# PLASMA CONTACTOR FOR THE ISTP/POLAR SPACECRAFT*

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## ABSTRACT

We have designed, developed and tested a plasma contactor to afford control of the electrostatic potential of the POLAR Spacecraft, a part of the International Solar Terrestrial Physics (ISTP). The plasma contactor, referred to as the Plasma-Source Instrument (PSI) in POLAR nomenclature, consists of a small Penning discharge plasma source, a power supply, and a xenon feed system. The plasma source will deliver >1 mA of ion current with an input power of <10 W. The paper discusses the scientific objectives and the operating principles and design of the plasma contactor. Test results and operating characteristics of the plasma contactor are presented. Block diagrams of the power processor and xenon feed system required to operate the plasma contactor are also presented.

## NOMENCLATURE

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|---|---|
| ISTP | International Solar Terrestrial Physics |
| POLAR | One of the ISTP scientific spacecraft |
| PSI | Plasma Source Instrument |
| TIDE | Thermal Ion Dynamics Experiment |

## INTRODUCTION

ISTP/POLAR is a scientific spacecraft with the mission of documenting and furthering the understanding of the natural space plasma surrounding the earth. To effectively perform this mission it is necessary to detect and measure the velocity of ions with energies of <1 eV. Previous scientific spacecraft have been able to only detect ions with energies of a few eV or higher, because photoemission causes spacecraft to charge in a manner that makes it energetically impossible for the lower-energy ions to reach the spacecraft. The plasma contactor will enable scientists to actively control the potential of the spacecraft to within a few tenths of a volt of space-plasma potential and thereby enable the detection and measurement of the velocity of the lower-energy ions.

A plasma contactor operates on the concept of establishing a dilute plasma cloud near the spacecraft surface which is composed of relatively low-energy electrons and ions. This conductive plasma cloud enables the transport of ions and electrons through space as required to effectively "ground" the spacecraft to the surrounding space plasma. By biasing the plasma contactor relative to the spacecraft frame, the spacecraft potential can be actively controlled. The plasma contactor will operate on xenon gas, which has an atomic-mass number of 131. This will permit easy discrimination of $Xe^+$ from the natural space plasma, which is not expected to contain ions with atomic-mass numbers above 32.

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## BACKGROUND

ISTP is a collection of projects intended to provide a coordinated approach to obtaining a comprehensive data set describing the ambient plasmas in the Earth's vicinity. Five European, two U.S., and one Japanese spacecraft are planned. The U.S. POLAR spacecraft will orbit the Earth in an elliptical (and non-sun-synchronous) polar orbit of dimensions 1.8 by 9.0 $R_e$ (Earth radii). The PSI is one of a dozen instruments which will fly on POLAR and is being flown in support of the Thermal Ion Dynamics Experiment (TIDE). TIDE's mission is to construct a 3-dimensional map of the outflow of ionospheric plasma from the polar regions. From these data, it is hoped that we can determine the degree to which plasma, upwelling from the polar regions, is lost to the solar wind, or becomes trapped and energized in the magnetotail plasma sheet. The role of a suspected low-energy ion population will also be investigated.

In previous attempts to observe the outflowing ionospheric plasma, two key problems have hampered observations. The first is the extremely low flux of particles in the high polar region. Previous instruments, with geometric factors (product of the effective aperture of the instrument and its solid-angle of acceptance) in the range of $10^{-6}$ $m^2sr$, simply did not have the sensitivity to make useful measurements. TIDE, which employs unique design features to obtain a geometric factor of $10^{-4}$ $m^2sr$, is expected to overcome the sensitivity limitation.

The second key difficulty has been the spacecraft-charging problem, which prevents observation of low-energy ions. Spacecraft become electrically charged as a result of four principal processes: electron and ion bombardment by the ambient space plasma, secondary-electron emission, and photoelectron emission (when the spacecraft is in sunlight). These processes cause the spacecraft to come to a potential such that, in equilibrium, the four currents sum to zero. In the high orbit traversed by POLAR, the fluence of bombarding electrons is very low (and the ion current is far smaller still), so that photoelectron current becomes the dominant charging process. In equilibrium, the spacecraft floats positive a few volts, so that only the higher-energy portion of the photoelectron spectrum can escape: just enough electrons leave to balance the incident space-electron flux. Because of this positive spacecraft bias, ions having energies below a few eV are energetically unable to reach the ion spectrometers aboard the spacecraft, and even ions which can marginally be detected have their energies and trajectories altered by passage through the spacecraft E-fields.

When high-orbit spacecraft drift into eclipse, only the tiny secondary-electron and ion-bombardment currents are available to balance the incident electron flux, so the spacecraft charges slowly negative. In one earlier mission, a scientific spacecraft entered eclipse, and as its potential drifted downward through zero (momentarily removing the energy barrier to ambient low-energy ions), a comparatively large flux of heavy, low-energy ions was observed. If this observation proves to be reproducible, it may herald a previously undiscovered ion population which could cause significant revisions of present models of ionospheric plasma transport. The PSI, by providing precision control of the spacecraft potential, will afford the TIDE instrument the opportunity to chart this newly-discovered territory.

## PLASMA CONTACTOR OPERATION

There are two main parts to plasma contactor operation: how contactors generate plasma, and how emission of plasma controls the spacecraft potential.

### Generation of Plasma

The PSI plasma contactor (plasma source) is a conventional Penning discharge with a novel anode geometry; its low operating power and gas flowrate (<10-W, 0.5 sccm) make it especially well suited to operation on spacecraft with modest power and mass budgets.

The design of the PSI plasma source is illustrated schematically in Figure 1. Electrons are emitted from a 3.2-mm-diameter thermionic hollow cathode of conventional ion-propulsion-technology design. A strong axial magnetic field, produced by two rings of $SmCo_5$ magnets, has a maximum near the cathode tip and a zero on axis near the exit plane of the discharge chamber. A disk-shaped anode, which has a central aperture, is located just downstream of the magnetic-field zero. The anode is guarded by the outward-directed magnetic-field lines which emanate from the downstream ring of magnets. Xenon gas is introduced to the discharge chamber through the cathode tube. In operation, electrons emitted from the cathode oscillate along the field lines in the conventional Penning manner, reaching the anode only after experiencing a number of ionizing collisions. The geometry of the plasma source

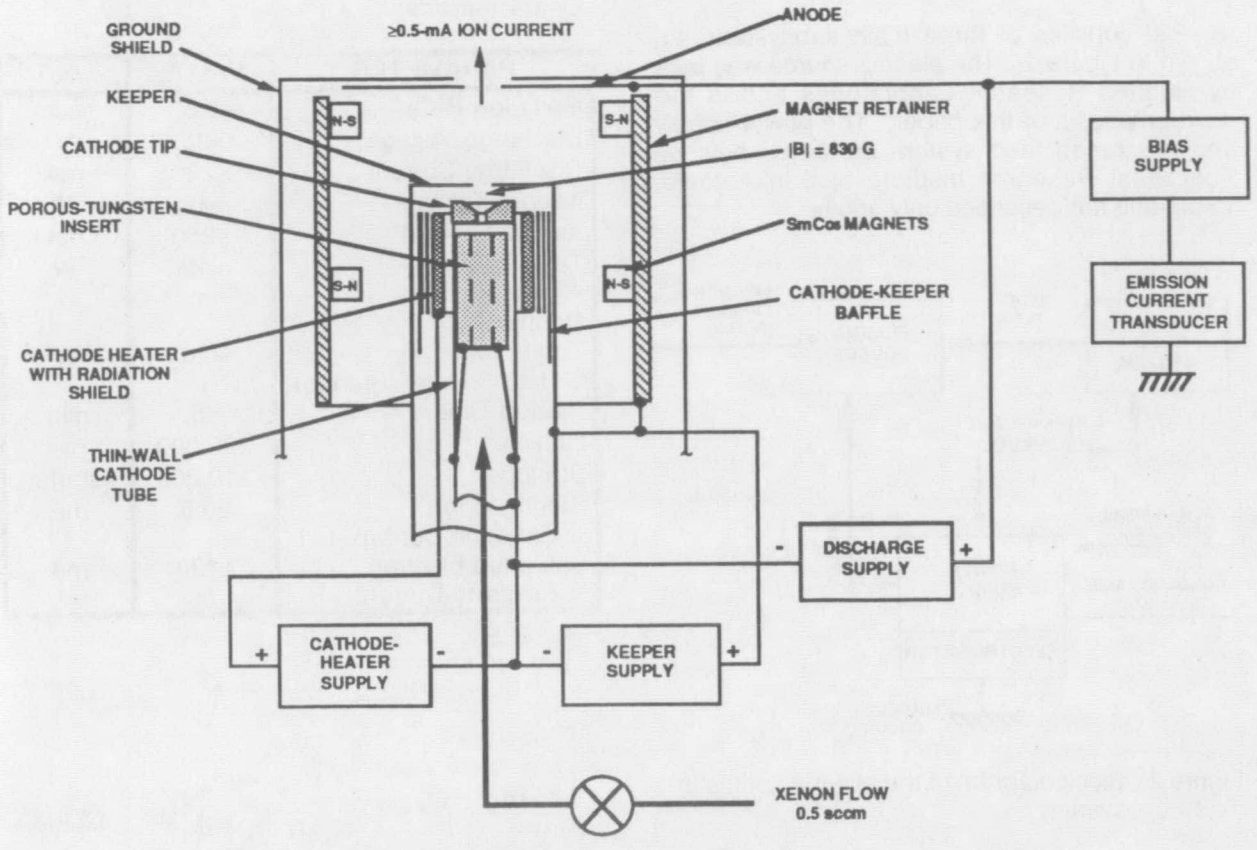


Figure 1. Schematic drawing of the plasma source.

produces a cusped-field region just upstream of the anode, affording high plasma production close to the exit aperture.

## Spacecraft Potential Control

Plasma generated within the plasma source is produced close to anode potential. As shown in Figure 1, the plasma source is electrically floating relative to the spacecraft, except for the connection from the anode, through the bias supply and emission-current transducer, to spacecraft ground. In operation, plasma emitted from the plasma source will be in the shape of a plume which is continually "torn" away from the spacecraft by its orbital motion through the ambient magnetic field. Since the plasma plume has high electrical conductivity and is in intimate contact with the ambient space plasma, charged-particle currents will flow along the plume, causing the anode to float near space-plasma potential. The bias supply can then be used to adjust the spacecraft frame potential relative to the PSI anode. This mechanism allows very precise control of the spacecraft potential relative to space; we anticipate that it will be possible to maintain spacecraft-to-space potential differences of a few tenths of a volt. The foregoing simple description of the operation of plasma contactors is being studied both in theory and ground experiments at a number of institutions.[1,2,3] The references provide deeper insight into the nature of the plasma-contacting process.

The plasma-contacting process has been amply demonstrated in the past on the ATS-6 and SCATHA spacecraft.[4,5,6] These spacecraft traversed higher-density plasmas closer to the Earth, and suffered high negative charging potentials (up to -10 kV) during eclipse. Operation of an ion thruster on ATS-6 and a small ion/plasma source on SCATHA rapidly brought spacecraft frame potentials close to space potential. Precision charge control on high-orbiting spacecraft such as POLAR has, to our knowledge, not been previously attempted.

## PLASMA SOURCE INSTRUMENT (PSI)

PSI consists of three main subsystems as shown in Figure 2. The plasma source was built by Hughes Research Laboratories and is the main emphasis of this paper. The power supply and the xenon feed system are being built by Southwest Research Institute of San Antonio, Texas and are described only briefly.

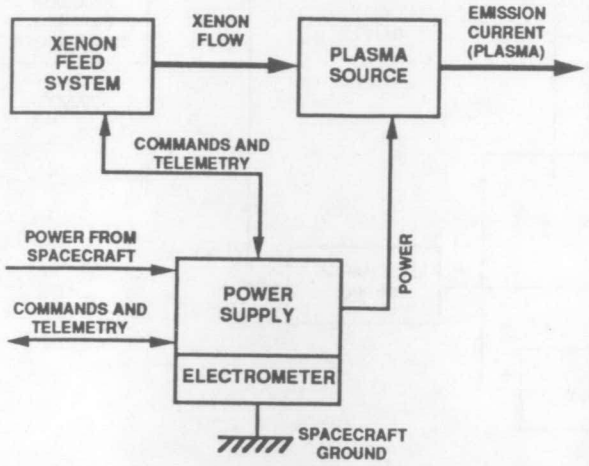


Figure 2. Block diagram of the plasma contactor system.

### Plasma Source

The plasma source used as the plasma contactor for this application is a direct derivative of the xenon ion thrusters which Hughes has been developing for the past seven years and has its heritage rooted in 32 years of ion thruster research at Hughes. It provides a medium-density ($\approx 10^{16}/m^3$), inert-gas plasma to neutralize differential charge buildup between various surfaces of the spacecraft and also to form an electrically conducting "bridge" between the spacecraft and the natural space plasma. The nominal operating characteristics of the plasma source are listed in Table 1.

A cross section of the plasma source design is shown in Figure 3. It is designed to be a hermetically sealed unit so that it can be evacuated (through a remove-before-launch cap) and operated during ground testing and spacecraft integration; however, the ISTP/POLAR mission does not require this capability. The cathode, keeper, and anode are all electrically isolated from the ground

Table 1. Plasma Source General Operating Characteristics.

| PARAMETER | VALUE | UNIT |
|---|---|---|
| Gas Flow Rate | 0.5 | sccm |
| Discharge Voltage | ≈25 | V |
| Discharge Current | ≤200 | mA |
| Keeper Voltage | ≈18 | V |
| Keeper Current | ≤250 | mA |
| Total Power (Into Source - Running) | <12 | W |
| Total Power (Into Source - Startup) | <20 | W |
| Startup Time | ≤5 | min |
| Lifetime | ≥20,000 | h |
| Startups | ≥10,000 | starts |
| Saturated Ion Emission Current | ≥0.5 | mA |
| Saturated Electron Emission Current | ≥100 | mA |

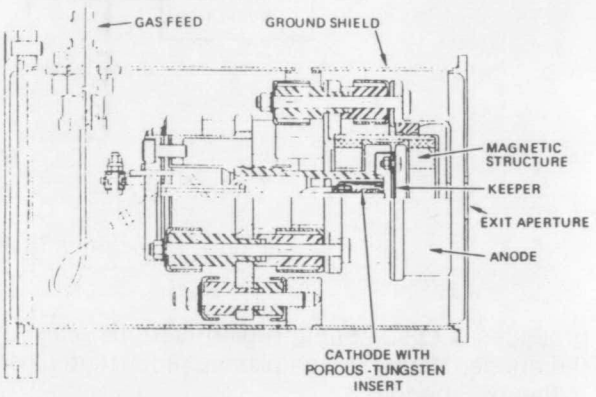


Figure 3. Cross section of the plasma source design.

shield so that the anode can be biased relative to the satellite and the return current from the satellite can be measured. The ground shield is fabricated from cold rolled steel and thus serves as a magnetic shield for the permanent magnets inside the source. External fields are <100 nT at 1 m in any direction. A photograph of the assembled plasma source is shown in Figure 4 and a photograph of the plasma source in an exploded configuration is shown in Figure 5.

The plasma source is mounted via a 9.6-cm (3.780-in.) square base with rounded corners.

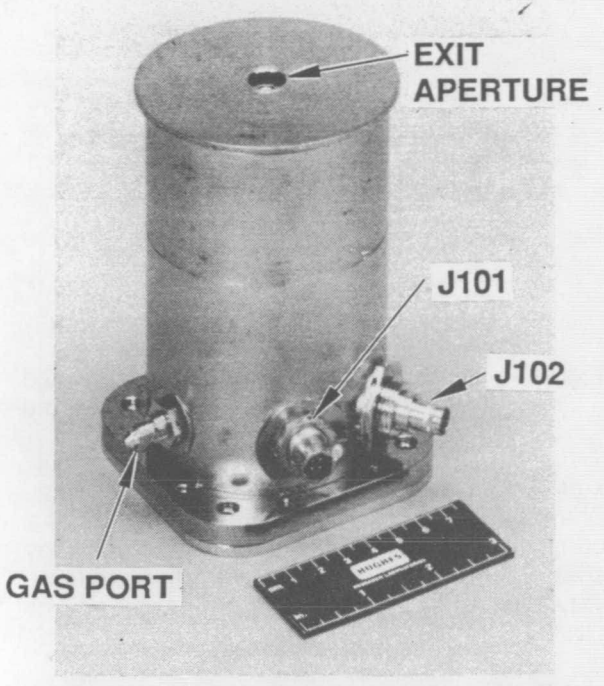


Figure 4. Photograph of the assembled plasma source.

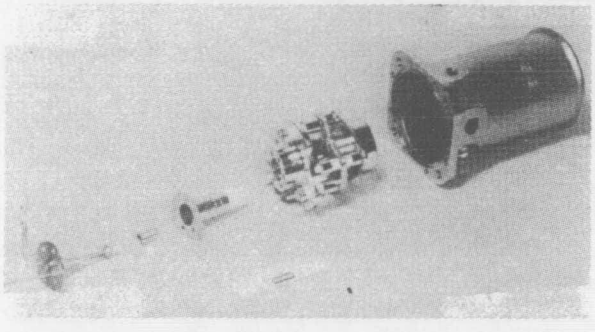

Figure 5. Photograph of the plasma source in an exploded configuration.

This base is fitted with four 1/4-28 self-locking Helical threaded inserts on a 9.83-cm (3.870-in.) diameter bolt circle and mounts with 1/4-28 screws from below. The plasma source is 13.97 cm (5.50 in.) high with a main body diameter of 8.26 cm (3.25 in.) and has a mass of 1.65 kg (weight of 3.64 lb).

Power supply connections are made to the source through two connectors; J101 and J102. J101 is a hermetically sealed 4-pin connector to carry the cathode common, cathode heater, and anode leads. J102 is a hermetically sealed high-voltage coaxial connector to carry the keeper lead. The gas feed connection to the plasma source is a 37° flared fitting per MS33656-2.

Power Supply

The plasma source requires three constant-current-regulated dc power supplies for operation; a cathode heater, a keeper, and a discharge supply. The cathode heater is used for conditioning the cathode and for heating the cathode to approximately 1000°C for startup. During cathode conditioning, the cathode heater is turned ON at 1.72 A for 3 h, turned OFF for 30 min, and then turned ON at 2.4 A for 1 h. During startup, it is turned ON at 2.4 A for a 5-min period after which the plasma source discharges (keeper and anode) are started. The heater is then normally turned OFF and normally remains OFF during operation of the plasma source since ion-bombardment causes sufficient heating to maintain thermionic emission.

The keeper and discharge power supplies are used for normal operation of the plasma source. The keeper operates at nominally 250 mA and 18 V with a maximum voltage requirement of 30 V. For startup, the keeper requires an open circuit voltage of 1000 V, falling to 30 V by the time the current rises to ≈20 mA. The discharge operates at nominally 200 mA and 25 V with a maximum voltage requirement of 40 V and an open circuit voltage of ≈100 V. The current, voltage, regulation, and ripple requirements for all three power supplies are listed in Table 2.

Table 2. Plasma Source Power Supply Requirements.

| POWER SUPPLY | OUTPUT | | REGULATION | | RIPPLE |
|---|---|---|---|---|---|
| | A | V | V or I | % | % |
| HEATER | | | | | |
| Conditioning - Low Current | 1.72 | 3.4 | I | 5 | 5 |
| Conditioning - High Current | 2.40 | 6.8 | I | 5 | 5 |
| Startup | 2.40 | 6.8 | I | 5 | 5 |
| Maximum Output | 3.00 | 10.0 | I | 5 | 5 |
| KEEPER | | | | | |
| Nominal Operation | 0.25 | ≈18 | I | 5 | 5 |
| Maximum Output | 0.25 | 30 | I | 5 | 5 |
| Open Circuit | 0.00 | 1000 | – | – | 5 |
| DISCHARGE | | | | | |
| Nominal Operation | 0.20 | ≈25 | I | 5 | 5 |
| Maximum Output | 0.30 | 40 | I | 5 | 5 |
| Open Circuit | 0.00 | 100 | – | – | 5 |
| BIAS | | | | | |
| Nominal Operation | ±1 mA | ±10 | V | 5 | 5 |

Figure 6 is a block diagram of a typical power processor for operating the plasma source. The power processor contains the discharge, keeper,

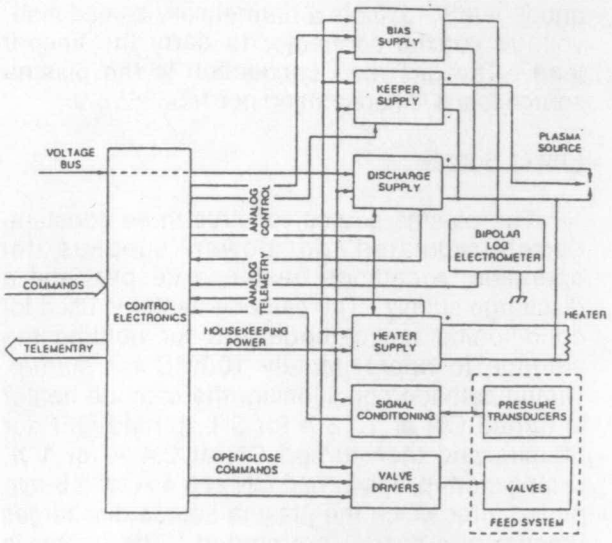


Figure 6. Block diagram of a typical power processor for operating the plasma source.

and heater supplies for operation of the source; a bias supply to control the satellite potential relative to space; a bipolar log-electrometer to measure the net emission current from the plasma source (this constitutes the return current from the satellite); valve drivers; analog telemetry signal conditioning; and the satellite command and telemetry interface.

Xenon Feed System

The plasma source requires a 0.5±10% sccm steady state flow rate of xenon while it is in operation. The gas flow can be turned ON when the plasma source is started, and turned OFF when the plasma source is shut down.

The block diagram of a typical feed system for operating this source is shown in Figure 7. The feed system consists of a storage tank, valves, pressure regulator, flow impedance, and pressure transducers to provide the source with the steady-state 0.5-sccm flow rate. The xenon tank contains 600 standard liters of xenon, which is enough for 20,000 hours of operation. The tank is fitted with a pressure transducer (to indicate the quantity of remaining xenon) and a manually operated fill valve.

The xenon flows from the tank through a high-pressure valve (which is included to save the xenon when the source is OFF if a slow downstream leak should develop) to the pressure regulator. The pressure regulator reduces the

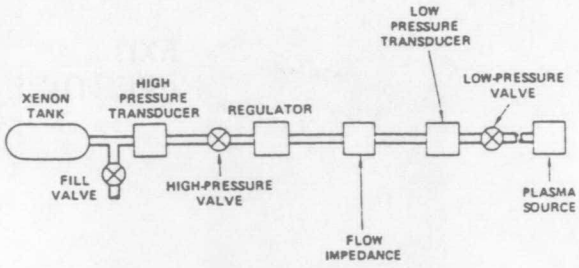


Figure 7. Block diagram of a typical xenon feed system for operating the plasma source.

xenon pressure to a constant 69 kPa (10 psia). The 69 kPa is applied to the upstream side of a constant flow impedance to maintain a steady state flow rate of 0.5 sccm. The low-pressure valve turns the flow to the plasma source ON/OFF.

The low-pressure transducer is located between the flow impedance and the low-pressure valve and is used to indicate whether the low-pressure valve is open or closed. With the valve closed the pressure builds up to 69 kPa providing an indication that the valve is closed. When the valve is open, the pressure drops to approximately zero, providing an indication that the valve is open.

## PLASMA SOURCE PERFORMANCE

The plasma source is designed for nominal operation at a keeper current of 250 mA, a discharge current of 200 mA, a flow rate of 0.50 sccm, and with the heater off. Under these conditions it produces ≈1.2-mA of net ion current. Figure 8 shows that the discharge voltage, keeper voltage, and total power into the plasma source vary only slightly over a wide range of flow rate. This figure also shows that the ion emission current increases as the flow rate decreases; this is expected since at lower flow rates the reduced neutral-gas density in the discharge allows a higher electron temperature and therefore a higher ionization rate.

The plasma source also has two other operating points that are of interest. The first of these produces ≈0.7 mA of ion emission current and is a "keeper only" mode where the discharge and heater supplies are both turned off and the keeper is operated at a current of 400 mA. The

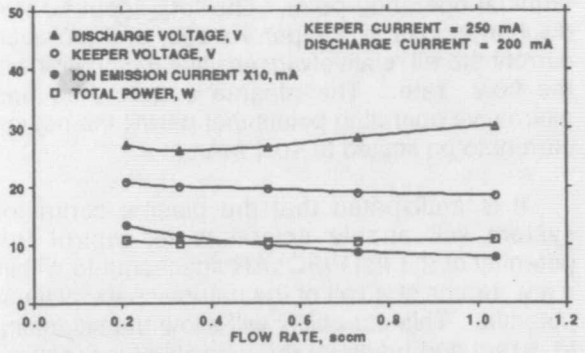


Figure 8. Variation of discharge voltage, keeper voltage, ion emission current, and total power with flow rate for the nominal operating point of 250-mA keeper current and 200-mA discharge current.

variations of the keeper voltage, total power into the plasma source, and ion emission current with flow rate for this mode are shown in Figure 9. All three parameters increase slightly as the flow rate decreases.

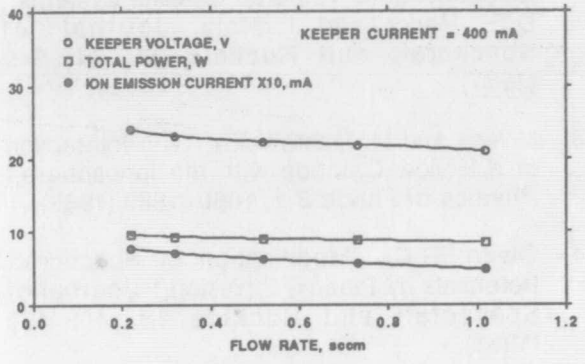


Figure 9. Variation of keeper voltage, total power, and ion-emission current with flow rate for the 400-mA keeper-only operating point.

The second alternative operating point uses the heater to supply part of the power required to keep the cathode hot, allowing the plasma source to operate at low keeper currents with the discharge supply turned off. In this mode the plasma source produces relatively low and variable ion emission current providing a means to study the control of the satellite potential with lower ion current capability. The variations of keeper voltage, total power into the plasma source, and ion emission current versus keeper current are shown in Figure 10. The heater current is constant at 1.723 A (≈7.3 W) and the flow rate is 0.51 sccm. The ion emission current varies from 0.10 mA to 0.35 mA as the keeper current is varied from 100 mA to 250 mA.

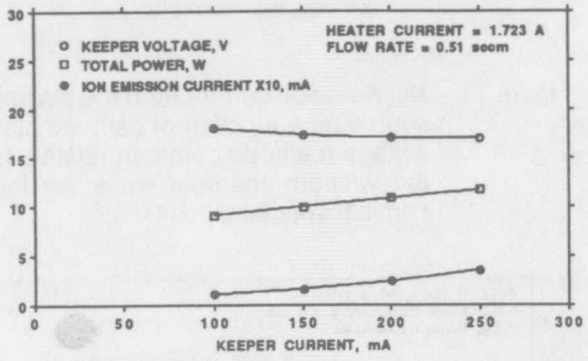


Figure 10. Variation of keeper voltage, total power, and ion emission current versus keeper current for the low ion emission current operating point (heater current of 1.723 A and discharge off).

The plasma source will also produce >100 mA of electron current for any of the described operating points. A graph of the net emission current from the plasma source versus cathode bias voltage is shown in Figure 11 for the nominal operating conditions. The figure clearly shows that the plasma source will emit at least two orders of magnitude more electrons than ions. Figure 12 is an expansion of Figure 11 to show the ion emission characteristics in more detail. Approximately 10% of the total ion current produced by the plasma source was collected by its ground shield with the remaining ≈90% going to the vacuum chamber walls. The plasma source produced a net emission current of zero when the anode was ≈20-V positive with respect to the vacuum chamber walls. Theory predicts that the anode potential required to produce a net emission current of zero in the presence of another plasma (such as exists in low earth orbit) should be within a few volts (<5) of the plasma potential of the other plasma.

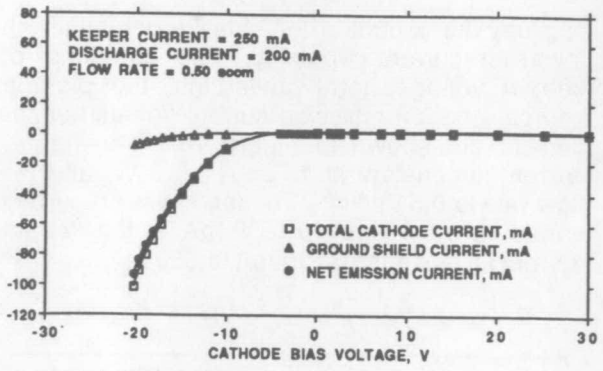


Figure 11. Net emission current from the plasma source as a function of cathode bias voltage (cathode common relative to the vacuum chamber walls) for the nominal operating point.

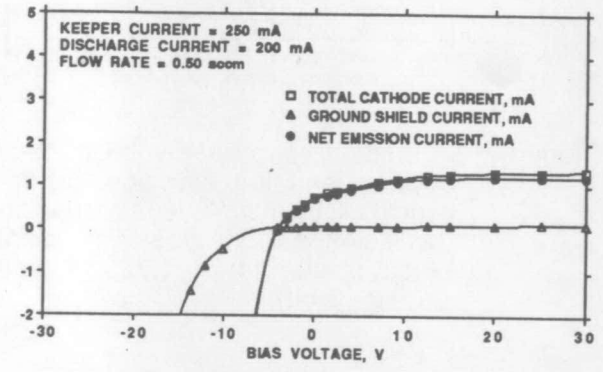


Figure 12. Net emission current from the plasma source as a function of cathode bias voltage showing the ion emission characteristics in detail.

## SUMMARY

The plasma source for a plasma contactor system for the ISTP/POLAR spacecraft has been designed, fabricated and tested. The plasma source will operate on <10-W with a xenon flow rate of 0.5 sccm. It produces >1-mA of net ion current and >100-mA of net electron current at its nominal operating point. The total input power, discharge voltage, keeper voltage, and emission current are all relatively insensitive to variations in the flow rate. The plasma source also has alternative operating points that permit the net ion current to be limited to ≤0.1 mA.

It is anticipated that the plasma contactor system will enable scientists to control the potential of the ISTP/POLAR spacecraft to within a few tenths of a volt of the natural space plasma potential. This capability will allow the scientists to detect and measure the velocity of low-energy ions that have previously been obscured by the positive potential that spacecraft normally equilibrate at in space under sunlight conditions.

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