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Plasma Contactors for Electrodynamic Tether

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SUMMARY

The role plasma contactors play in effective electrodynamic tether operation is discussed. Hollow cathodes and hollow cathode-based plasma sources have been identified as leading candidates for the electrodynamic tether plasma contactor. Present experimental efforts to evaluate the suitability of these devices as plasma contactors, conducted concurrently at NASA Lewis Research Center and Colorado State University, are reviewed. These research programs include the definition of preliminary plasma contactor designs, and the characterization of their operation both as electron emitters and electron collectors to and from a simulated space plasma. Results indicate that ampere-level electron currents, sufficient for electrodynamic tether operation, can be exchanged between hollow cathode-based plasma contactors and a dilute plasma.

INTRODUCTION

A variety of propulsion and power generation applications have been identified for space tethers, involving electrodynamic interactions of the tether wire with planetary magnetic fields (refs. 1 to 3). These scenarios require that an electrical circuit be completed via the surrounding ionospheric plasma by the use of "plasma contactors" at each end of the electrodynamic tether. Effective electrodynamic tether operation is critically dependent on the development and demonstration of plasma contactor technology.

Figure 1 shows a schematic diagram of an electrodynamic tether system. As the orbital motion of the conducting tether wire cuts across geomagnetic field lines, a potential difference is generated between its two ends. If one provides an electrical connection through the space plasma between these two ends, then an electrical load can be connected into the circuit in the manner suggested in figure 1 and useful power generated by the tether can be dissipated in the load. In order for this system to operate at high efficiency, however, it is necessary that the potential drops that occur at the plasma contactors, the tether wire and through the ionospheric return path be small. As figure 1 suggests, the two plasma contactors required on the electrodynamic tether differ in that one must collect electrons from the ionosphere while the other must emit them. Since it is desirable to be able to reverse the direction of current flow in the tether so it can be used as either a generator of electrical power or as a propulsion device (via the Lorentz force), it is necessary that the plasma contactors be reversible, i.e., each of them should be able to emit or collect electrons on demand. Further, to minimize tether size requirements and associated dynamic instabilities, and to provide sufficient power generation and propulsion capabilities, current levels of tens of amperes must flow in the tether system. Of particular concern when these large currents are involved are the problems of establishing an electrical reference potential, and preventing vehicle charging. Consequently, four generic performance criteria required of the plasma contactor for effective electrodynamic tether operation can be identified as: (1) The plasma contactor must provide a low-impedence electrical connection between the spacecraft and the surrounding ionospheric plasma, with a minimum power requirement; (2) The plasma contactor should be capable of fully-reversible operation; (3) The plasma contactor must provide multiampere level current capability; and (4) The plasma contactor must maintain the user spacecraft at or near space plasma potential.

A contactor that should be capable of matching these performance criteria would be one that generates a dense, neutral plasma that makes the connection to the diffuse space plasma. Closer examination of the plasma plume region of a contactor that generates a dense, neutral plasma might involve a structure like that shown in figure 2. The plasma source generates a high density and, therefore, high conductivity plasma plume which is small in extent compared to the distance from the contactor to the unperturbed space plasma. Between the high density plume region and the unperturbed space plasma lies the sheath region in which the bulk of the voltage drop driving the current occurs. Low impedance implies that the ratio of voltage drop between the two boundaries divided by the current flowing be small. In this intermediate region, space charge effects limit the currents of the electrons and ions which flow in opposite directions. Electrons, because of their much smaller mass, conduct the bulk of the current, but the ions play the important role of limiting space charge effects.

The surface area of the boundary between the unperturbed plasma and the space charge limited region must be sufficiently large so that the current flowing divided by this area yields a current density that is equal to the random electron current density associated with the unperturbed space plasma. For the upper plasma contactor, shown in figure 1, electrons would be drawn from the unperturbed space plasma toward the plasma source and ions would flow from the plasma source out to the unperturbed space plasma. It is because the ions and electrons counterflow in this region that the term "double sheath" is used. In the case of the lower plasma contactor, shown in figure 1, electrons provided by the plasma source flow outward toward the unperturbed space plasma and ions from the unperturbed space plasma are drawn in toward the ion source to produce the double sheath effect. As one increases the production of plasma from an ion source, either emitting or collecting electrons at a prescribed current level, one would expect the high density plume region to expand while the boundary at the unperturbed space plasma would remain fixed. Thus the size of the space charge limited double sheath region would be expected to shrink. Theory suggests that the voltage drop across the double sheath region decreases as its size decreases.

In the limit the high density region would extend to the region of the relatively unperturbed space plasma and the voltage drop associated with this device would approach the ideal situation, that is, essentially zero voltage drop at the design current level. Figure 3 shows the characteristic associated with an ideal plasma contactor in the form of a plot of contactor electron emission current as a function of contactor potential measured relative to space plasma. As the figure indicates, the ideal plasma contactor can conduct any current required by the system with a negligible potential drop, i.e., this device has a zero impedance characteristic. Figure 3 also shows the characteristic of electron and ion guns. These devices are also considered as candidate plasma contactors; but as figure 3 indicates they are not particularly well suited to this function as they have horizontal (high impedance) rather than vertical (low impedance) characteristics. A gun would be inadequate if its operating current, J_e, is less than the electron current being collected by the spacecraft. The spacecraft would then charge progressively more negative. If on the other hand, the current that was coming to the spacecraft dropped below J_e, then the spacecraft would begin to charge positively until it reached the accelerating voltage of the gun (V_e). It is apparent that the device would control the potential of the vehicle only if the gun current could be controlled exactly to balance the electron current to the spacecraft from all other sources. Further, if the spacecraft began to collect ions, then it would become necessary to switch over from operation with an electron gun to operation with an ion gun. This switching could also involve some difficulty and the ion gun would again exhibit the same high impedance, difficult control behavior as the electron gun.

A device which has been suggested as the basis for many plasma contactors is the hollow cathode, shown schematically in figure 4. A significant level of experimental and theoretical work on these devices has been conducted at NASA Lewis, Colorado State University, and Hughes Research Laboratory in conjunction with ion propulsion programs. These efforts have resulted in the development of hollow cathodes to a high state of technology readiness. Hollow cathodes ranging from 0.32 to 1.27 cm diameter have been tested with mercury and inert gases at emission current levels from hundreds of milliamperes to in excess of 40 A, with projected lifetimes of 10 000 to 30 000 hr. These efforts have resulted most recently in the development of a detailed account of hollow cathode physics by Siegfried and Wilbur (ref. 4). Hollow cathodes have also been flown in space demonstrating both ampere-level electron emission current to the space plasma from ion thruster operation (Space Electric Rocket Test-II), and spacecraft charge control capability (ATS-6). Given also the low power requirement of hollow cathodes, these devices would appear to provide a good match in attaining the required performance criteria of the plasma contactors for the electrodynamic tether. However, there has been no experimental work conducted to investigate the electron current collection capabilities of hollow cathodes or hollow cathode-based plasma sources from a dilute plasma; that is, a demonstration of fully-reversible operation of these devices is lacking.

Research programs were, therefore, initiated at NASA Lewis and at Colorado State University (CSU) to evaluate the potential of hollow cathodes/hollow cathode-based plasma sources as plasma contactors for the electrodynamic tether. These programs include five elements: (1) Definition of preliminary hollow cathode-based plasma contactor designs, and characterization of their operation both as electron emitters and electron collectors; (2) Concurrent evaluation of theoretical models of the plasma coupling process between plasma sources and a dilute plasma; (3) Determination of the extent to which geomagnetic fields will affect the plasma coupling process; (4) Determination of the extent to which surfaces near the plasma contactor may affect its ability to couple to the space plasma; and (5) Definition of potential hollow-cathode based plasma contactor flight experiments. It is envisioned that these research programs would evolve into a technology program to develop, integrate, test, and characterize a protoflight hollow cathode-based plasma contactor system suitable for multiampere particle exchanges between space systems and the space environment.

The remainder of this paper is an overview of the research activities and results at NASA Lewis and CSU with reference to the first program element; that is, a discussion of the extent to which the hollow cathodes and hollow cathode-based plasma sources investigated approach the behavior of the ideal plasma contactor characteristic identified in figure 3. The joint research programs at NASA Lewis and CSU represent complementary efforts in two different operating regimes. As a consequence of facility capabilities, the NASA Lewis program involves characterization at high contactor discharge and bias power levels, whereas the CSU program is an analytically-based effort involving characterization at low power levels.

APPARATUS

This section discusses the design and operation of hollow cathodes and hollow cathode-based plasma sources presently being investigated as potential plasma contactors. A discussion of the test facilities is also presented.

Hollow Cathode-Based Plasma Contactors

Standard hollow cathode. - These devices, shown in figures 4(a) and (b), consist of a tantalum tube electron beam welded to a thoriated tungsten orifice plate. The tube is typically several millimeters in diameter, while the orifice in the plate is a fraction of a millimeter in diameter. The insert, which is located within the hollow cathode, and serves as a low work function electron source, is electrically connected to the cathode tube. Operation of the hollow cathode is effected by turning on an expellant which flows through the tube and out of the orifice into the region downstream of the hollow cathode. This flow establishes a pressure within the hollow cathode that is of the order of 10 torr. In order to start the cathode, a disc or toroidal anode, positioned 1 to 2 mm downstream of the cathode is biased a few hundred volts positive of the cathode and the heater shown is energized. Operation of the heater eventually results in heating of the low work function insert to a temperature where thermionic electron emission occurs (1100 °C). These thermionic electrons tend to flow through the orifice toward the anode and have ionizing collisions with the high density gas within the hollow cathode. This results in the production of electron/ion pairs and, hence, a dense plasma within the cathode tube. The electrons are unable to return to the insert wall because they have been accelerated through a potential and have lost the energy associated with that acceleration as a result of collisions and they, therefore, flow through the orifice toward the anode. Ions, on the other hand, are unable to negotiate what is to them an adverse potential difference across the orifice plate and they are drawn back to the insert. When the ions bombard the insert, they heat it, and because of this, it is possible to turn off or turn down the heater after the cathode discharge has ignited. Electrons that flow through the orifice are collected by the anode and, in the process, they can collide with the neutral atoms flowing through the orifice producing electron/ion pairs downstream of the orifice. It is this production of ion electron pairs that facilitates the formation of the plasma downstream of the hollow cathode. As an ion production device, however, the hollow cathode is quite inefficient because the neutral gases escaping from the orifice are at low density so the probability of their being ionized is low. In addition, many of the electrons that come through the orifice will be able to reach the anode directly, thereby depositing their energy at the anode rather than ionizing atoms. The ion production rate in the region downstream of a typical hollow cathode is the order of a milliampere or less.

If one places an electrode downstream of the hollow cathode assembly shown in figure 4, and biases it positive or negative (of the hollow cathode plasma downstream of the orifice plate) then it can collect electrons or ions respectively from the hollow cathode plasma. Thus, in the hollow cathode discharge, one has a plasma contactor which can serve as either an ion or electron emitter. Further, the downstream electrode can be a plasma instead of a metal electrode, and the electrons in it will be collected by the hollow cathode when it is biased to emit ions. Biasing the cathode to emit electrons would in this case cause the hollow cathode to collect ions from space plasma.

Ring-cusp ion source. - Figures 5(a) and (b) show cross-sectional views of the NASA Lewis and CSU ring-cusp ion sources, respectively. These geometries are derivatives of a highly-efficient plasma containment scheme developed for ion propulsion by Sovey (ref. 5) and most recently investigated by Patterson (ref. 6). These sources, which operate on the same number of power supplies as the standard hollow cathode, are constructed so as to increase the ionization efficiency of a simple hollow cathode. They utilize the same hollow cathode geometry as that used in the hollow cathode plasma contactor, but in place of the toroidal or disc anode is a cylindrical anode shell or cylindrical sheet anode. These devices derive their name from the shape of the magnetic field within them. The magnetic field is created by samarium-cobalt magnets arranged in rings of alternating polarity located along the back and sides of the discharge chamber. The body of the ring-cusp ion source serves to confine the neutral expellant fed into the discharge chamber so that it must exit from the downstream end of the contactor. While some of the expellant used in this device is fed through the hollow cathode, the majority of the expellant is fed through a main flow plenum. The smaller CSU source utilizes reverse flow only so that the expellant will be directed upstream, thereby increasing the probability of ionization in the discharge chamber.

In order to understand the beneficial effects of the ring-cusp ion source, it is desirable to follow typical electrons, ions and neutral atoms in the discharge chamber. Electrons from the hollow cathode, for example, are accelerated into the discharge chamber plasma where they tend to be confined by the magnetic field until they have had inelastic (ionizing and exciting) collisions and lost their energy. They can then be collected at the anode. Electron energy is utilized more effectively to produce ions in the ring-cusp source than it is in the hollow cathode contactor so its efficiency as an ion producer is greatly enhanced.

Ions which are produced as a result of electron collisions with neutral atoms, tend to exit primarily through the downstream open area because electrons, which are unable to migrate across magnetic field lines, tend to constrain ion motion and limit ion losses to the discharge chamber walls where they could recombine. Neutral atoms introduced into the discharge chamber tend to bounce around from surface to surface until they exit through the downstream end of the discharge chamber. One would expect improved ion production capability from this source and, as a result, a greater capacity to emit ions and collect electrons from a background dilute plasma than could be attained from the hollow cathode contactor.

As indicated in figure 5(a), baffles with varying aperture open areas were used on the downstream end of the LeRC ring-cusp ion source to investigate the effects of changes in the plasma extraction area on the performance of the 28 cm diameter contactor. This was motivated by the observation that a significant fraction of the contactor expellant was being lost at the contactor periphery without undergoing inelastic collisions with energetic discharge electrons. By masking down the baffle open area, two competing effects should occur to establish an optimum aperture size: (1) Decreasing the baffle area increases the neutral density of expellant in the discharge chamber which consequently increases the ion production rate, however;. (2) by decreasing the baffle open area, the ratio of ions which are extracted from the source to the total created in the discharge plasma is decreased.

Closed-drift ion source. - Another potential plasma contactor investigated is the closed-drift ion source, shown in figure 6. This device is a derivative of a Soviet developed electric thruster which has demonstrated low ion energy production capability at low power requirement. Recent efforts conducted in the United States by Patterson, et al. (ref. 7), indicate that reasonably efficient ion production may be achieved with this geometry as well. As in the case of the ring-cusp ion source, the closed-drift source utilizes the same hollow cathode geometry as that of the hollow cathode plasma contactor. However, unlike the ring-cusp ion source, the hollow cathode for the closed-drift contactor is located exterior to the discharge chamber. During operation the device utilizes backstreaming electrons from the external hollow cathode to ionize the expellant. A radial magnetic field at the downstream end of the acceleration channel reduces electron diffusion toward the upstream anode, increases the ion production rate and, consequently, reduces neutral expellant losses.

Facilities

Space plasma simulator. - Both at NASA Lewis and at CSU, a hollow cathode assembly similar to that shown in figure 4a was used as a space plasma simulator to generate a dilute background plasma. During operation of a candidate plasma contactor, electron current was emitted to and collected from this background plasma. The dense plasma generated between the hollow cathode and anode diffuses through the space simulation chamber. In the region extending downstream from the simulator, the plasma density drops until it reaches about 10^6 ions and electrons per cubic centimeter, about 1 m from the simulator.

Space simulation chambers. - Tests of candidate contactors at NASA Lewis were conducted in a vacuum tank of dimensions 4.6 m diameter by 19.2 m long, having a base pressure (without expellant flow) of about 2×10^{-6} torr. The operating pressures were generally less than 7×10^{-6} torr for all expellant flow rates investigated. The distance between the plasma contactor and the space plasma simulator during contactor characterization was approximately 10 m.

The vacuum tank at CSU is 1.2 m in diameter by 5.3 m in length. During the tests, the vacuum tank pressure was in the range of 4 to 6×10^{-6} torr. The contactor and the simulator were separated by a distance of 2.7 m during the contactor characterization experiments.

PROCEDURE

In order to investigate the behavior of the plasma contacting devices, test configurations like those shown in figures 7(a) and (b) were assembled. In general, as previously discussed, the test scenario consists of one of several possible plasma contactors and a space plasma simulator both located within a vacuum tank. The contactor and the simulator are separated by the distance indicated in the figures. The NASA Lewis scenario (fig. 7(a)) also included a stationary array of Langmuir probes between the contactor and the simulator, whereas the CSU scenario (fig. 7(b)) included both a Langmuir and an emissive probe which could be swept along the centerline joining the contactor and simulator. These were used to measure plasma properties including the plasma potential profile along the distance between the contactor and simulator. In both test configurations the space plasma simulator is tied to tank ground, whereas the plasma contactor is tied to a bias supply whose opposite side is then tied to tank ground. The plasma contactor can then be biased with respect to both the tank and the plasma generated by the simulator so that the contactor can emit or collect electron current from the background plasma. The electron current emission/electron current collection capabilities of each plasma contactor were then investigated as a function of: (1) bias voltage, (2) contactor operating condition (expellant flow rate and discharge power level), and (3) expellant type (both argon and xenon gases). In the course of conducting these tests, the plasma contactor was changed, however, the simulator was the same for all tests. The space plasma simulator for all experiments in the high-power test regime of NASA Lewis was operated at a nominal condition of 5.0 standard cubic centimeters per minute (sccm) of expellant (either argon or xenon) and about 70 W of discharge power to generate the background plasma. The simulator used in the CSU experiments was operated at a nominal xenon flow rate of 1.4 sccm and about 6 W of discharge power.

RESULTS AND DISCUSSIONS

This section presents a synopsis of the results and general performance characteristics of the various plasma contactors tested. For clarity, results from the complementary research programs are presented in separate discussions of low-power and high-power plasma contactor experiments. More detailed information on the performance of these devices, and the individual CSU and NASA Lewis research programs can be found in references 2, 8, and 10. A few general observations of the high-power plasma contactor experiments and their potential impact on the electrodynamic tether concept are made.

Performance of Plasma Contactors

Hot wire filament. - Contactor experiments were initially conducted with a hot filament that would provide electron emission without an accompanying generation of a dense plasma. This was used as a standard of merit against which the hollow cathode/hollow cathode-based plasma contactor performance could be measured. This "plasmaless" contactor was constructed of a simple 1/4 mm diameter tungsten wire, heated by an alternating current power supply to thermionic emission temperatures. Figure 8 shows the performance of the filament observed when biased relative to the tank and simulator plasma. This figure is plotted in terms of the same variables (electron emission current and plasma contactor potential) as those used in figure 3. When the hot filament is biased 150 V negative of the tank and simulator plasma at a tank pressure of 4×10^{-6} torr, the data shows about 50 mA of electrons are emitted from the filament. Essentially all of this current is drawn to the tank walls rather than the simulator. If the pressure in the tank is increased by admitting additional xenon, so that the pressure is 6×10^{-6} torr, then the filament emission current increases. At either pressure, however, increasing the potential on the contactor causes the current to drop to zero and it remains zero as the contactor potential is raised to 150 V. This shows that the hot filament is not a particularly effective plasma contactor. It cannot collect electrons very effectively because it has a relatively small surface area and it produces no plasma, and therefore, has no density plasma plume in its immediate vicinity to contact the space plasma.

Low-power plasma contactor experiments. - The performance of those plasma contactors investigated at CSU - the standard hollow cathode (fig. 4(a)) and the 6 cm diameter ring-cusp ion source (fig. 5(b)) - with the test scenario indicated in figure 7(b), are presented here.

For the test of the hollow cathode plasma contactor, the hollow cathode was operated with a 1.4 sccm xenon flow rate through the cathode and the discharge power (i.e., the anode power supply output) was about 10 W. In order to conduct the test, the hollow cathode assembly was biased with respect to the simulator anode and tank which were connected together. Figure 9, which shows the performance of this plasma contactor, suggests it is quite effective as an electron emitter emitting about 1000 mA of current when the anode of the hollow cathode is biased 40 V negative of tank and simulator anode. Contactor potential in this case is defined as the potential of the hollow cathode contactor anode measured relative to the tank and simulator anode. When the contactor is biased positive with respect to the tank and simulator anode in this case an electron current can be collected. Figure 9 shows it to be the order of 25 mA of electron collection at a contactor potential of +150 V (note the current below the axis has been multiplied by ten to make the data readable). The ion production current associated with the hollow cathode was measured and found to be less than 1 mA. Therefore, it is obvious that most of the current that is flowing is electron current from the simulator. Figure 9 shows that the hollow cathode plasma contactor performs far better than the hot filament and at least in the electron emission region its performance approaches that of the ideal plasma contactor.

The next plasma contactor tested, the 6 cm diameter ring-cusp plasma contactor, utilizes the same number of power supplies as the hollow cathode, but is constructed so it will be a more effective ion producer. The performance test conducted on it, however, is essentially the same as that conducted on the hot filament and on the simple hollow cathode. Figure 10 shows the performance of the ring cusp ion source compared to the data for the hot filament and hollow cathode from figures 8 and 9. In this case, the ring cusp ion source was operating with 7 sccm of xenon flowing into it. One-fifth of that flow was through the hollow cathode and four-fifths was fed through downstream plenum shown in figure 5(b). The source was operated at a slightly higher power (20 W) than the hollow cathode as figure 10 indicates. The figure shows that the performance of the ring cusp ion source was better than that of the hollow cathode particularly in the electron collection region where the plasma contactor potential is positive of the simulated space plasma. In this case, the device could draw about 500 mA of electron current from the plasma simulator when the potential difference between anodes of the simulator and the contactor was about 80 V. It is noted that the measured ion production rate of the ring cusp contactor at 7 sccm and 20 W was approximately 60 mA.

It is instructive to consider the potential variation that exists between the plasma contactor and the plasma simulator in these low-power experiments. Plasma potentials were, therefore, measured at several operating conditions for the hollow cathode and the ring cusp ion source. These included conditions where electrons were being collected by the contactor as well as those where they were being emitted. Plasma potentials were measured using an emissive probe that could be moved along the centerline joining the contactor and the simulator. Figure 11 shows typical examples of axial potential profiles in which zero potential corresponds to the common potential of the tank and the anode of the simulator. The upper curve corresponds to a hollow cathode contactor, operating at the flow and power conditions indicated which was collecting 21 mA of electrons. At this operating condition the half-solid triangular symbol (at zero position) shows a contactor anode potential of about 135 V while the solid symbol shows the cathode potential of the contactor was a little over 100 V. The plasma potential varied from near 120 V a few centimeters downstream of the hollow cathode location to a potential of about 40 V some 30 cm downstream of the contactor position. At distances beyond this the potential appears to level out or rise slightly. It should be recognized that the potential profile if it were to continue on to 270 cm, would have to drop to a value near zero. The potential drop from about 45 V to zero would then correspond to the potential drop that exists at the simulator. These data suggest, therefore, a contactor anode-to-space plasma potential difference of 135 - 40 = 95 V might be observed in space at this operating condition. The remainder of the simulator anode-to-contactor anode potential difference is associated with simulator operation in this test. When the hollow cathode anode and cathode potentials were reduced to 80 and about 50 V, respectively, the data associated with the circular symbols in figure 11 were obtained and an electron collection of current of 5 mA was effected by the hollow cathode. In this case, the plasma potential shows similar behavior to that observed with the triangular symbols in that the plasma potential levels off after about 30 cm downstream of the contactor. These data suggest that the sheath region in which the potential was dropping extends about 30 cm downstream of the hollow cathode. The extent of any high density plume region suggested in figure 2 is not obvious from the data although they do suggest the potential profile might be quite flat in the region extending from the hollow cathode to a few centimeters downstream of it.

In the case of the ring cusp plasma source collecting electrons at a rate of 107 mA, the sheath appears to have a slightly different shape and the region where the potential seems to drop off extends beyond about 30 cm.

When the ring cusp plasma source was operated to emit 500 mA of electrons, its anode was just a few volts negative of the tank and simulator anode potential, as shown by the half-solid diamond symbol. The cathode was about 30 V negative of the zero reference potential and the plasma potential was relatively constant at about -15 V. Again the plasma potential would have to rise to about zero potential at a location 270 cm downstream of the plasma contactor. This potential profile is observed to be quite flat. In the case of the hollow cathode operating to emit 100 mA of electrons, the data shown by the square symbols were obtained. These data show behavior similar to that observed with the hollow cathode except for the fact that there appears to be a well in the region between zero and 120 cm, i.e., the plasma potential dips down and then rises again. This is particularly interesting because it suggests that electrons attempting to leave the hollow cathode discharge and go to the simulator tend to be repelled in the region immediately adjacent to the hollow cathode plasma contactor. This means only the most energetic electrons can escape while any ions that are present are being drawn from the discharge in an effort to fill the well and flatten the potential profile. The fact the ring cusp plasma source profile is flatter suggests the availability of greater numbers of ions from the ring cusp plasma source. These data suggest that the flatter profile observed with the ring cusp plasma source is observed because this source produces some 60 mA of ions while the hollow cathode produces less than 1 mA of ions at the operating conditions of figure 11.

High-power plasma contactor experiments. - The performance of those plasma contactors investigated at NASA Lewis (the 28 cm diam. ring-cusp ion source (fig. 5(a)) and the closed-drift ion source (fig. 6), with the test scenario indicated in figure 7(a)) are presented here.

A few general observations of these high-power plasma contactor experiments should be made prior to a presentation of the data: (1) characterization of plasma contactor performance was restricted to investigating the electron current collection capabilities of these devices; that is, an analysis of how well these contactors mimic the behavior of an ideal plasma contactor in the fourth quadrant of figure 3; (2) under all test conditions, with no discharge power to the plasma contactor ("off"), multiampere level electron currents could be drawn from the dilute plasma to the plasma contactor with bias voltage and neutral expellant flow only, and (3) in conjunction with (2), a large plume was observed emanating from the plasma contactor, with an extent and luminosity proportional to the bias voltage (termed here the "ignited-mode").

Figure 12 shows the performance of the 28 cm ring-cusp plasma contactor with grid. The ring-cusp contactor was biased with respect to the simulator cathode and tank which were connected together. Electron current could be drawn to this geometry (over the 10 m distance indicated in fig. 7(a)) when the bias supply was tied to the grid. Electron currents ranging from 100 mA to 10 A were collected at the plasma contactor for xenon expellant flow rates of 10 to 20 sccm. The minimum argon flow rate to draw electron current to the plasma contactor was 80 sccm for bias voltages less than 300 V positive of simulator cathode. Onset of the "ignited-mode" was observed at contactor potentials above 80 V. The electron current levels to the plasma contactor with and without discharge power were comparable, at comparable expellant flows and bias voltages. Electrons from the simulator plasma are accelerated by a sheath established external to the plasma contactor and undergo both elastic and inelastic collisions with the neutral expellant, thereby producing ions which permit even greater electron flow and reduce contactor impedance. Comparable electron current levels, with and without discharge power, indicate that the ion production rate as a consequence of the bias voltage greatly exceeds that of the rate generated by the discharge power alone.

Although the grid on this ring-cusp plasma contactor increases the discharge chamber neutral density, it also decreases the ion transparency. Consequently, there is a decrease in the overall ion production efficiency of the source. In addition, "hot-spot" was observed to form on the center of the grid during high current coupling which indicated that most of the electron current collection/ion production was occurring on axis. Therefore, a modification to the contactor geometry was made by replacing the grid with a 30 cm diameter disc of sheet metal, with a centered 7.6 cm diameter hole. The disc was isolated from contactor anode potential by an isomica ring. Because all exterior surfaces of the contactor upstream of the exit plane are covered with ground screen, the only path for the electron collection was through the hole in this baffle to interior surfaces of the discharge chamber. With this geometry, the current to the plasma contactor with and without discharge power was again comparable and at the multiampere level. The contactor performance is presented in figure 13. The discharge power to the contactor (when on) was approximately 150 W.

Plasma contactor experiments were also conducted with a 12 cm diameter closed-drift ion source (fig. 6). The minimum xenon contactor expellant flow rate to draw appreciable electron current levels was approximately 15 sccm, independent of discharge power level. Figure 14 presents the performance of this contactor in comparison with the two ring-cusp geometries. It is noted that the 28 cm ring-cusp plasma contactor with grid was best capable of collecting electron current, with approximately 6 A at 100 V positive of space plasma simulator.

Impact of Results on Electrodynamic Tether

The question arises as to whether these plasma contactor experiments (especially in the high-power regime) are an adequate simulation of the space plasma, and of the contacting process. It is clear that if the bias voltage between the plasma contactor and the space plasma simulator appeared over the extent of their separation, we would in effect be creating a large discharge with the contactor and simulator being alternately the anode and cathode. However, in both operating regimes, the potential profile indicates that the majority of the voltage drop occurs at the plasma contactor. In the high-power experiments, the plasma potential rapidly dropped to a few volts positive of tank ground within 2 m of the contactor (over a total separation of 10 m). In this "ignited-mode," extensive ionization occurred in the volume exterior to the plane of the plasma contactor. Multiampere level electron currents could be collected at the plasma contactor without discharge power to the contactor. Extensive excitation was observed the bulk of the plasma, with a maximum near the contactor. The remainder of the bulk plasma exhibited a very diffuse glow in the space simulation chamber. No intense excitation was observed over the contactor-simulator separation to indicate a direct coupling. Present experimental efforts to measure electron energies in the bulk plasma should indicate whether the collected currents are comprised of "hot" simulator electrons, or are from a thermalized distribution.

Theory suggests that in the electron emission mode, the results of the plasma contactor experiments in the ground facilities can be directly applied to the behavior one would expect in the ionospheric plasma. However, the correlation between operation of the plasma contactors in the electron collection mode in the ground facilities and that expected in space is less certain.

This is because an infinite source of low energy electrons (such as the ionosphere) may not be adequately simulated in the relatively small vacuum facilities. It has been observed in the high-power experiments that the operating characteristics of the hollow cathode space plasma simulator are a function of the plasma contactor bias voltage; the simulator anode voltage varies inversely with bias voltage by greater than 50 percent. However, it does not appear that the electron current collection capabilities of the plasma contactor are a direct function of the simulator operating condition. Other facility-associated problems including determining the extent to which surfaces near the plasma contactor may affect its ability to couple to the background plasma, are presently being investigated. It is clear, however, that flight verification of the electron current collection capabilities of these plasma contactors will be required.

The results of the plasma contactor experiments in the two different operating regimes suggest that an optimized ring-cusp ion source may be capable of satisfying the four generic performance criteria identified as requirements for the tether contactor. During operation in the electron current emission mode, discharge power to the plasma contactor will be required, depending on the current level emitted. However, during the electron current collection mode, discharge power to the plasma contactor may be required only during operation of the tether system at low-current levels. At high-power, high-current operation, significant electron current collection may occur without discharge power to the plasma contactor by using a portion of the total induced voltage in the tether to accelerate space plasma electrons at the contactor to create a self-generated plasma ("ignited-mode"). A portion of the electron current collected is then, presumably, electrons from electron-ion pairs of ionized neutral expellant from the contactor. The question then arises as to what may be termed an adequately low impedance at the plasma contactor. From the high-power experiments, the voltage drop (less than 300 V) required to operate the plasma contactor in this passive mode would be small compared to the total induced voltage in the tether (which for a nominal 20 km tether would be approximately 4000 V). Experimental efforts are underway to identify what physical parameters of the contactor define the level of electron current collected in these regimes.

A determination of the operating characteristics of these plasma contactors is important not only in evaluating the viability of the tether concept for power generation, but also for evaluating the propulsion capabilities of the tether system as well. Although the tether propulsion concept has no reaction mass associated with it, the hollow cathode-based plasma contactors require an expellant mass flow-rate to efficiently exchange current with the ionospheric plasma. The thrust is directly proportional to the cross-product of this current and the geomagnetic field. Consequently, a correlation can be made between the plasma contactor expellant mass flow-rate, and the thrust and an "effective" specific impulse of the tether system. Assuming a 20 kW/10 A tether system and a thrust-to-power ratio of 0.125 mN/kW (ref. 11), an "effective" specific impulse of greater than 86 000 sec is calculated based on the demonstrated performance of the 28 cm ring-cusp ion source (fig. 12). These performance numbers would indicate a clear advantage of the tether over electric propulsion (1000 to 4000 sec at 40 to 100 mN/kW) for some mission applications.

Table I lists plasma contactor performance objectives applicable to a technology program to develop a protoflight hollow cathode-based plasma contactor system. Table II lists the results, from these research programs as to how well the standard hollow cathode and the hollow cathode-based sources meet these objectives. Although some of the objectives are not addressed specifically in the research programs (e.g., system cost), best estimates are provided based on past experience with ion propulsion flight systems.

CONCLUDING REMARKS

Present experimental efforts to evaluate the suitability of hollow cathodes and hollow cathode-based plasma sources as plasma contactors for electrodynamic tether applications, conducted concurrently at NASA Lewis Research Center and Colorado State University, were reviewed. These programs include definition of preliminary plasma contactor designs, and characterization of their operation both as electron emitters and electron collectors. Results obtained with several ring-cusp ion sources indicate ampere-level electron emission current may be emitted to a simulated space plasma. During electron current collection experiments, two regimes were identified. In the low-power experiments, ampere-level electron currents could be drawn from a simulated space plasma to a 6 cm ring-cusp plasma contactor at 80 V potential difference with 20 W of discharge power. In the high-power experiments, multiampere electron currents could be collected from a simulated space plasma to two ring-cusp plasma contactor geometries at approximately 80 V bias independent of whether or not discharge power was applied to the plasma contactor. The level of electron current collection was to first order a function of expellant type, expellant flow rate, contactor potential, and contactor geometry only. This regime, termed the "ignited-mode," indicates that multiampere current levels can be achieved by using the voltage drop at the plasma contactor to accelerate space plasma electrons to ionize neutral expellant flow from the contactor. The voltage drop required to operate the plasma contactor in this passive mode could be small compared to the total induced voltage in the tether. The demonstrated ampere-level current exchange between these hollow cathode-based devices and the background dilute plasma would be sufficient for electrodynamic tether operation both for propulsion and power generation applications.

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TABLE I. - PLASMA CONTACTOR PERFORMANCE OBJECTIVES APPLICABLE TO TECHNOLOGY PROGRAM

- Expellant compatibility with space transportation system/science experiments
- High electron production capability
- High ion production capability
- High reliability (for starting and operation)
- Self-regulating emission control
- Switchover capability (between ion/electron emission)
- Low ion and electron energies
- Low system mass
- Low expellant consumption rate
- Low power consumption
- Rapid startup capability
- Simplicity
- Low system cost
- Operation independent of vehicle orientation

TABLE II. - DEMONSTRATED AND PROJECTED PERFORMANCE CAPABILITIES OF HOLLOW CATHODES/HOLLOW CATHODE-BASED PLASMA SOURCES AS PLASMA CONTACTORS

Objective	Demonstrated/projected capabilities	
	Standard hollow cathode	Hollow cathode-based plasma sources
Expellant compatibility	Argon/xenon	Argon/xenon
Electron production capability/ion production capability	Multiampere/1-10 mA	Multiampere/10-1000 mA
Reliability	~10^4 hr/~10^3 starts	~10^4 hr/~10^3 starts
Emission control	Passive	Passive
Switchover	Automatic	Automatic
Ion energy level	~0.03 eV	Similar
Electron temperature	~1 eV	Similar
System mass	Negligible cathode mass Two power supplies One valve	Negligible source mass Two power supplies One valve
Expellant consumption rate	1-6 sccm	1-20 sccm
Power consumption	~30 W ~10^3-10^4 eV/ion	~30 W ~10^2-10^3 eV/ion zero watts during "ignited mode"
Startup time	<2 min	<2 min
Simplicity	~5 components ~2 power ckts.	~10 components ~2 power ckts.
System cost	~1-10 percent ion propulsion system	~1-10 percent ion propulsion system
Operation independent of vehicle orientation	?	?

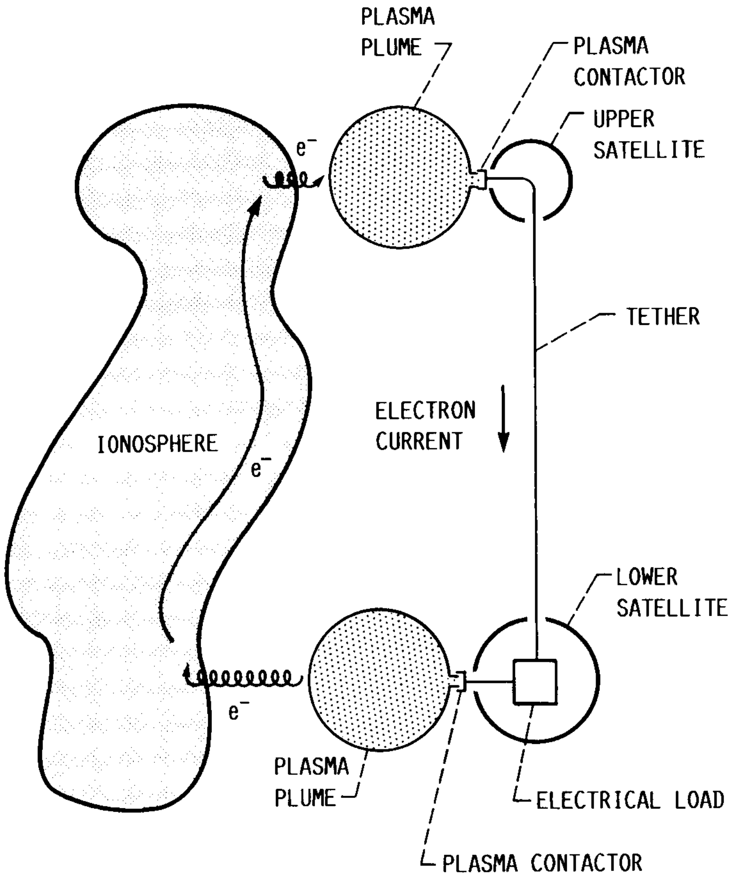


FIGURE 1.- SCHEMATIC DIAGRAM OF ELECTRODYNAMIC TETHER SYSTEM.

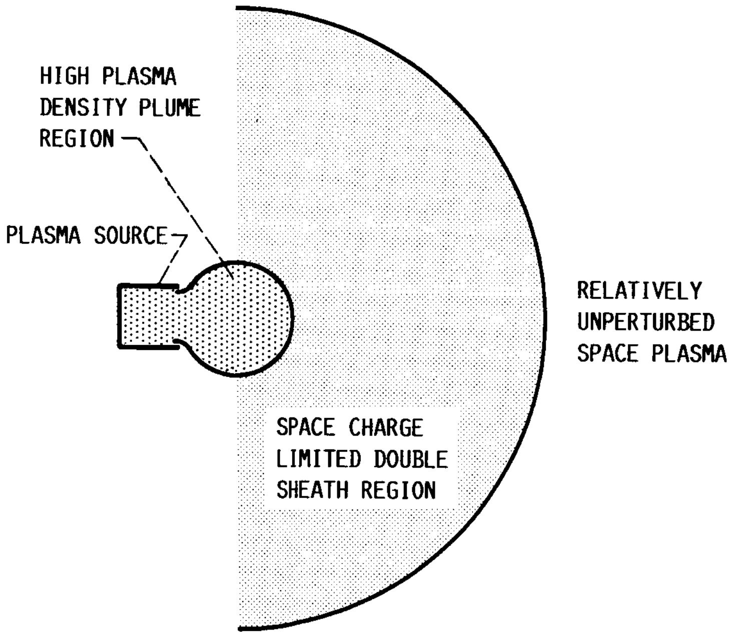


FIGURE 2.- STRUCTURE OF CONTACTOR PLASMA PLUME REGION.

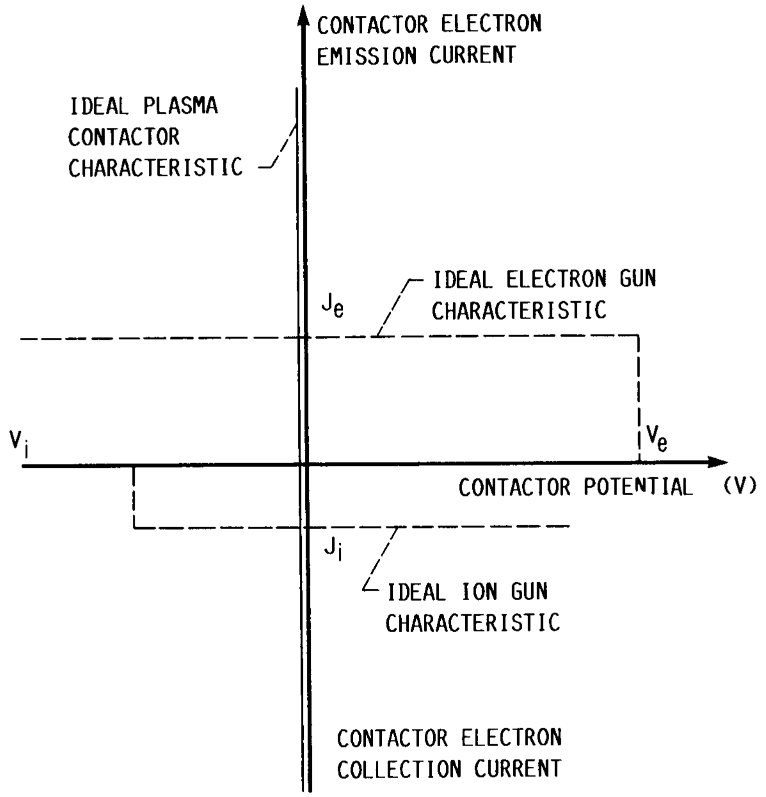
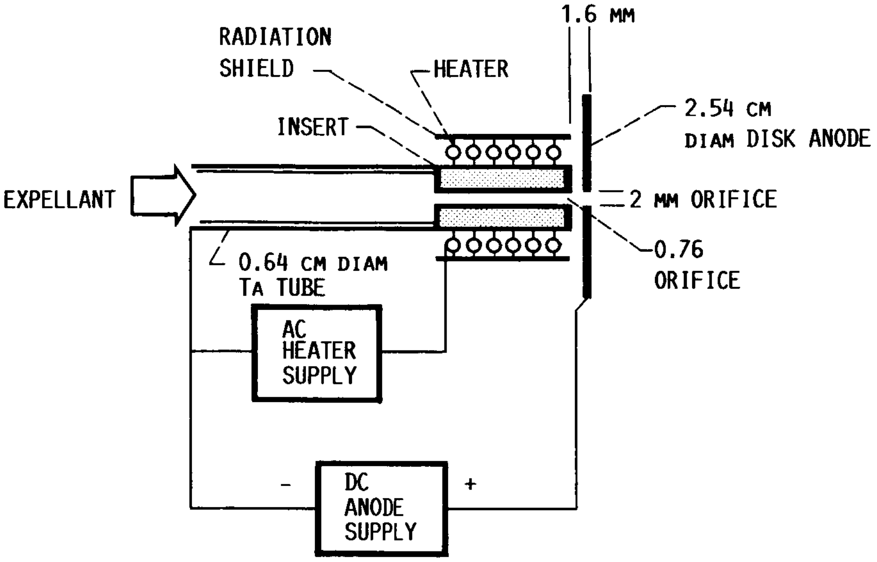
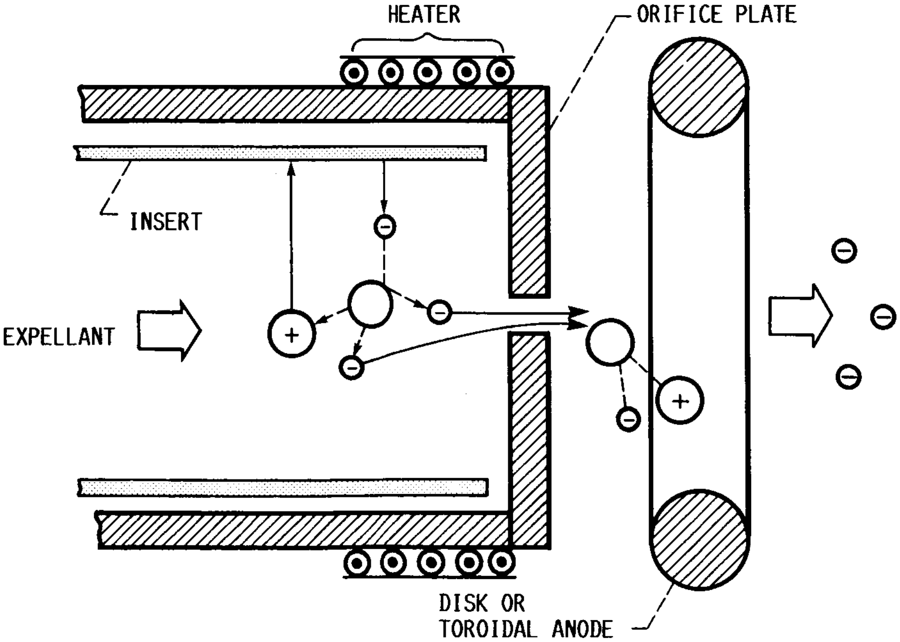


FIGURE 3.- CURRENT-VOLTAGE CHARACTERISTIC OF CANDIDATE PLASMA CONTACTORS.

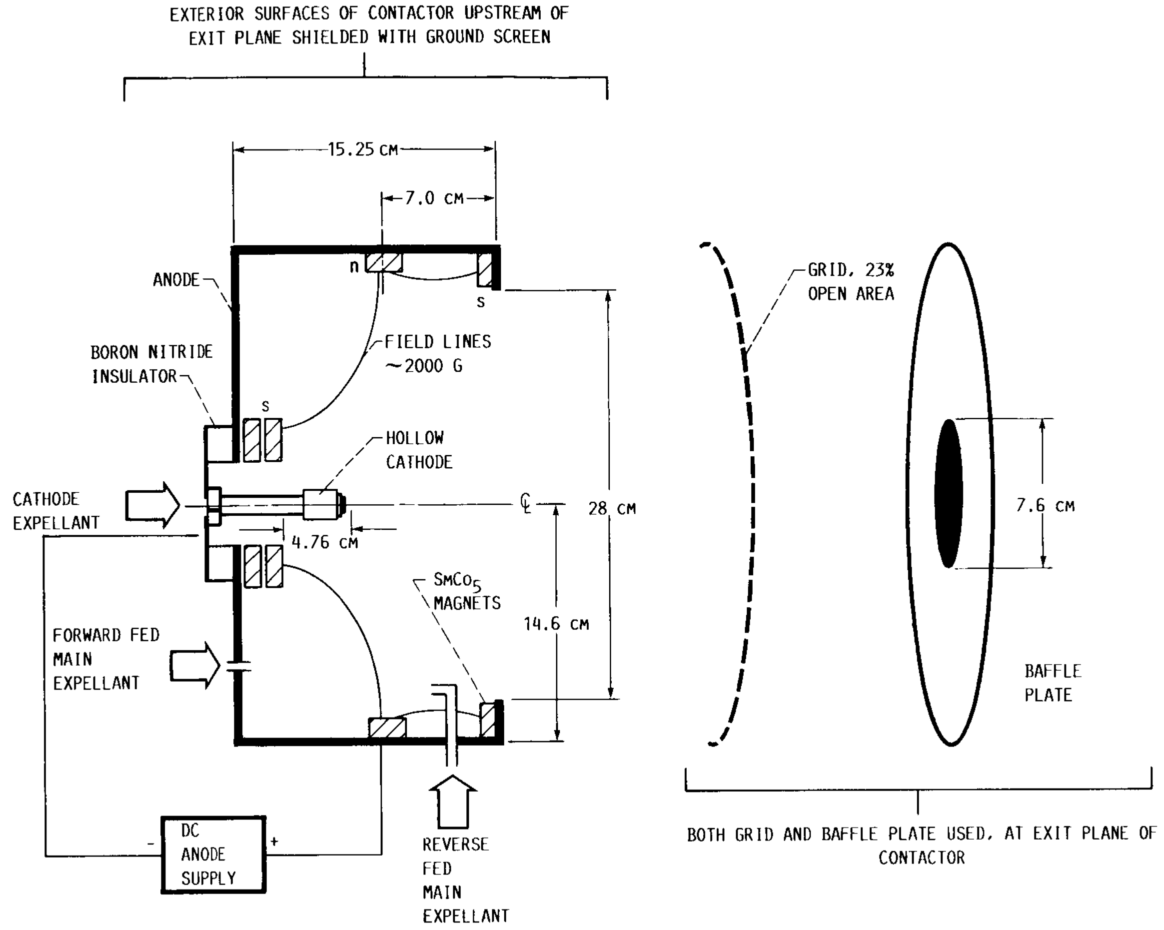


(A) Electrical and mechanical schematic of a hollow cathode.

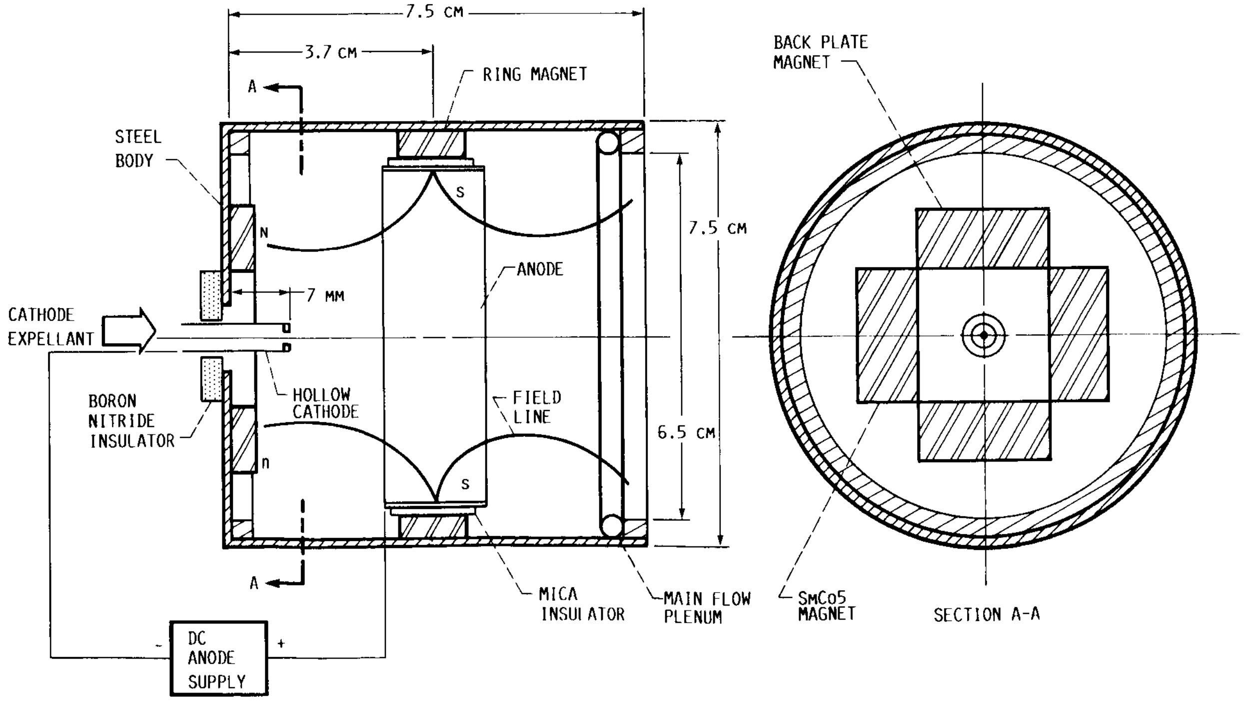


(B) Cross-section of hollow cathode in operation.

Figure 4.- Standard hollow cathode geometry.



(A) ELECTRICAL AND MECHANICAL SCHEMATIC OF NASA-LERC 28 CM DIAM RING-CUSP ION SOURCE.



(B) ELECTRICAL AND MECHANICAL SCHEMATIC OF CSU 6 CM DIAM RING-CUSP ION SOURCE.

FIGURE 5.- RING-CUSP ION SOURCE.

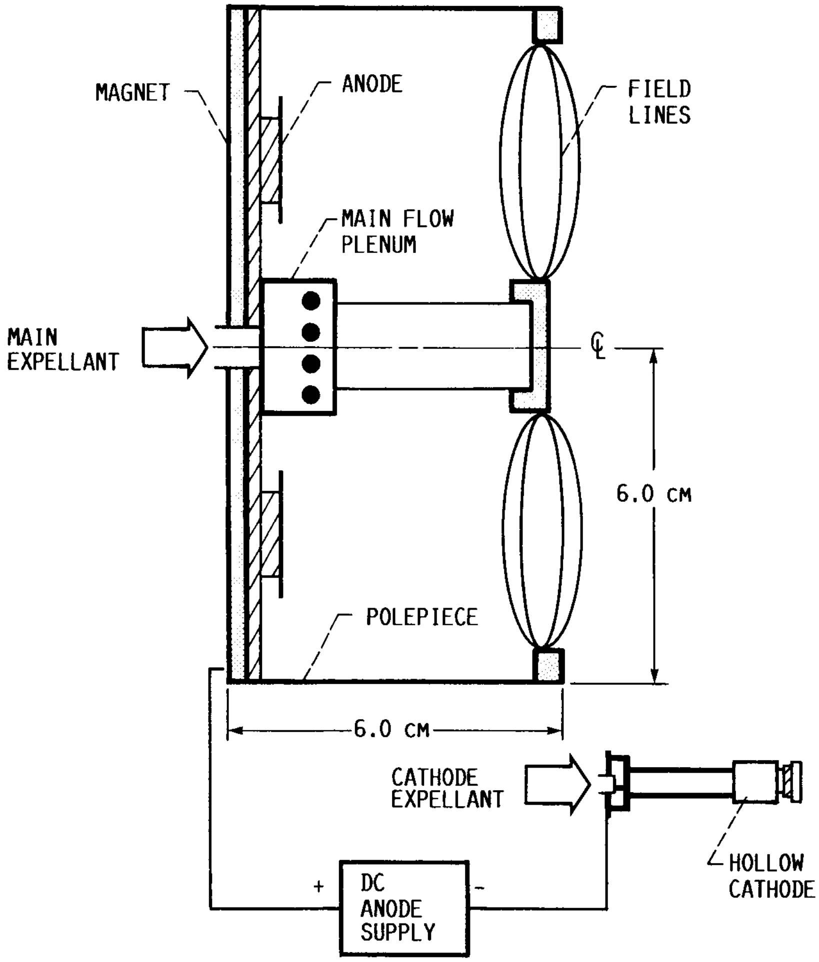
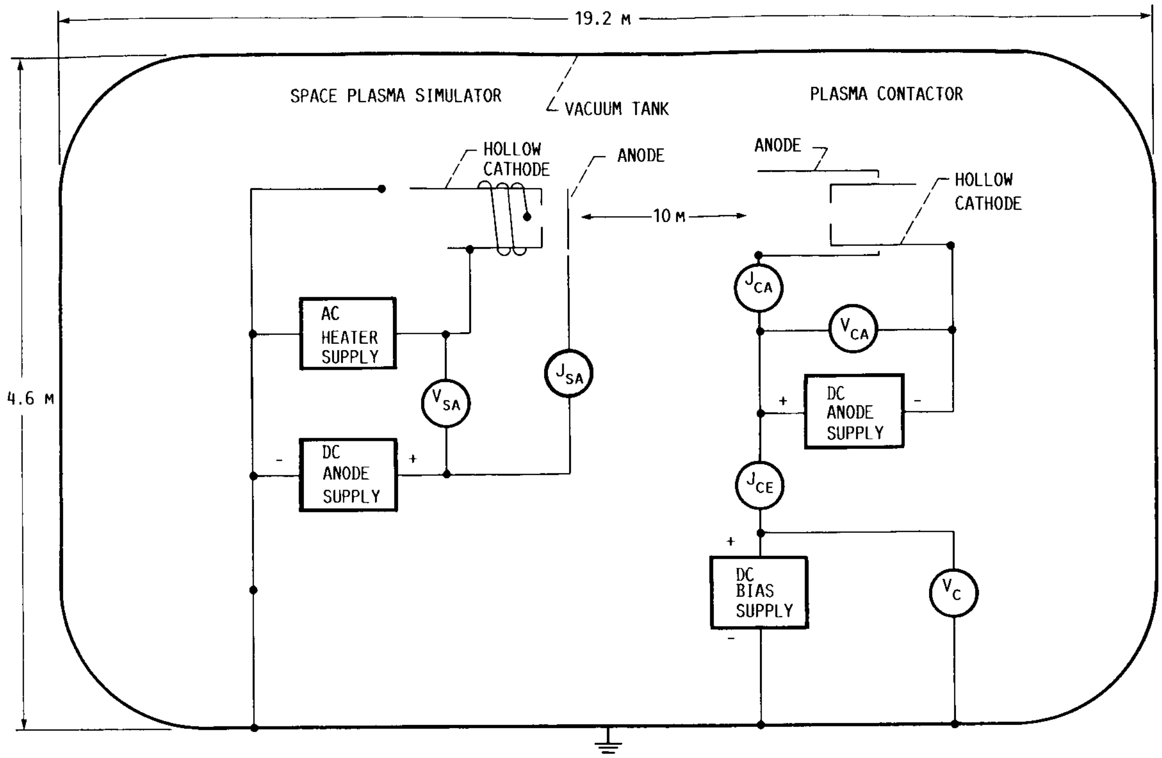
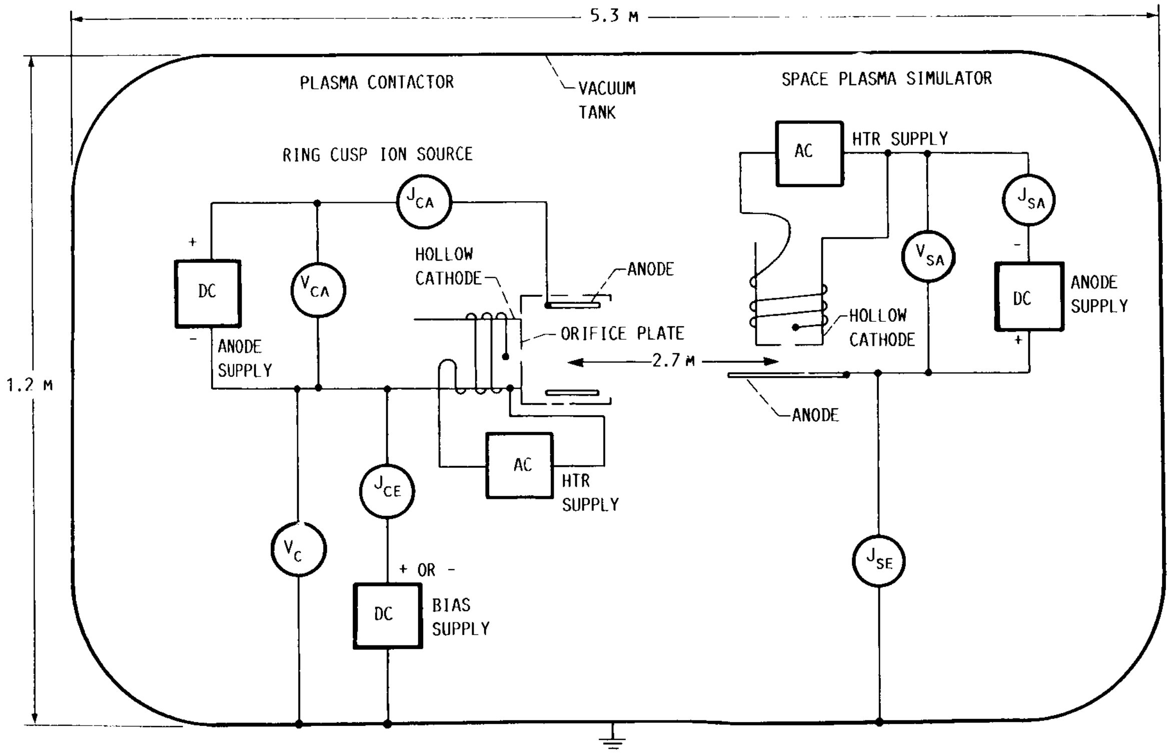


FIGURE 6.- ELECTRICAL AND MECHANICAL SCHEMATIC OF NASA LERC 12 CM DIAM CLOSED-DRIFT ION SOURCE.



(A) Electrical and mechanical schematic of NASA LeRC plasma contactor test scenario; note, plasma contactor varied from test to test.



(B) Electrical and mechanical schematic of CSU plasma contactor test scenario; note, plasma contactor varied from test to test.

Figure 7.- Test scenarios.

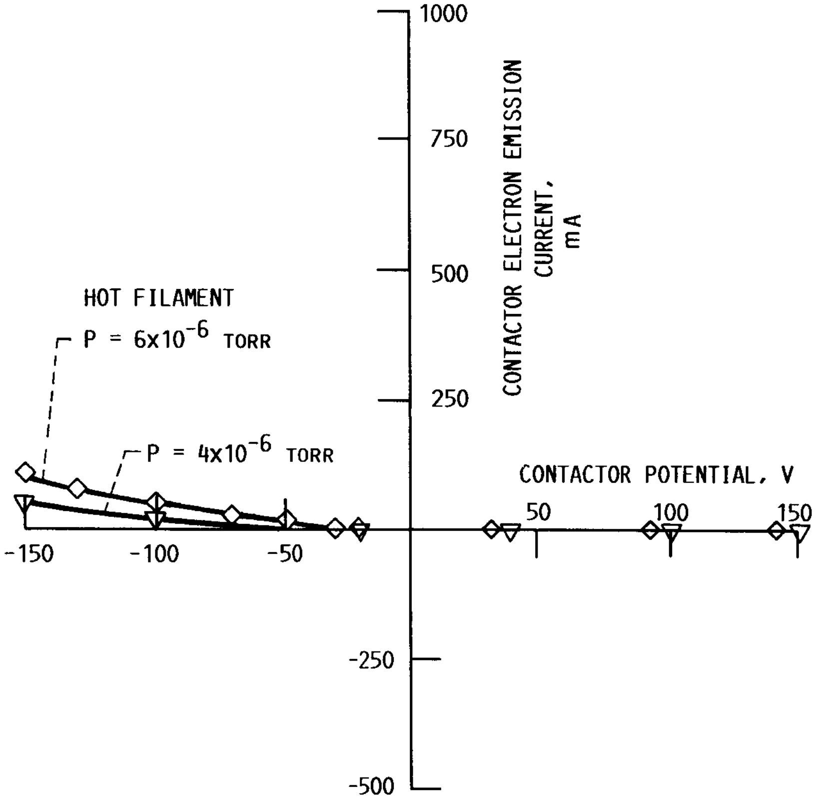


FIGURE 8.- PERFORMANCE OF A HOT FILAMENT AS A PLASMA CONTACTOR.

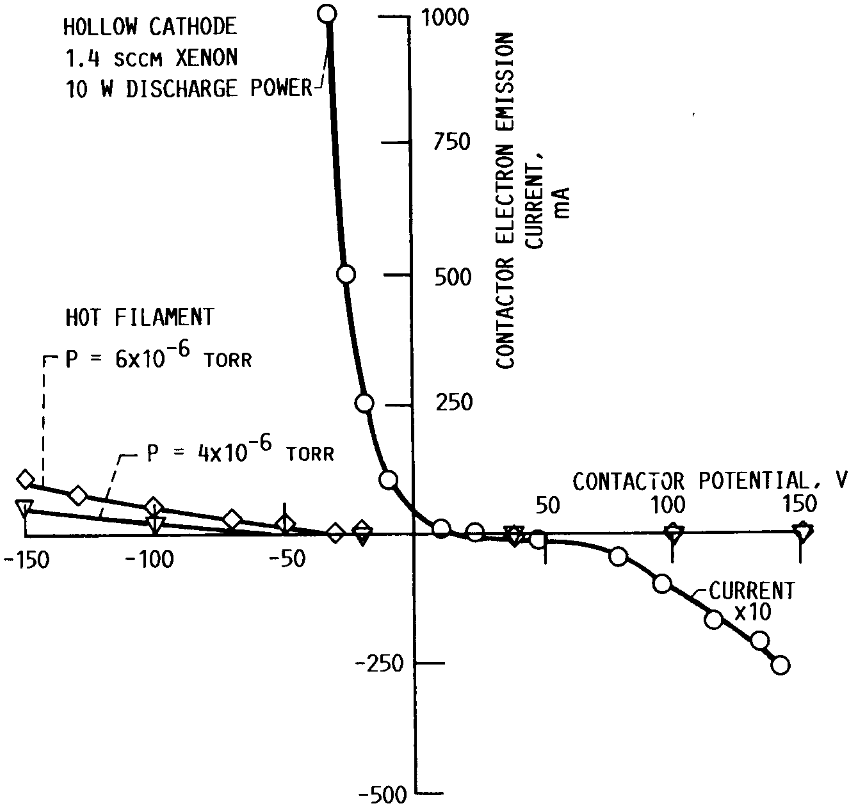


FIGURE 9.- PERFORMANCE OF A HOLLOW CATHODE AS A PLASMA CONTACTOR.

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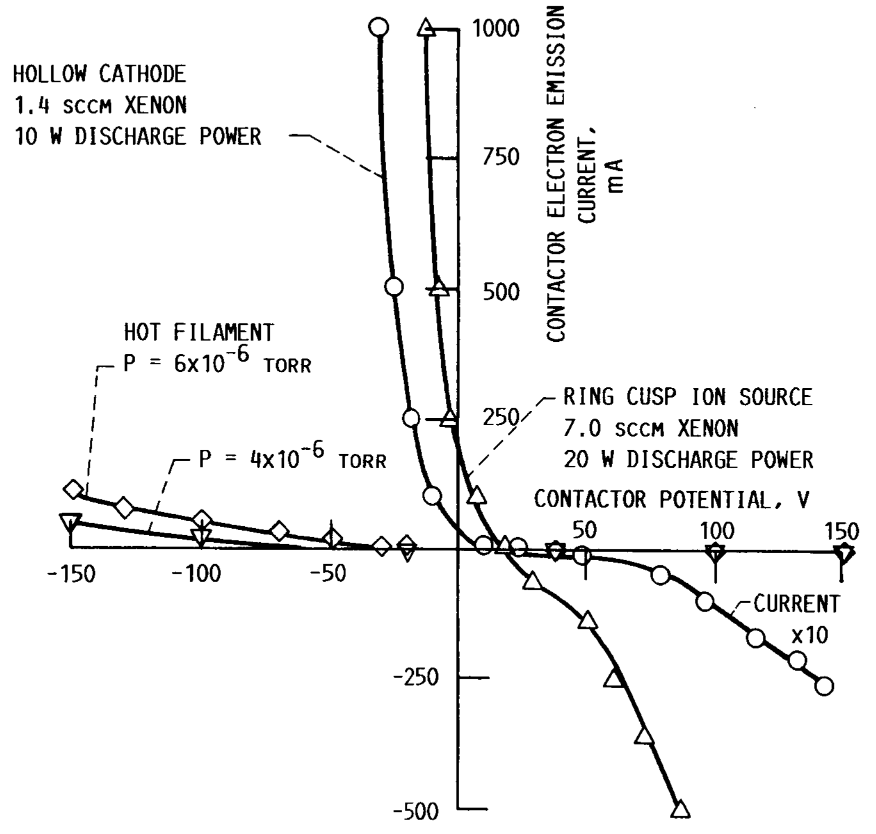

FIGURE 10.- PERFORMANCE OF CSU 6 CM RING-CUSP ION SOURCE AS A PLASMA CONTACTOR.

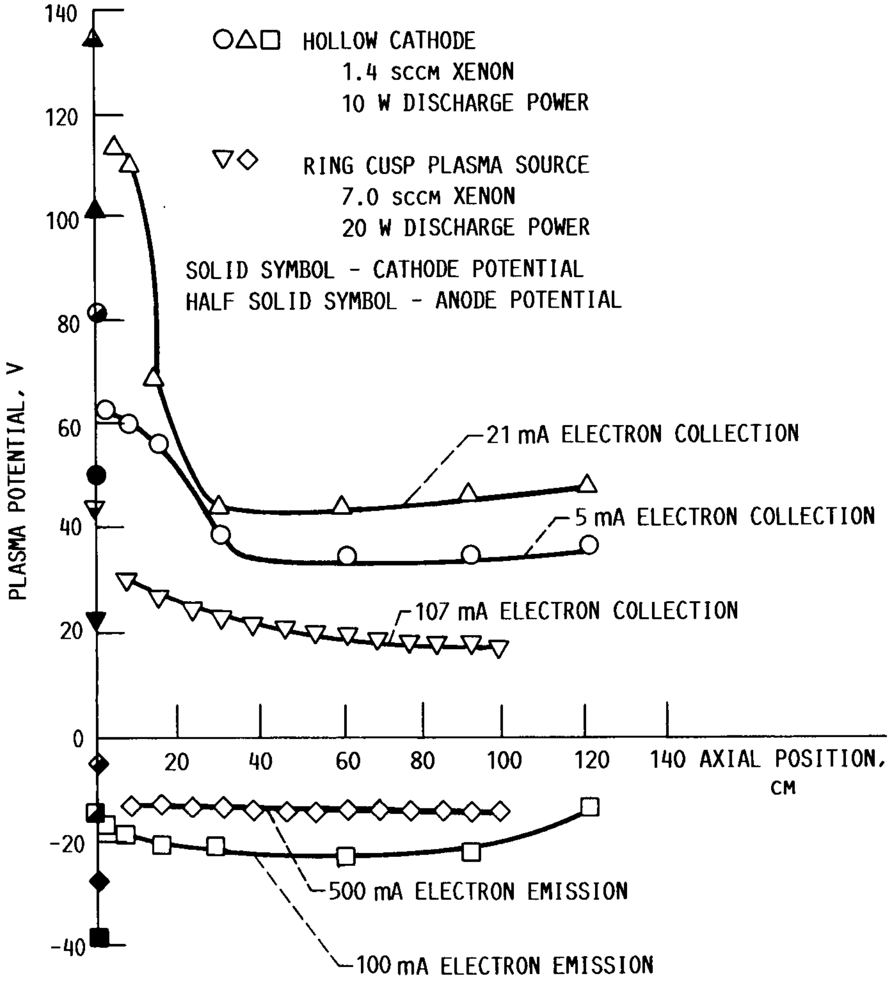

FIGURE 11.- POTENTIAL PROFILE ALONG SEPARATION BETWEEN PLASMA CONTACTOR AND SPACE PLASMA SIMULATOR FOR LOW-POWER EXPERIMENTS.

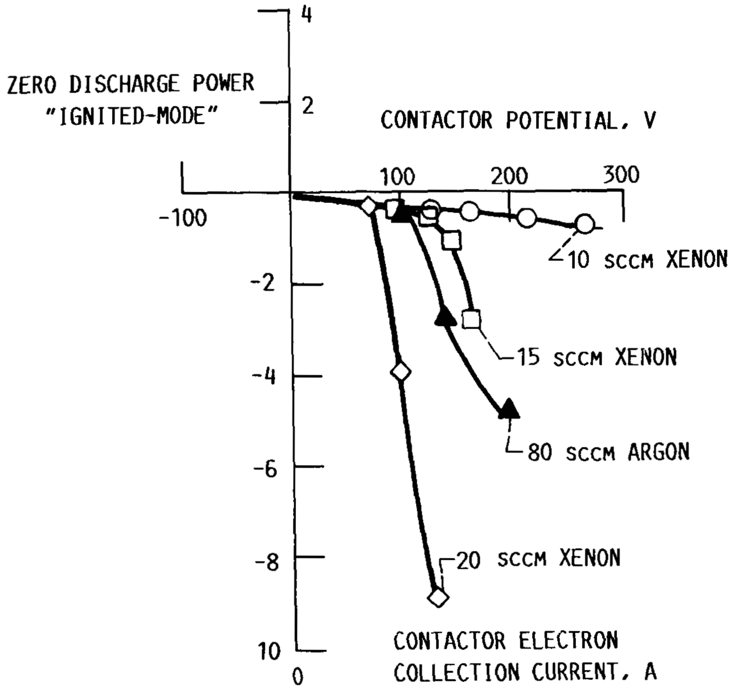

FIGURE 12.- PERFORMANCE OF NASA LeRC 28 CM RING-CUSP ION SOURCE WITH GRID AS A PLASMA CONTACTOR.

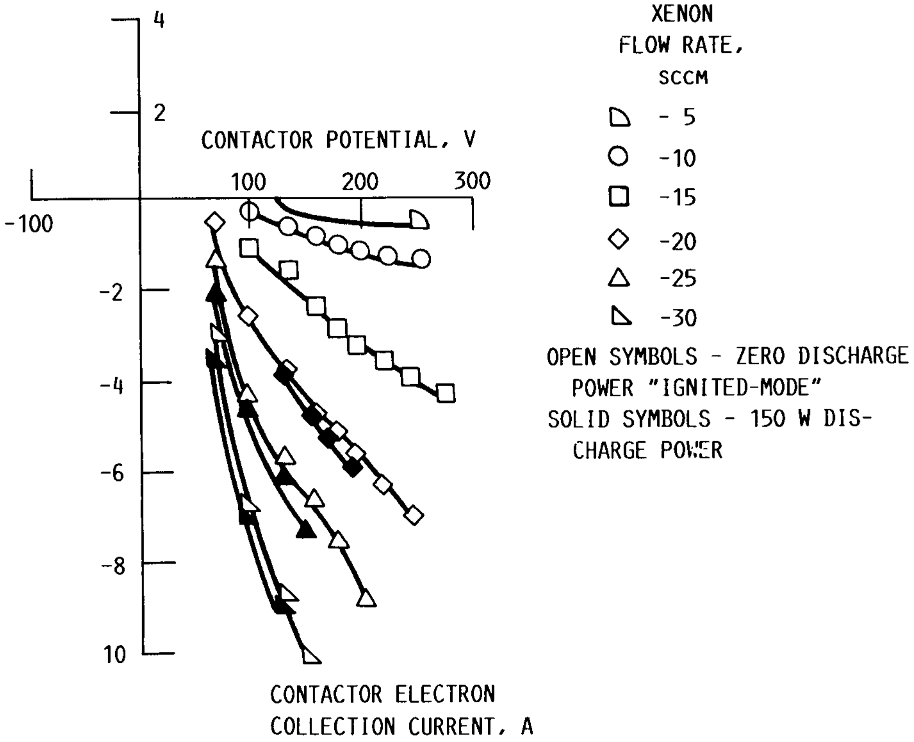

FIGURE 13.- PERFORMANCE OF NASA LERC 28 CM RING-CUSP ION SOURCE WITH BAFFLE AS A PLASMA CONTACTOR.

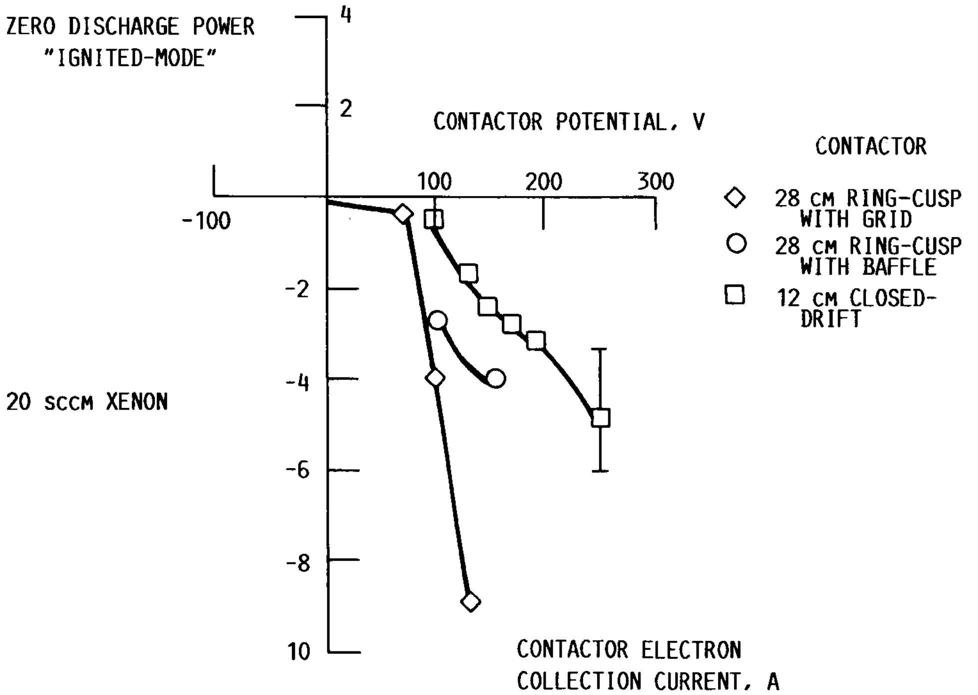

FIGURE 14.- PERFORMANCE OF NASA LeRC 12 cm CLOSED-DRIFT ION SOURCE AS A PLASMA CONTACTOR; COMPARISON TO RING-CUSP ION SOURCES.

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16. Abstract

The role plasma contactors play in effective electrodynamic tether operation is discussed. Hollow cathodes and hollow cathode-based plasma sources have been identified as leading candidates for the electrodynamic tether plasma contactor. Present experimental efforts to evaluate the suitability of these devices as plasma contactors, conducted concurrently at NASA Lewis Research Center and Colorado State University, are reviewed. These research programs include the definition of preliminary plasma contactor designs, and the characterization of their operation both as electron emitters and electron collectors to and from a simulated space plasma. Results indicate that ampere-level electron currents, sufficient for electrodynamic tether operation, can be exchanged between hollow cathode-based plasma contactors and a dilute plasma.

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