also seen to increase 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 sheath (35 to 45 V) is roughly equal to the sheath potential drop

(V_{SH}). This suggests that primary electrons found in the high density plume are indeed those that have been accelerated across the sheath from the Maxwellian electron group in the ambient plasma. This result also supports the proposed physical model of the electron collection process.

When the retarding potential analyzer (RPA) is used to measure the azimuthal profile of the current density of ions expelled across the double-sheath of a contactor collecting electrons at the conditions listed on Fig. 8, the data of Fig. 9 are obtained. One can integrate these ion emission current density data over a hemispherical surface with the radius of the RPA sweep arc (18 cm) to determine the overall ion emission current flowing from the contactor to the ambient plasma. The result of so doing is 4.2 mA in this case. Applying a simple model describing space-charge-limited electron collection through a spherical double sheath (Wei and Wilbur, 1986) one computes an ion emission current (2 mA) that is approximately one half of the measured value. Considering the uncertainties associated with these measurements and the space-charge-limited model being applied, this is considered to be acceptable agreement.

If the current being collected through the double sheath is space-charge-limited, theory (Langmuir, 1929; Wei and Wilbur, 1986) indicates the ion and electron currents counterflowing through the sheath should be related linearly and should be independent of other conditions such as expellant flowrate and sheath voltage drop. Figure 10 shows this linear variation between ion centerline current density, which is proportional to the total ion emission current, and electron collection current. It is noted, however, that the slope of the line in Fig. 10 corresponds to an ion-to-electron current ratio that is about (1/250). This value is nearly twice the expected theoretical value (1/490--the square root of the electron-to-ion mass ratio). The could be due to geometrical differences between the actual shape of the double sheath and that assumed in the simple theoretical analysis.

When the size and shape of the double sheath and the voltage drop across it are changed dramatically, the ion emission current is unaffected provided the electron collection current is held constant. For example, Fig. 11 shows the changes induced in the equipotential contour maps of a contactor collecting 900 mA of electrons by increasing the xenon flowrate from 2.7 to 11 sccm. The data of Fig. 12 show such flowrate changes induce a substantial change in the sheath voltage drop, but no significant change in the centerline ion emission current density occurred.

Ion Production to Support Electron Collection. The location of the upstream boundary of the double sheath is determined by the rate at which low energy ions are supplied to it. Increasing this supply rate causes the upstream boundary to move downstream and this causes the sheath voltage drop to decrease (Williams, et al., 1987). The means by which the ions are produced in the plume region of a contactor collecting electrons is therefore a matter of interest. Some ions are produced by electrons that are drawn through the hollow cathode orifice and collide with neutral atoms in this region, however, production by this mechanism may be insufficient to induce a low voltage drop. It is believed, in fact, that these ions will sustain a low voltage drop only to an electron collection current level of about 100 mA. Above this electron collection current, test results indicate a new mechanism of ion production, related to the onset of the ignited mode of operation identified in Fig. 5, becomes important. This transition, which is accompanied by a sudden and dramatic increase in the luminosity of the contactor plume, is believed to occur when the voltage drop across the double sheath is sufficient to induce excitation and ionization of expellant atoms coming through the cathode orifice by the electrons being collected. Evidence that excitation reactions are occurring in the ignited mode is provided by plume luminosity. The fact that increased electron collection current accompanies the transition (Fig. 5) suggests that ion current flow also increases to sustain operation at space-charge-limited conditions. Because increased ion production would be required to sustain this ion current, the electron collection current increase implies increased ionization accompanies the transition.

Additional evidence of substantial ionization in the plume of a contactor collecting electrons in the "ignited mode" is obtained by calculating the streaming electron/atom ionization rate in the contactor plume. This has been accomplished by measuring the neutral density distribution downstream of a hollow cathode using the movable Shultz-Phelps gauge and then computing the ion production induced by electrons streaming from the ambient plasma through this atomic cloud toward the hollow cathode. A rough calculation suggests the resulting ion production is more than sufficient to supply the total ion current required to sustain operation at the space-charge-limited condition for a spherical double-sheath (Williams and Wilbur, 1989).

Effects of Anode Area on Electron Collection. Typical plasma potential data measured downstream of a contactor operating with a 3 cm diameter anode are compared to those measured near a contactor with a 12 cm diameter anode in Fig. 13. The most striking differences between these data are the higher voltage levels, the spreading of the double-sheath and the reduction in the size of the contactor plume when the smaller anode is used. Although the relative position, magnitude and shape of the equipotential contours are different, it is argued that the voltage difference that exists must be sustained because acceleration of counterflowing ion and electron currents is occurring in both cases. Thus, the potential structure associated with both anodes must reflect the essential phenomena associated with a double sheath. The differences between the sheaths shown in Fig. 13 appear to develop because the inner boundary of a double sheath must remain anchored to and therefore have a dimension that is about equal to the associated anode diameter. This constraint on the sheath size at the contactor is reasonable when one recalls that the charge carried by electrons collected into the plume must eventually reach the anode.

A simple double-sheath model (Williams and Wilbur, 1987) can be applied to determine the voltage drop across the near-spherical double sheath associated with the large anode data given in Fig. 13. Although this model is not suited to the irregular shape of the double-sheath associated with the small anode, it is expected that the smaller anode case can be modeled numerically provided the double-sheath phenomena are reflected in the model. It is noted that the potential structure shown for the 3 cm anode is similar to structures reported by Patterson and Aadland (1987) for tests involving electron collection from what appears to have been a rather low ambient density plasma at current levels above

1 A on a contactor that utilized a 24 cm diameter anode. A review of their data together with data obtained by the authors suggests a double sheath takes on an irregular (non-spherical) shape when the current being collected exceeds the ambient plasma random electron current density times the area of a hemispherical double-sheath with a radius that is about equal to that of the contactor anode.

Although double sheaths observed in the laboratory appear to tie themselves to the contactor anode, it is considered possible that a large double sheath that might develop in space could be spherical and not be tied to the outer boundary of an anode. Whether or not this would occur appears to depend on whether or not such a double sheath would be stable (Hastings and Blandino, 1989). In any event it is considered important to utilize an anode that is as large as practicable to realize a high electron collection current capability with a low voltage drop in a space plasma.

Electron Emission

The plasma potential field measured downstream of a typical contactor emitting electrons is shown in Fig. 14. The contactor cathode (at the 0,0 location) is at the lowest potential (-14 V) of any point in the maps. Downstream of that point the potential rises to a ridge along which the potential peaks before it drops off and then levels out. The peaked potential structure is particularly noteworthy and was initially unexpected. It is noted that the data in Fig. 14 were collected using an emissive probe and this probe becomes increasing inaccurate as it is moved closer to the cathode. More specifically, it indicates potentials that fall progressively further below the true plasma potentials as it is moved into denser plasmas, i.e. into regions closer to the cathode orifice. This inaccuracy arises because the probe cannot be held at the temperature required to assure adequate electron emission in the plasma environment close to the cathode without burning out. Thus it can be stated that the potentials rise to even higher peak values than those indicated at the crest of the ridge shown in Fig. 14.

Potential profiles measured downstream of a contactor emitting electrons, when the tank is floating relative to the contactor and simulator (tank bias switch in Fig. 3 open), are shown in Fig. 15. The low emission current potential profile (15 mA) is considered to be quite accurate because plasma densities are low close to the cathode in this case and the emissive probe should, therefore, indicate accurately. In this case the potential hill is obvious. At the higher current (250 mA) where plasma density close to the cathode is high, however, the probe error would be expected to be greater, and the potential hill is not very obvious.

Downstream of the potential hill the data of Fig. 15 show a region of relatively uniform plasma potential before the potential rises to the ambient plasma potential. These potential structures should be measured correctly by the emissive probe so they are considered accurate. The complexity of the complete potential structure suggests that electron emission is at least as interesting phenomenologically as electron collection.

Some light can be cast on the mechanisms that could induce the potential profile data shown in Figs. 14 and 15 by considering the simplified schematic and corresponding potential profile shown in

Fig. 16. In the potential environment close to the cathode, electrons from the cathode could be accelerated through the potential gradient at the cathode until they had the kinetic energy needed to excite and ionize neutral atoms that would be present at a high density level near the cathode orifice. At a sufficiently high cathode emission current, the ionization could be sufficient to produce an overabundance of ions that would cause a potential hill to develop near the cathode. This ion overabundance is expected because the electron kinetic energy would typically exceed the ionization energy. Thus the electrons coming from the reaction would tend to leave the region of ionization more rapidly than the ions (Langmuir, 1929). Immediately downstream of the peak potential, the potential drops and forces develop that decelerate the electrons and accelerate the ions in an effort to maintain plasma neutrality. Beyond this region, ions and electrons stream outward and expand to the point where another double sheath can develop to accommodate coupling of the ambient and expansion region plasmas. This sheath, which is typically located 40 to 100 cm downstream of the emitter, exhibits a potential rise of ~10 V. It serves as a boundary between the plasma coming from the emitter and the ambient plasma that fills the majority of the vacuum chamber. It is considered possible that is it is stabilized by interactions with the vacuum chamber wall. Whether or not this is the case has not been verified, but it is noted that the existence of the sheath is not influenced by switching the tank between contactor cathode to floating potentials. On the other hand, connecting the tank to the simulator anode causes it to disappear.

Additional insight into the phenomenological model associated with Fig. 16 can be obtained by considering plasma property data collected throughout the regions shown. Figure 17 presents data collected at a 750 mA electron emission current with the tank bias switch (Fig. 3) open. The solid plasma potential curve shows data measured using the emissive probe. The dashed line indicates what is expected considering emissive probe errors in the high density plasma at the emitter cathode. While the height of this hill is not known for certain, preliminary RPA probe measurements of ions coming from it into the plasma expansion region suggest it may be a few tens of volts high.

The plasma density, temperature and energy data of Fig. 17, which were collected using a Langmuir probe, show the plasma expansion region contains primary (mono-energetic) electrons but essentially no Maxwellian ones. The energy of the primary electrons suggests they came from the cathode--their energy (15 eV) is about equal to the expansion region plasma potential measured relative to the cathode. The density of these primary electrons drops off rapidly with distance from the cathode to a level below that of the 5 eV Maxwellian electrons in the ambient plasma (middle plot of Fig. 17). A more detailed study of the plasma expansion region (Williams and Wilbur, 1989) has shown that primary electron density decays there as $1/r^2$. This suggests in turn that a collisionless, spherical expansion model of the region between ~10 and 40 cm is appropriate.

The plasma expansion model of the region between the potential hill and the ambient plasma regions is similar to that used by Davis et. al. (1987). Their model differs in that it involves Maxwellian electron expansion in accordance with the barometric equation rather than mono-energetic electron expansion.

Finally, it is noted that the ambient plasma contains mostly Maxwellian electrons with a temperature near 5 eV. The fact that primary electrons there have an energy near the plasma potential associated with the ambient plasma measured relative to the cathode suggests primary electrons come from the cathode and that they produce the ions needed to sustain the ambient plasma.

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Conclusions

Hollow cathode plasma contactors can be used to establish a low potential difference connection between an object attached to the hollow cathode and an ambient plasma under conditions where the object is either positive or negative of the ambient plasma, i.e. electrons are being collected or emitted, respectively. The potential structure and therefore the voltage drop associated with the electron collection process is dominated by the development of a space-charge-limited double sheath. This double sheath maintains a boundary near the outer diameter of the contactor anode. The process of electron collection is more efficient when the contactor is "ignited" and some of the ion current required to sustained the double sheath is created by electrons that are being collected.

The potential structure associated with the electron emission process appears to be dominated by a "potential hill" and a plasma expansion region that develops downstream of the contactor. The potential hill and expansion region appear to facilitate the ion production needed to establish a low impedance plasma bridge between the contactor cathode and the ambient plasma.

A contactor designed to both emit and collect electrons should be connected with its anode attached to the largest conducting surface on the spacecraft. This assures a large effective anode area and efficient electron collection (a low voltage difference between the contactor and the ambient plasma). The size of the anode doesn't appear to influence electron emission process significantly.

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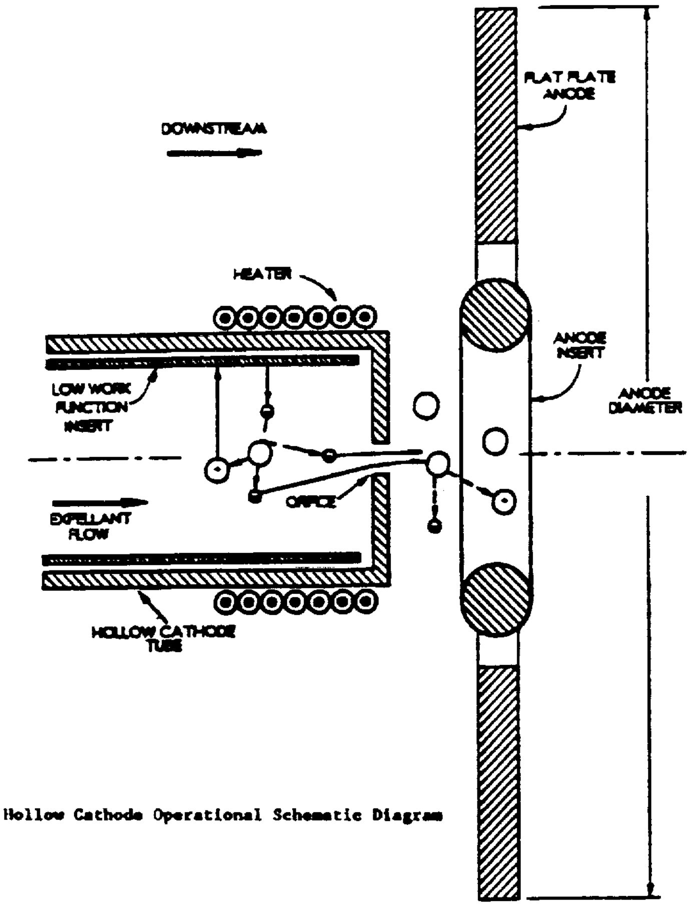


Fig. 1 Hollow Cathode Operational Schematic Diagram

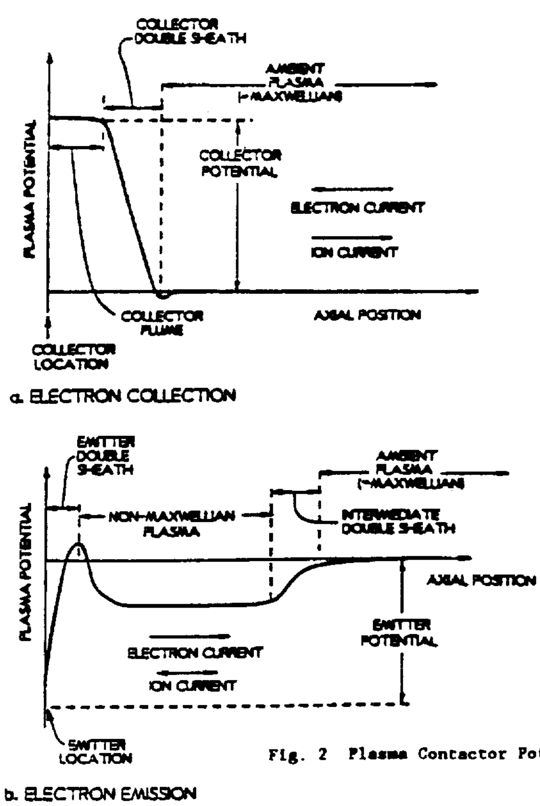


Fig. 2 Plasma Contactor Potential Structure Definitions

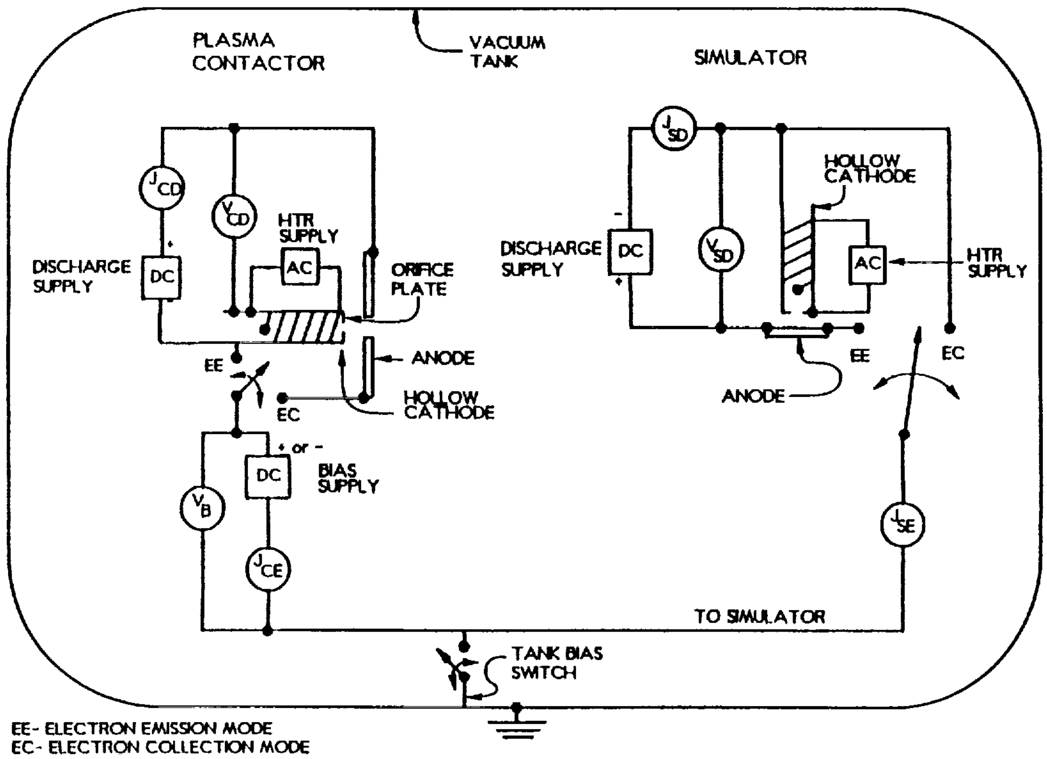


Fig. 3 Test Apparatus Electrical Schematic Diagram

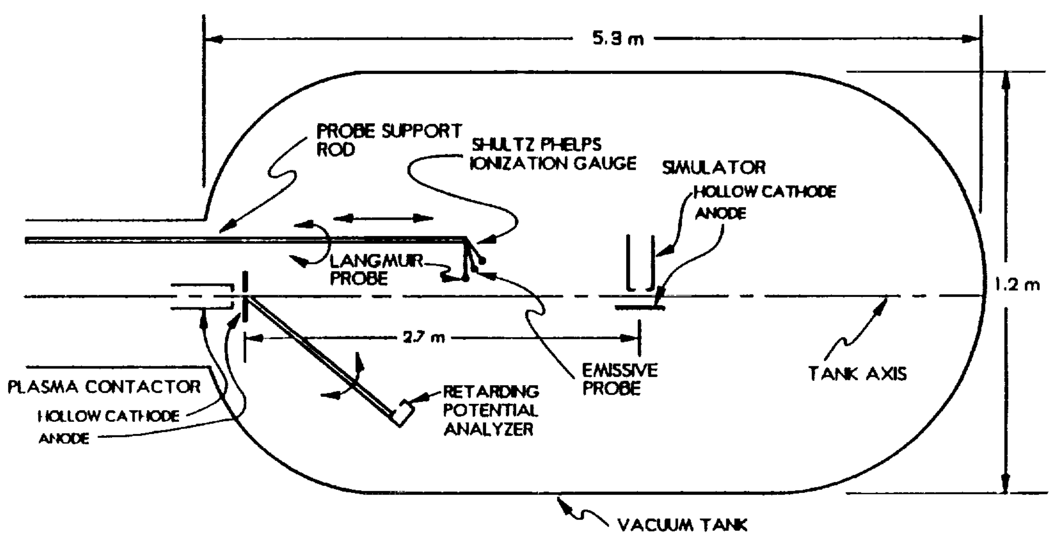


Fig. 4 Mechanical/Instrumentation Schematic Diagram

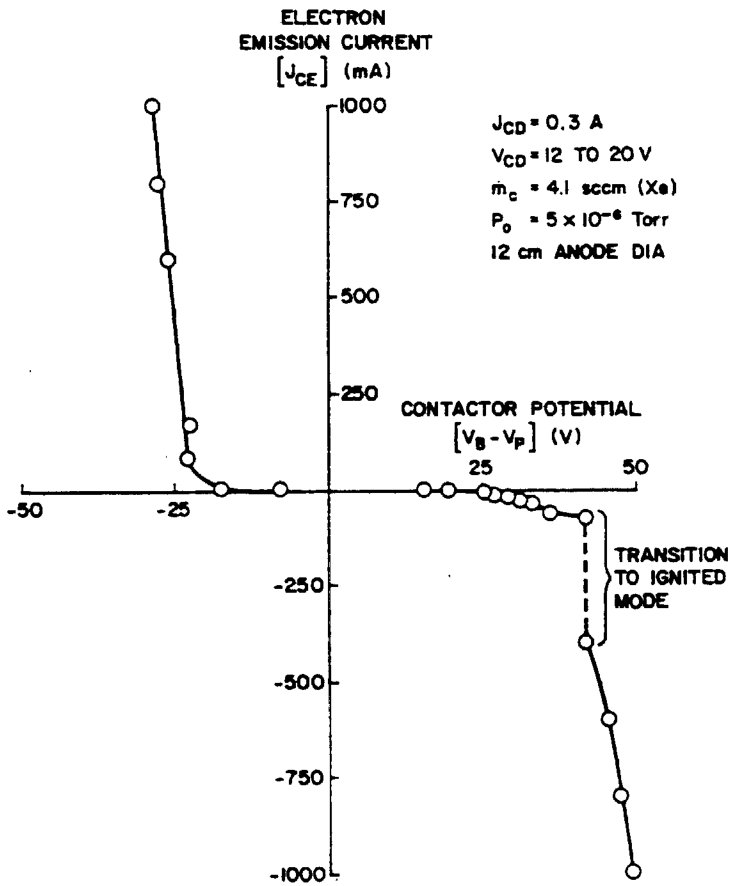
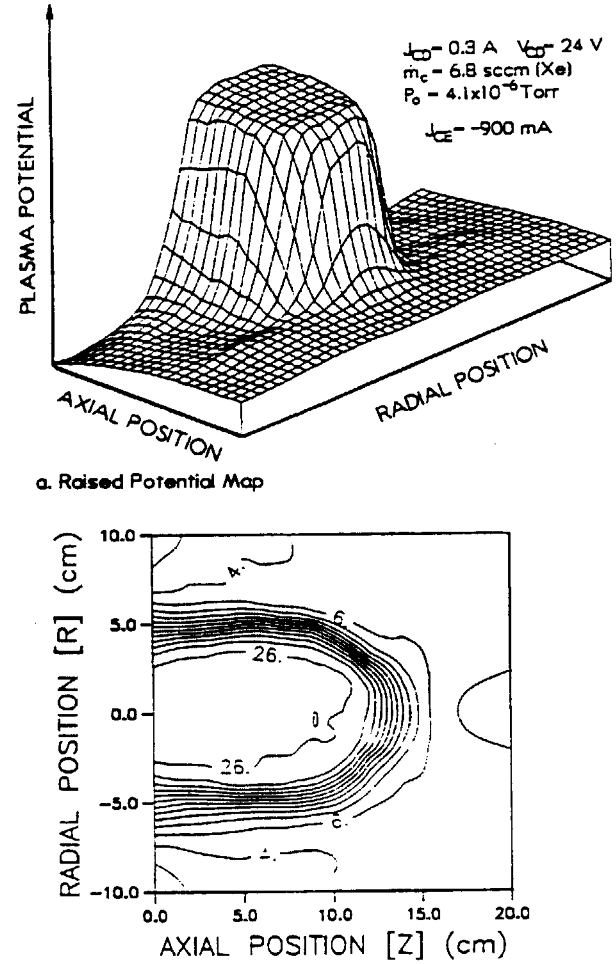


Fig. 5 Typical Plasma Contactor Performance Curve



a. Raised Potential Map

b. Equipotential Contour Map

Fig. 6 Typical Plasma Potential Variation Near a Contactor Collecting Electrons

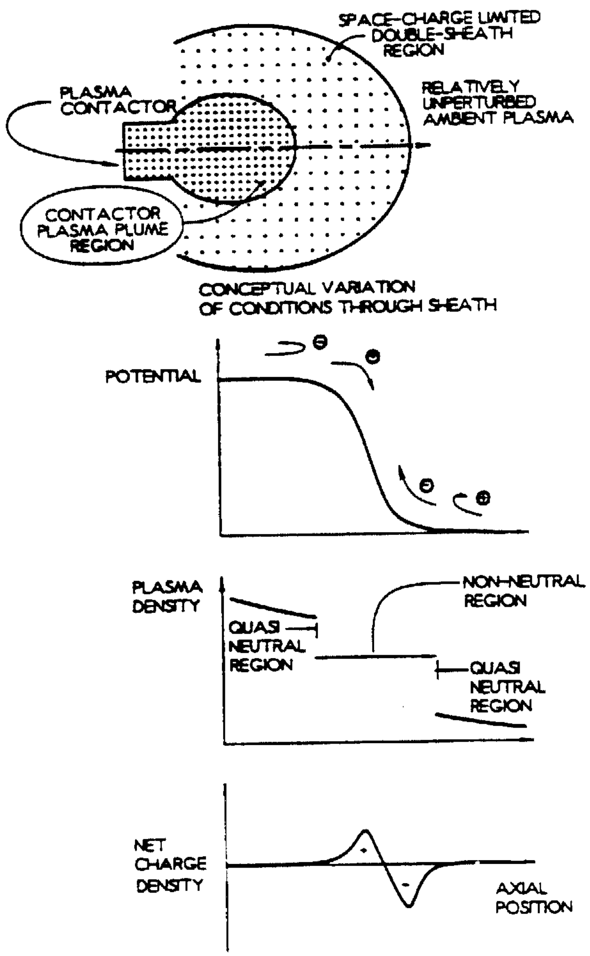


Fig. 7 Conceptual Model of Electron Collection

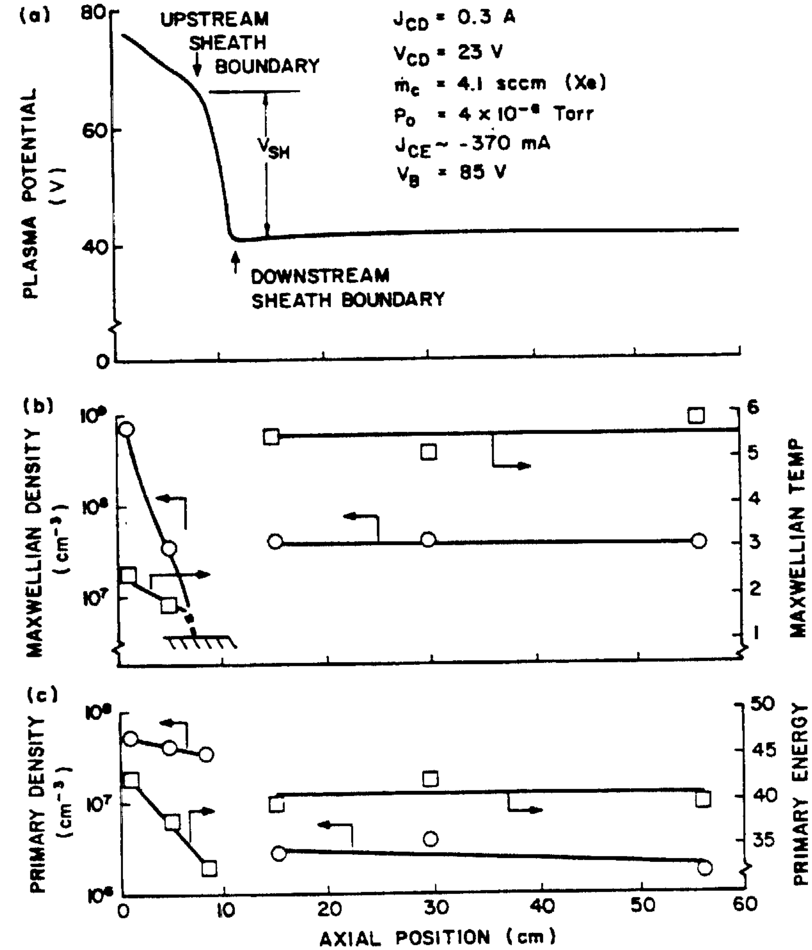


Fig. 8 Typical Centerline Plasma Property Profiles - Electron Collection

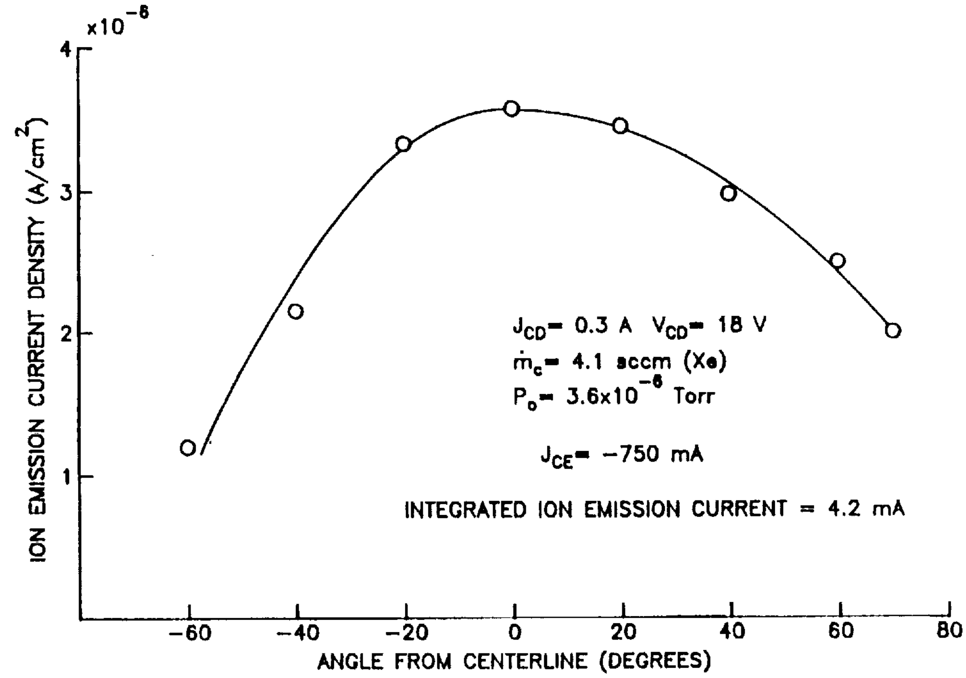


Fig. 9 Azimuthal Variation of Current Density of Ions Emitted from the a Contactor Collecting Electrons

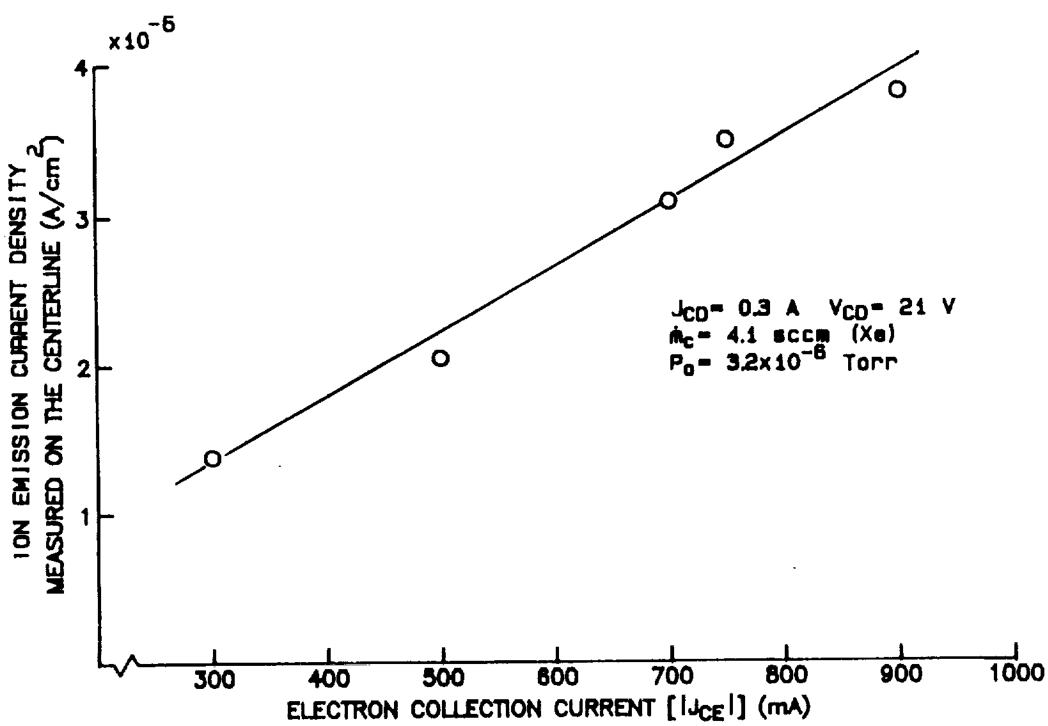


Fig. 10 Measured Correlation of Ion Emission and Electron Collection Currents

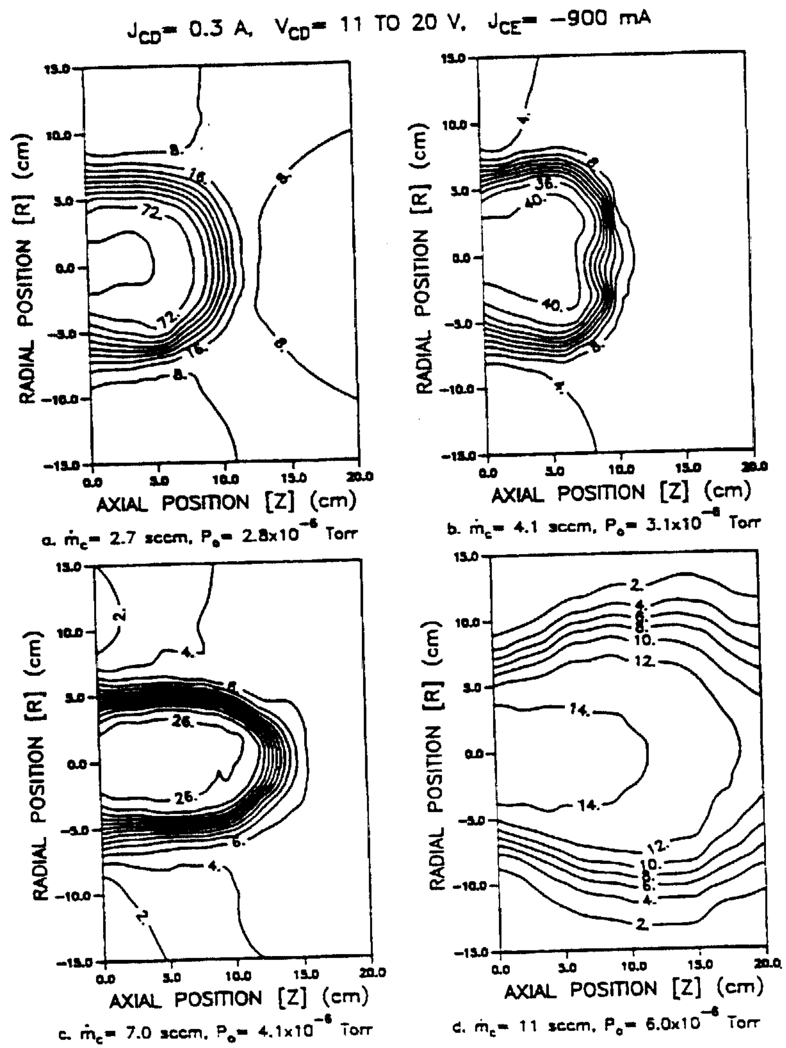


Fig. 11 Effect of Flowrate on Potential Field - Electron Collection

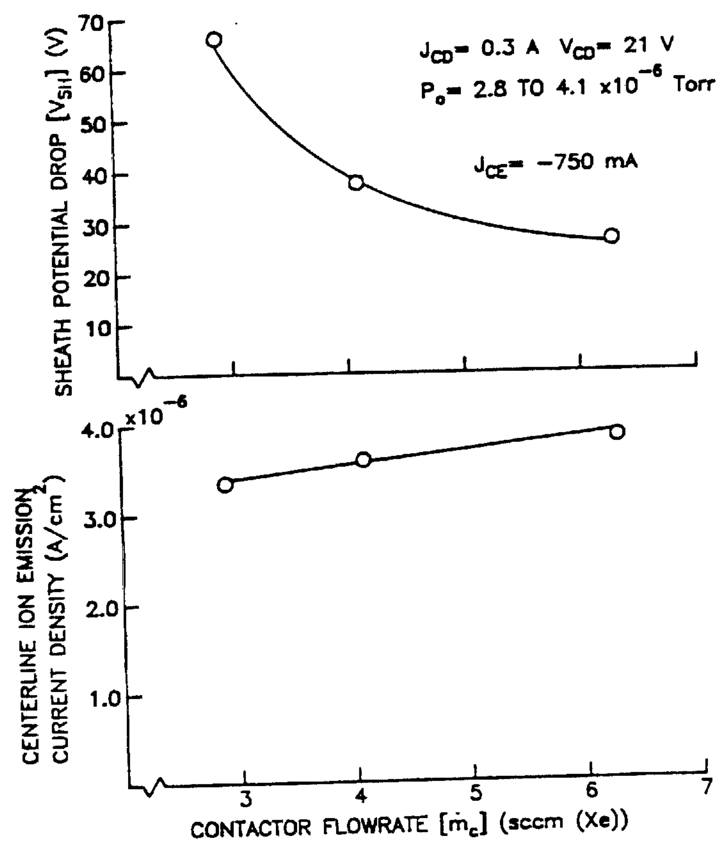


Fig. 12 Effects of Flowrate on Sheath Potential Drop and Ion Emission Current Density - Electron Collection

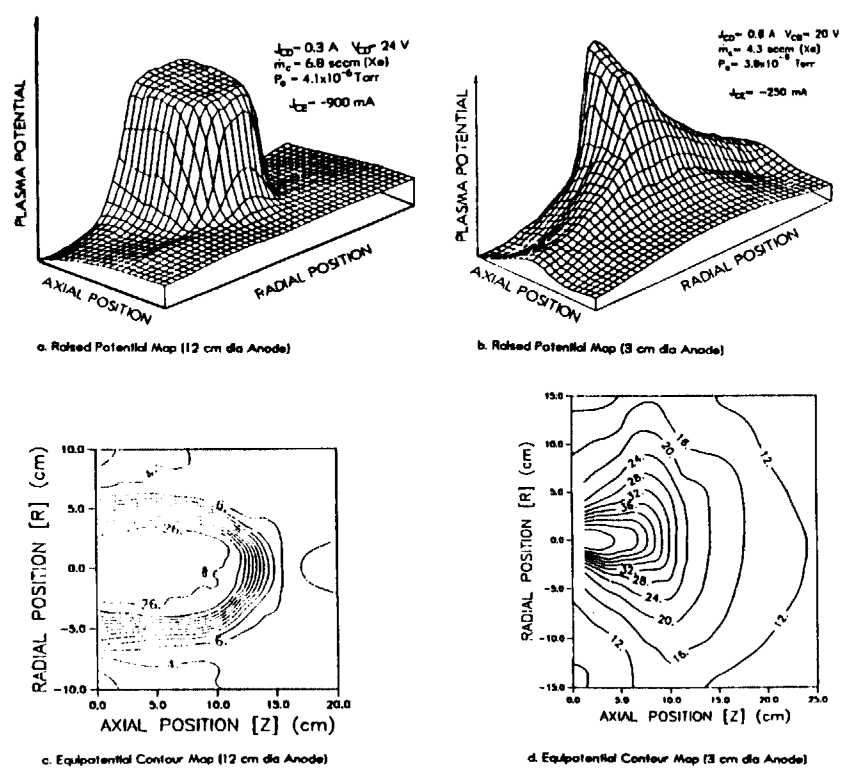


Fig. 13 Effect of Collector Anode Diameter on Potential Field

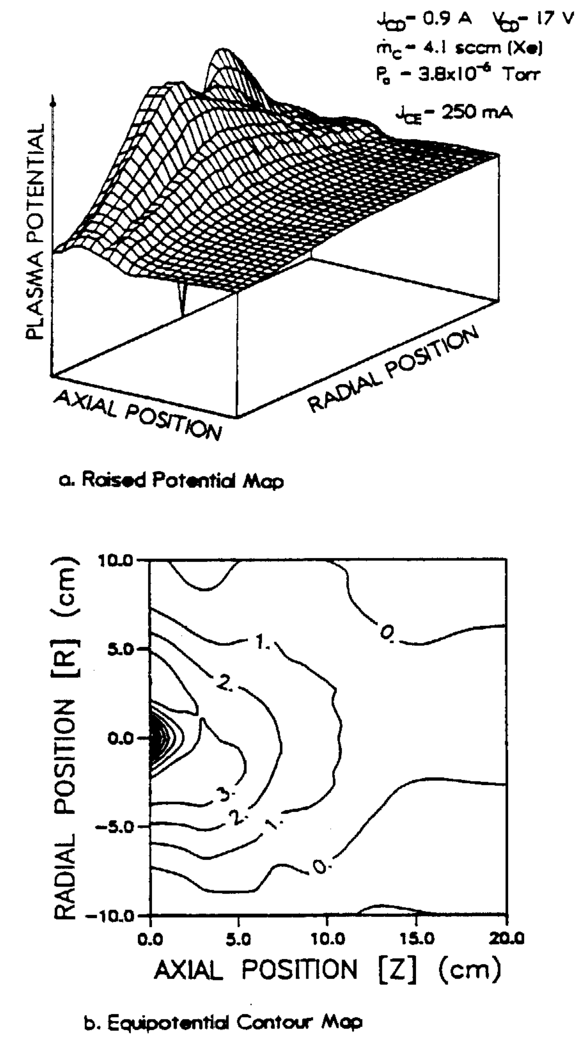


Fig. 14 Typical Plasma Potential Field near a Contactor Emitting Electrons

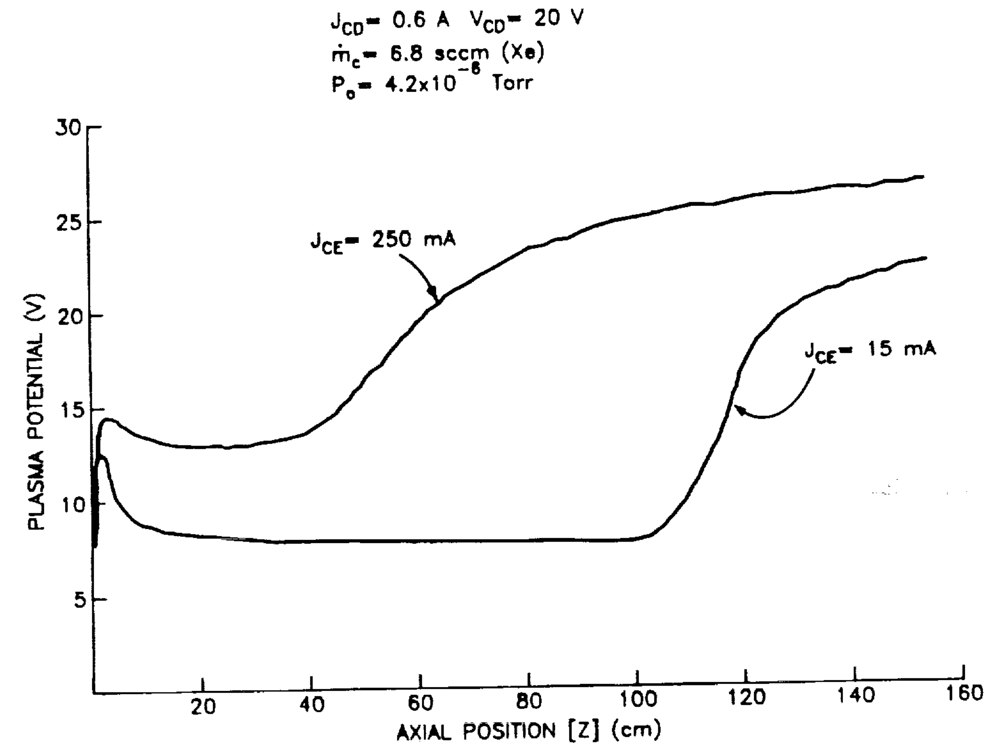


Fig. 15 Effects of Electron Emission Current on Centerline Plasma Potential Profiles

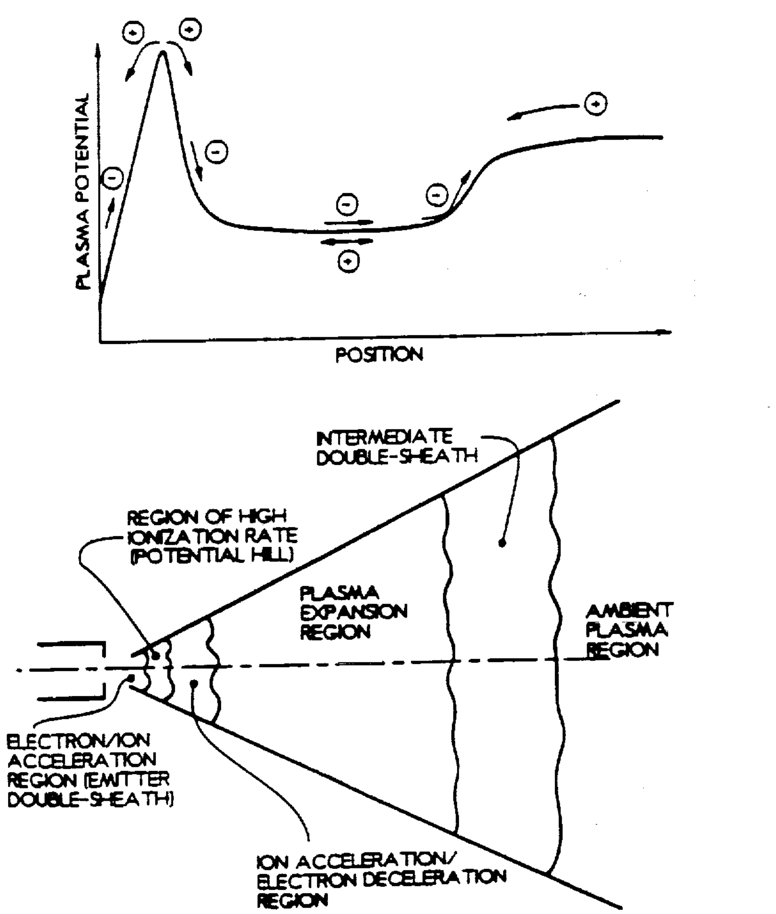


Fig. 16 Simple Physical Model of Electron Emission Process Observed within a Vacuum Chamber

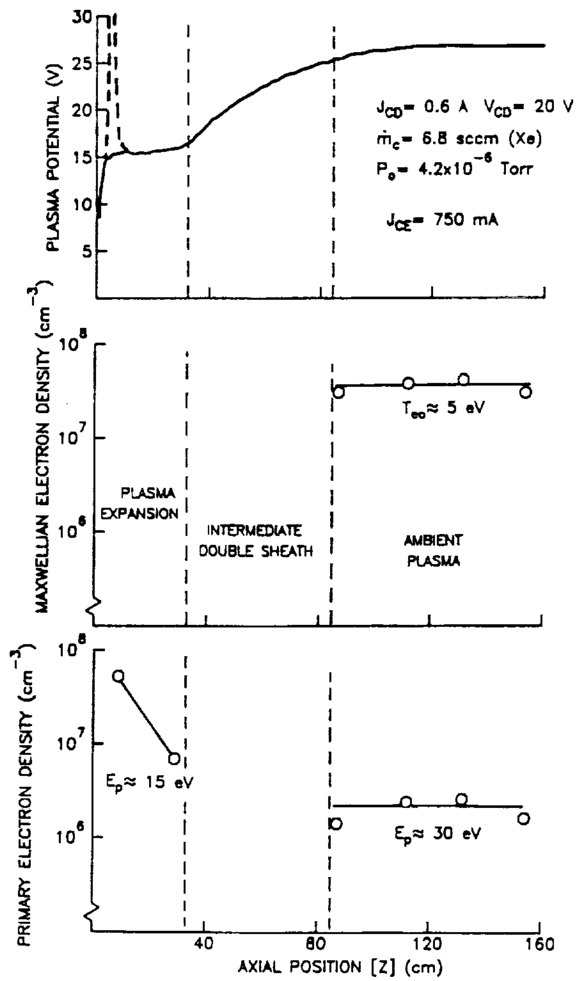


Fig. 17 Typical Plasma Property Profiles - Electron Emission