IN-75
198074
31 P

NASA Technical Memorandum 106425
IEPC–93–246

Plasma Contactor Development for Space Station

Michael J. Patterson, John A. Hamley, and Charles J. Sarmiento
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

David H. Manzella, Timothy Sarver-Verhey, and George C. Soulas
Sverdrup Technology Inc.
Lewis Research Center Group
Brook Park, Ohio

and

Amy Nelson
Purdue University
West Lafayette, Indiana

Prepared for the
23rd International Electric Propulsion Conference
cosponsored by the AIAA, AIDAA, DGLR, and JSASS
Seattle, Washington, September 13–16, 1993

(NASA-TM-106425) PLASMA CONTACTOR DEVELOPMENT FOR SPACE STATION (NASA) 31 p

N94-18861

Unclas

G3/75 0198074

NASA

Plasma Contactor Development for Space Station

Michael J. Patterson*, John A. Hamley*, and Charles J. Sarmiento*
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

David H. Manzella, Timothy Sarver-Verhey, and George C. Soulas
Sverdrup Technology Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

Amy Nelson
Purdue University
West Lafayette, Indiana 47907

Plasma contactors have been baselined for Space Station (SS) to control the electrical potentials of surfaces to eliminate/mitigate damaging interactions with the space environment. The system represents a dual-use technology which is a direct outgrowth of the NASA electric propulsion program and in particular the technology development effort on ion thruster systems. The plasma contactor subsystems include the plasma contactor unit, a power electronics unit, and an expellant management unit. Under this pre-flight development program these will all be brought to breadboard or engineering model status. Development efforts for the plasma contactor unit include optimizing the design and configuration of the contactor, validating its required lifetime, and characterizing the contactor plume and electromagnetic interference. The plasma contactor unit design selected for SS is an enclosed keeper, xenon hollow cathode plasma source. This paper discusses the test results and development status of the plasma contactor unit subsystem for SS.

Introduction

The Space Station (SS) power system is designed with high voltage solar arrays which operate at output voltages of typically 140-160 volts. The power system is configured with a "negative ground" that electrically ties the habitat modules, structure, and radiators to the negative tap of the solar arrays. The solar arrays represent a large surface area for electron current collection from the space plasma due to exposed surfaces along the solar cell edges. These surfaces are at positive potentials, relative to the negative ground, up to the maximum array potential. The exterior surfaces tied to the negative array tap, however, are insulated from the space plasma because the radiators are coated with non-conducting high-emissivity paint and the habitat modules are coated with an anodized layer for thermal control. This electrical configuration and the plasma current balance that results will cause the habitat modules, structure, and radiators to float to voltages as large as -120 V with respect to the ambient space plasma (Figure 1).[1]

As a result of the large negative floating potentials, there exists the potential for deleterious interactions of SS with the space plasma. These interactions may include arcing through insulating surfaces (both spontaneous and debris induced) and sputtering of conductive surfaces due to acceleration of ions by the spacecraft plasma sheath. Both of these processes result in changes in surface material properties, destruction of coatings, and contamination of surfaces due to redeposition. Additionally there is concern that the arcing will result in conducted and radiated electromagnetic interference (EMI) and/or SS power system current surges and power loss.

A variety of solutions were identified to alleviate/eliminate the potentially deleterious interactions

*Aerospace Engineer, Member AIAA

with the space plasma, including modifying the solar cell design or surface coatings and/or adding a plasma contactor system. Each of these options was proposed as a means of either increasing the impedance for electron collection on the solar array or increasing the ion conduction of the plasma sheath surrounding the structure. Both modifications would drive the negative potential surfaces closer to space plasma potential and possibly below the threshold voltage for arcing to occur. Based on potential effectiveness and impact on the SS flight program cost and schedule, a decision was made in April 1992 to baseline a plasma contactor system on SS as the solution to alleviate SS/space plasma interactions.[2] NASA-Lewis Research Center (LeRC)/Work Package (WP) 4 was therefore directed to initiate a plasma contactor development program as part of the SS electrical power system.

A plasma contactor is a device which can control the spacecraft potential relative to the local space plasma potential by establishing a low-impedance plasma bridge. There are a variety of plasma contactor types which vary in the level of design maturity, effectiveness, complexity, and operational requirements. Contactor types include electron and ion guns, passive conducting surfaces, neutral gas releases, and a variety of plasma sources including pulsed magnetoplasma dynamic (MPD) devices[3] and hollow cathode plasma sources.[4]

For the SS application, efficient and rapid emission of high electron currents is required by the plasma contactor under conditions of variable and uncertain current demand. A hollow cathode plasma contactor is well suited for this application. Most work to date with hollow cathodes was accomplished with mercury as the hollow cathode expellant, or "working fluid." For a variety of reasons, including ground facility and spacecraft contamination, present hollow cathodes preferentially utilize inert gases (primarily xenon) as the expellant. Subsequent to the transition from mercury to xenon in the early 1980's, there have been, and continue to be, failures of hollow cathodes in the United States, in Europe, and in Japan. These have impacted both research and development activities and flight programs. The failures have apparently been primarily due to inadequate procedures and protocols to control contamination during fabrication, assembly, testing, storage, handling, and operation of the cathodes. To date only one extended-duration test of a xenon hollow cathode at high () 1 A) emission currents has been reported which has not suffered large deviations in performance which are likely attributable to contamination.[5]

The operational requirements for the SS plasma contactor are extremely demanding and go well beyond the current state-of-the-art for xenon hollow cathodes. These requirements include a 17,500 h lifetime and electron emission currents that vary from a few hundred milliamperes to up to 10 A with complex, time-dependent dynamic response characteristics. Additionally, the plasma contactor is on a crewed vehicle and is considered a mission-critical system requiring single-fault tolerant reliability. These considerations dictated initiation of a plasma contactor development effort, including a hardware definition and testing task.

Development Objectives

As identified in Table I, the SS plasma contactor system (PCS) consists of four subsystems including the plasma contactor unit (PCU), the power electronics unit (PEU), the expellant management unit (EMU), and the orbit replaceable unit (ORU). Figure 2 shows a conceptual design lay-out for the plasma contactor system. Figure 3 illustrates the interdependence of each of the contactor subsystems, and their dependence on externally-imposed design and operational requirements.

The hardware definition and testing task is responsible for: (1) parametric testing of plasma contactor unit and system components, (2) establishing design requirements for a long endurance plasma contactor system, and (3) acquiring long term endurance data for components and systems to support flight hardware development. The specific hardware development objectives include:

Development of the plasma contactor unit (PCU) to engineering model status. The PCU, which is the active electron emitter source, will be brought to a sufficient level of maturity to make the flight hardware development a build-to-print effort.

Development of the power electronic units (PEU) to breadboard level. The PEU consists of the power supplies for operation of the PCU and the gas feed system valves, and a controller for command and telemetry. The flight PEU could be developed with any one of several topologies, and the approach of bringing the PEU to only a breadboard level in the in-house effort allows for flexibility in the flight hardware design. Areas being addressed in the PEU development include definition of the critical interfaces and control functions with the PCU, gas feed system, and with SS, and identification of control laws and requirements for autonomous, fault-tolerant system functions.

Development of the expellant management unit (EMU) to breadboard level. The EMU consists of a high-pressure gas storage tank, the xenon expellant, and gas feed system components including lines, valves, and regulators. Areas being addressed in the EMU development include definition of the xenon flow control requirements, and contamination control requirements and limits.

The fourth subsystem, the ORU, is a standard SS avionics box which provides the structural, thermal, electrical, and data interfaces, as well as providing micrometeoroid protection. This subsystem will be provided by the prime contractor responsible for PCS integration.

Table I lists the technology issues associated with each of the major PCS components and identifies the functions and hardware phase each component will be developed to under the hardware definition and testing task. In addition to these specific hardware objectives, numerous performance, integration, and lifetime tests will be conducted on components, subsystems, and systems to verify functionality and support the flight hardware development task.

Operational Requirements

Under the directive provided to WP 4 to develop a plasma contactor for SS, the single primary design requirement is stated that "the Space Station structure floating potential at all points on the Space Station shall be controlled to within 40 volts of the ionospheric plasma potential using a plasma contactor."[6] The 40 volt potential is estimated to be below the threshold potential for arcing to occur. It is estimated that induced potentials on the station, caused by the structure cutting through the Earth's magnetic field, may be as high as 20 volts.[7] This reduces the operating margin available to the plasma contactor to approximately 20 volts to satisfy the 40 volt limit.

The PCU will achieve potential control of SS by having the cathode emitting potential of the PCU electrically tied to the negative single-point ground of the SS main truss segment, as illustrated in Figure 4. This arrangement allows for the emission current to rapidly track the variable and uncertain current demand

The plasma contactor system must be single-fault tolerant because the potential control function is considered mission critical. This requirement will be satisfied by having two completely independent plasma contactor systems co-located on the SS main truss segment, one operating and one as a back-up.[8] Each system will have a single-string PCU-PEU-EMU architecture and will be housed in separate ORU avionics boxes, with separate interfaces to SS. Additional requirements for the PCS include an operating lifetime of 17,500 hours and instrumentation to monitor the PCU emission, or plasma return, current.[8]

The electron emission current requirements for the PCU to control SS potentials unfortunately cannot be characterized by a "typical" emission profile versus time. However bounds on the requirements may be drawn from the following considerations:[9]

Active emission to the space plasma of electron current at least matching the net electron current collected on the spacecraft (referred to as "clamping" mode) is required during approximately one-third of the orbital period, from dawn through noon when the solar arrays are illuminated, generate power, and face in the ram direction. During the remainder of the orbital period the plasma contactor unit will remain on, operating in an "idle" mode.

The plasma contactor system is scheduled to be launched in-place on mission build (MB) 4, which is the launch of the main truss segment. As the space station evolves during the build-up phase, additional solar array wings will be added until the station is completely assembled by MB 17 with a total of 6 wings. As the station is undergoing construction, and as its flight attitude is changed with respect to the velocity vector, the peak emission current required will increase due to higher generated power levels and larger surface areas exposed to electron current collection. The maximum required emission currents are expected to scale as the array area. Hence, the anticipated peak emission current at the permanently-manned capability (PMC) at MB 17 with 6 solar array wings is anticipated to be 6 times greater than that required during MB 4 which has one deployed wing.

The peak emission current may vary by a factor of two from orbit to orbit and by a factor of five from day to day, during any portion of the station operations (build-up or PMC).

Models describing the required dynamic behavior of the emission current (principally, the rise and decay times during active emission) cannot time-resolve the current variations below approximately one minute intervals with any certitude. However, large variations (> 10%) in required emission current are not expected to be on time scales less than tens to hundreds of seconds, except during entry into and exit from eclipse periods.

Any predicted emission current is estimated to have a factor of four uncertainty due to the combined uncertainties in estimating the station surface area for electron current collection and predicting the ambient space plasma properties.

From these considerations, a requirement was derived that the PCU be capable of emitting 10 A of electron current to the space plasma. This and other major derived operational requirements for the SS PCS are listed in Table II. Figure 5 shows the required time-dependent electron emission current predicted for the plasma contactor unit during MB 6 for a single orbit under solar maximum conditions.[10]

Technical Approach

An extensive series of tests of all PCS subsystems is underway at NASA-LeRC and at Georgia Technology Research Institute (GTRI).[11] These tests include hollow cathode and other PCU component performance and wear tests of successively longer duration to resolve cathode design, materials, and contamination issues. PCU performance, design optimization, and life tests are being conducted under appropriate operating and environmental conditions. System-level integration tests and assessments of plume, optical, and EMI emissions of the contactor unit and system are being carried out. Also, PEU development and PCU-PEU integration efforts are proceeding, and EMU requirements are being defined and validated.

The objective of the GTRI effort is to provide quantitative information regarding the interaction of the low work function impregnated insert of the plasma contactor hollow cathode with the ambient environment in which it is manufactured, handled, assembled, and stored. Also under evaluation is the insert's interaction with the operating environment of the cathode including effects of the expellant gas, including impurities contained in it, and the thermal conditions prevailing during all modes of operation. These studies will define critical specifications for xenon gas purity, the cathode insert activation procedure, and control of ambient conditions during PCU assembly and pre-launch storage and handling. This program also addresses the development of appropriate specifications for the fabrication of the flight inserts.

This paper discusses the test results and development status of the SS PCU. Detailed discussions of the development status of the PCU components such as the cathode and heater, and of other subsystems including the PEU can be found in companion publications.[12-14]

First-Order Considerations

Source Type

As mentioned previously, the SS application requires rapid emission of high electron currents under conditions of variable and uncertain current demand. A hollow cathode plasma contactor is well suited for this application. Hollow cathode plasma contactors have a demonstrated low impedance and high current capability and they operate in a self-regulating emission control mode. They are acknowledged to be the optimal charge-control concept for electrically active spacecraft by the spacecraft-charging community.[15-17] Additionally, this type of contactor device has demonstrated potential control of SS structures (a 1/82 scale solar array wing, a full-sized solar array circuit, and small scale anodized plates) in ground testing at NASA-LeRC under simulated space plasma conditions. The hollow cathode plasma contactor effectively clamped the electrically floating structures to within a few volts of plasma ground, prevented arcing on the structure, and operated in a stable manner.

The hollow cathode is the key element of the hollow cathode plasma contactor. Hollow cathodes have been developed to an advanced state of technology readiness for ion propulsion. In ground tests they have demonstrated high emission currents ($>$ 30 A), long lifetimes (with mercury propellant), and modest ($<$ 100 W) power requirements. Hollow cathode plasma sources have demonstrated versatile and effective operation as plasma contactors in ground testing of various devices. This testing includes plasma bridge neutralizers for ion thrusters, plasma contactor demonstration experiments for the electrodynamic tether,[18] and the aforementioned SS structure potential control experiments.

Hollow cathodes have also been flown in space as components of ion propulsion systems and spacecraft charging/charge-control systems, including ATS-6[19], SERT-II[20], SCATHA[21], and SCSR-1[22] flight experiments. Demonstrated capabilities in space tests include lifetimes of 10,000 h and $>$ 300 restarts.[23] NASA flight experiments have demonstrated hollow cathode plasma contactors to be effective in controlling both spacecraft frame negative charging[20] and differential charging.[19] Hollow cathodes have been operated in space under a variety of orbital/environmental conditions, on spacecraft including an Agena vehicle, communication satellites, and the space shuttle. Environments include those of low-Earth orbits, sun-synchronous high inclination orbits, and geosynchronous orbits. For these reasons, a hollow cathode plasma source has been selected for the SS PCU.

The PCU will contain a hollow cathode consisting of a low-work function insert for electron emission, a body tube with a heater, and an electrical isolator. Additional components include anode(s), expellant injector(s), and possibly magnets to augment ionization efficiency and reduce the expellant consumption rate.

The hollow cathode itself consists of a tube with a welded orifice plate on one end. 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, serves as a low-work function electron source, and is electrically connected to the tube. Operation of the hollow cathode is initiated by turning on the expellant which flows through the tube and out the orifice into the downstream region of the hollow cathode. This flow establishes a pressure within the hollow cathode that is of the order of 10 torr. A typical starting sequence for a hollow cathode source involves biasing an anode downstream of the cathode to a few hundred volts positive of the cathode. The hollow cathode heater is energized and raises the cathode insert to thermionic emission temperatures so as to remove contaminants from the insert surface and to facilitate ignition. Thermionic electrons flow through the cathode orifice toward the anode and have ionizing collisions with the high density gas within the hollow cathode tube. This results in the production of a high density plasma within the cathode tube. Electrons flow through the cathode orifice to the anode, while ions, unable to negotiate the adverse potential difference across the orifice plate are drawn to the cathode insert. Ion bombardment heats the insert, and it is then possible to turn off the cathode heater.

Electrons that flow through the orifice are collected by the anode, and in the process, collide with neutral atoms flowing through the cathode orifice thereby producing a plasma downstream of the hollow cathode. It is this plasma production that facilitates the low impedance and high electron emission current capability of these devices.

As an ion production device, the hollow cathode is quite inefficient because the low density neutral gas escaping from the orifice has a low probability of being ionized. Additionally, much of the electron current collected on the anode does so without undergoing ionizing collisions. By appropriate anode design (location and geometry), application of magnetic fields, and use of multiple expellant injection sites, significant (10-100 X) improvements in the ionization efficiency of the hollow cathode can be realized, with benefit of reducing the expellant consumption rate for a given electron emission current.

By placement of a positively-bias electrode downstream of the hollow cathode source, electron current can be drawn from the hollow cathode plasma. In the case of the SS application, the downstream electrode is the space plasma which draws electron current from the negatively-biased PCU hollow cathode.

Expellant Selection

A number of considerations were taken into account for the selection of the expellant, or "working fluid" for the hollow cathode plasma contactor. The selection of the expellant has both implications for the PCU subsystem level, as well as other subsystems, and the system in total.

An over-arching consideration of course is that the expellant be non-contaminating and non-reactive with SS systems. Additionally, it must be compatible with the functional requirements of the hollow cathode. These considerations alone reduce the available options to the inert gases argon, krypton, and xenon. Xenon was selected because it's characteristics result in reduced mass flow rates (see Fig. 6), modest starting requirements, and reduced steady-state electrode voltages as compared to the other gases. These and other considerations leading to the selection of xenon are listed in Table III.

Operating/Control Mode

Active emission from the PCU is required for only a small portion of the orbital period. The option to operate the PCU continuously or only during periods requiring active emission is realized. A trade study was therefore conducted to look at continuous versus cyclic operating mode. For purposes of this study, it was assumed that for a contactor operating in a cyclic (on/off) mode, both the power and xenon gas would be cycled on/off. Additionally it was assumed that a contactor must be operational during each orbital period, and that the period of active emission is approximately one-third of a 90 minute orbit, or approximately 6000 accumulative on/off cycles per year.

Based on the results of the study, a decision was made to select a continuous mode of operation for the SS PCU. Although cyclic mode operation permits a reduction in the expellant consumption rate, it would accumulate a total number of thermal cycles 2 to 4 times greater than that previously demonstrated with similar, relevant hollow cathode technology. Additionally, cyclic mode operation would require a cue from another SS system element to ensure that the PCU operation be kept synchronous with the current demand.

A basic control mode was selected to minimize complexity and risk. In addition to continuous operation of the PCU, features of this basic control mode include:

steady-state, single-set-point expellant flow rate and anode current to the PCU with no throttling;

no active feedback loops on PCU operating parameters for expellant flow rate or input power control;

no active feedback loops on PCU operating parameters or emission currents from measurements of SS floating potentials; and

a high degree of system autonomous operational capability to maintain operations and detect and resolve failures.

Electrical Interface

The PCU will be electrically connected to SS as illustrated in Fig. 4. Additionally the PCU and contactor system design will accommodate monitoring and measurement of the PCU emission currents to space plasma. This will be accomplished by placing a low-voltage electrical isolator between the PCU and the grounded contactor system. This will permit measurement of the return current passing through a ground strap between the PCU and the SS single-point ground via current sensors in the power electronics unit. As there will be no plasma diagnostics package aboard SS, these data will be of value in establishing collateral evidence of SS potential control.

Additionally this data may be of value in correlating ground and space performance and life of the PCU. These first-order considerations in the design and operation of the PCU are summarized in Table IV.

Apparatus and Procedure

A prototype PCU test program was initiated to establish a baseline design approach and operating requirements for the SS PCU. This activity was initiated in parallel with several others, including PCU component, and PEU and EMU development efforts.

The results shown here were obtained at the NASA-LeRC tank 5 facility which is described in the appendix. For all tests, the xenon pumping speed of the facility was approximately 110,000 ℓ/s resulting in background pressures of $\leq 2 \times 10^{-6}$ torr. The electrical configuration of the tests is shown in the schematic of Figure 7. Two power supplies are used for the operation of the PCU including the heater supply (used in starting only), and the anode power supply. In steady-state operation, an electron current of fixed magnitude (referred to here as the anode current) passes from the PCU cathode to anode and is circulated through the anode supply. For most performance tests, commercial power supplies were used to operate the PCU. Some tests, including those to quantify radiated and conducted electromagnetic emissions, used the breadboard PEU, a description of which may be found in references 11 and 14.

An additional power supply, labeled as the bias supply, is used to vary the potential between the PCU and facility ground, and simulates the potential established between SS structures and space plasma. To quantify the electron emission capability of a PCU, the PCU cathode is biased negative with respect to facility ground, causing electrons produced by the PCU to be emitted from it and collected at the vacuum tank walls. This electron current is referred to here as the contactor emission current, and is, in space, equivalent to the electron current emitted by the contactor which was collected by the SS solar arrays depicted in Figure 7. The potential difference between PCU cathode and facility ground is referred to as the clamping voltage. When the contactor emission current is zero but the PCU cathode is emitting to the anode, the PCU is operating in an idle mode. When the contactor emission current is non-zero, the PCU is operating in a clamping mode.

To approximate the ion production rate of the PCU, the PCU is biased positive with respect to facility ground at PCU anode, with the ion current generated by the cathode-to-anode discharge collected at the vacuum tank walls. A more quantitative measure of the ion production rate requires use of an electrostatic probe. This is because the biasing technique has two potential sources of error. The potentials established in the region of the PCU by biasing positively with respect to the facility are different than during normal operation. Hence some ion current which would normally recombine on cathode potential surfaces may exit the PCU. Also, under clamping mode operation, the contactor electron emission current itself may contribute to the ion production rate of the source.

The approach used to develop the PCU was to design a hollow cathode plasma source that would accommodate both the electron emission current requirement (magnitude, range, and variation), and the ion production rate. The ion production rate has generally been considered a measure of total plasma production, with the ions serving to reduce the space charge, permitting large electron currents to flow at low potentials. Because the ion production rate was an unknown, two alternative PCU source types were pursued, with some expectation that both designs may satisfy the SS operational requirements. The two source types, depicted in Figs. 8 and 9, are an enclosed-keeper design, and a ring-cusp design. The fundamental distinction between the two types is a factor of 10 to 100 difference in their ion production efficiencies.

Both designs incorporate a hollow cathode and operate with a single anode in a diode configuration, but this is where the similarities end. The enclosed-keeper design incorporates a cylindrical anode which surrounds the hollow cathode in close proximity (1 to 2 mm). The anode is referred to as the keeper as it maintains, or keeps, the cathode emitting during conditions when no external emission current is demanded. The keeper is described as enclosed because it completely encapsules the hollow cathode except for a single aperture directly downstream of the hollow cathode orifice. This design is more efficient than an open-keeper geometry because of the higher internal pressures in the cathode/keeper region. Sources of this type have ion production rates of about 3 - 30 mA, with ionization efficiencies typically of less than 5%. They are simple and robust in design, and are typically used as high current (up to 3 A) electron sources in applications such as neutralizers for ion thrusters, and in ground-based space plasma simulation.

Unlike the enclosed-keeper design, the ring-cusp design incorporates magnetic fields to enhance its ionization efficiency. The ring-cusp design is derived from a highly efficient plasma containment scheme developed and used in ion thrusters.[24] This source uses the same hollow cathode geometry as that used in the enclosed-keeper design, but instead of a keeper anode, a cylindrical anode shell referred to as the discharge chamber is used, typically located 2 cm or more radially from the hollow cathode. (For this investigation, discharge chambers ranging form 7.6 cm to 11.4 cm in diameter were tested). The device derives its name from the shape of the magnetic field within it. The magnetic field is created by permanent magnets arranged in rings of alternating polarity located along the back and sides of the anode potential discharge chamber. The discharge chamber serves to confine the neutral expellant fed into it so that it must exit from the downstream end of the contactor. Unlike the enclosed-keeper design, only a small portion (typically 5 - 10%) of the expellant is fed through the hollow cathode, with the majority of the expellant fed through a main flow plenum. Typical ion production rates for this type of source are from 50 mA to several amperes, depending upon the size of the source, with ionization efficiencies ranging from 10 to 90%.

Test Results

The operation of the PCU can be characterized by several parameters which are important to its performance and lifetime. These include the clamping voltage, anode voltage and current, xenon consumption rate, contactor emission current, and input power.

Initial tests were conducted to define procedures and requirements to gain confidence in the transportability of the PCU emission characteristic from the ground test facility to the space environment. While a detailed discussion of these results is beyond the scope of this report, it is noteworthy that there are environmental and scaling effects which may impact the test results. These effects include the proximity and geometry of the external anode simulating the current draw to the space plasma, and the background neutral density. These impacts become more pronounced at higher contactor emission currents, and can be mitigated by conducting the testing in a large vacuum chamber where the PCU-collector distances are of the order of ≥ 2 meters, and the background pressures are a few 10^{-6} torr or less (which requires typically 〉 50,000 ℓ/s xenon pumping speed). Under these conditions, the PCU test results appear independent of whether or not additional plasma sources are concurrently used to generate a simulated background space plasma environment.

Design Selection/Optimization

The performance of approximately 15 different prototype plasma contactor units, 3 of the enclosed-keeper type and 12 of the ring-cusp type, were measured to determine the critical design and operating parameters governing the potential control characteristic. All of the contactors exhibited the vertical emission current characteristic seen in Figure 10 at currents up to 10 A when each was operated above a minimum threshold mass flow rate.

These tests indicated that when the PCU is operated in a clamping mode, the contactor emission current significantly enhances the PCU ionization efficiency. That is, both the fixed electron current to the anode and the contactor emission current contribute to ionization of xenon gas within the PCU. This enhanced ionization results in a rapid increase in current with voltage, which then eventually saturates when most neutrals are ionized. This is supported by several observations. The ability of a given PCU to emit amperes of electron current at low clamping voltages appears more sensitive to its mass flow rate than its ion production rate as generated by the anode discharge. Additionally, a high luminosity blue plume is emitted from the PCU during clamping mode operation, indicating enhanced ionization via contactor emission electrons. The intensity of the plume increases with increasing emission, and direct measurement of Xe(II) transitions have confirmed this enhanced ionization. These observations and data are in agreement with an analytical model of electron emitting contactors[25].

A few observations were pivotal in the down-selection of a SS PCU design approach. Firstly, there were no significant (within 20%) differences in the minimum mass flow rate for any of the contactors and it appears to be fairly insensitive to PCU design and anode discharge ion production rate (over a range of 3 to 100 mA investigated). This is believed to be due to the fact that the contactor emission current significantly enhances the ionization of the xenon gas. A second observation was that the magnitude of the clamping voltage varies directly with the PCU anode voltage, and not the anode discharge ionization efficiency or production rate. For example, the PCU design which exhibited the highest discharge ionization efficiency and lowest mass flow rate, also exhibited the highest anode voltages, which resulted in high (〉 20 volts) clamping voltages. This behavior is predicted by an analytical model[25] and is believed to be associated with the PCU plasma electron temperature and its dependency on the anode voltage.

The over-riding considerations in PCU selection were to design a PCU which satisfies the potential control requirement (≤ 20 volts clamping voltage) and maximizes expectations for long life. While minimizing consumables (xenon gas and power) is important, this is secondary to potential control and life. Additionally, however, a low clamping voltage at all emission currents is not an adequate sole measure of PCU viability. A down-selection of a baseline contactor design was therefore made between the ring-cusp and enclosed-keeper types. Table V summarizes the criteria for PCU selection and the relative rating for the two types. For all but the system mass, the enclosed-keeper type PCU holds a clear and distinct advantage over the other design. The typical xenon consumption rates for the enclosed-keeper type contactors were on the order of 5-10% higher than that of the ring-cusp designs. However the added complexity associated with the ring-cusp type EMU subsystem, as illustrated in Fig. 11, may negate any marginal system mass advantage this design has. Based on the criteria identified in Table V, a recommendation to select an enclosed-keeper PCU design for the SS application was forwarded to station management, and this recommendation was accepted and approved.

Subsequent to the down-selection of the enclosed-keeper type PCU, a second series of tests were initiated with prototype hardware. These tests were conducted to finalize critical PCU design parameters, quantify xenon flow rate requirements, demonstrate unit-to-unit repeatability, and begin PCU-PEU integration testing.

Figure 12 shows the typical emission current characteristics for the baseline prototype PCU design as a function of xenon mass flow rate. As indicated, the PCU exhibits low clamping voltages (⟨ 20 volts) for xenon mass flow rates down to about 16.3 kg/yr, or equivalently 5.3 sccm. Below this mass flow rate, at 15.7 kg/yr, the clamping voltage increases above 20 volts for emission currents greater than 2 amperes, but then collapses above 5 amperes contactor emission current due to gas breakdown. At 11.9 kg/yr, the electron emission current is limited by the gas flow rate, and the clamping voltage rapidly increases above 20 volts for emission currents greater than approximately 1.8 A. Typical anode voltages for the range of indicated flow rates, with no contactor emission current, were from approximately 15 to 18 volts. At these conditions, the ion production rate generated by the anode discharge is approximately 10 mA.

The data of Figure 12 were obtained at a fixed anode current of 2.0 A. This current level was selected to maintain the hollow cathode operating temperature in the range of 850-1150 degrees centigrade over the full range of contactor emission currents of 0 to 10 A. This rather high current reduces the total required hollow cathode emission range to a 6:1 variation (from 2 to 12 amperes). It would be advantageous to reduce the fixed anode current to 1.0 A or less, but this would require a reduction in the uncertainty, and magnitude, of the maximum predicted contactor emission current.

Figure 13 shows the variation in PCU input power with emission current, and it indicates approximately a 50% reduction in power going from 0 to 10 A contactor emission current. This is due to a corresponding reduction in anode voltage experienced with increased net hollow cathode emission. While the input power to the PCU and PCS decreases with increasing contactor emission, the power drain on the SS power system (the product of the contactor emission current and the clamping voltage) is increasing. Figure 14 compares the emission data obtained with two prototype plasma contactor units of comparable design, and good repeatability of performance is noted.

Several tests of prototype PCU's have been conducted with the breadboard PEU. The PEU has successfully demonstrated hollow cathode preheat, PCU ignition, and steady state operation of the PCU up to a 10 A net electron emission current.

Lifetesting

Lifetests of PCU components were initiated and are continuing. Several new cryopumped test facilities have been developed to support these efforts, and these are described in detail in the appendix.

The primary emphasis in component lifetesting to date has been to develop and validate procedures and protocols to eliminate contamination effects as the life-limiting agent for xenon hollow cathodes. These studies are to define the xenon gas purity, the cathode insert activation procedure, and the controls on ambient conditions during PCU assembly and storage, that will be implemented with the SS flight hardware. On-going wear tests appear to have validated these procedures. A xenon hollow cathode, of the design employed in the PCU, has demonstrated to date approximately 4600 hours of steady-state operation at 12 A emission current.[12] The test is progressing uneventfully with negligible change in parameters critical to lifetime. This test is nearly an order-of-magnitude longer than any previous test which has not shown performance variations attributable to contamination. Additionally, no significant changes in the cathode starting characteristics, or external structural condition, have been observed. This test will continue in order to demonstrate a significant lifetime against that which is required for the PCU.

Additional lifetests of hollow cathodes have been initiated to verify procedures, demonstrate transportability of results between test stands, and provide quantification of contamination control requirements imposed on the EMU. A concurrent lifetest of 4 hollow cathodes has accumulated approximately 400 hours to date, with all cathodes operating at a steady-state emission current of 10 A. Two of the cathodes employ active gettering systems incorporated in the xenon feed system, and 2 cathodes are operating without gettering systems. Excellent unit-to-unit repeatability has been observed from externally-measured parameters (cathode tip temperature, and voltages, for example), and no variations in performance attributable to insert contamination have been observed with any cathodes to date. The test is scheduled to continue for a maximum of a few thousand hours, at which time destructive examinations of the cathodes will be conducted to evaluate insert conditions. This test stand will then be used for lifetesting of engineering model plasma contactor units under conditions simulating the time-dependent emission current profiles expected on orbit. These tests will be used to verify PCU lifetime, including the integrity of the braze and weld joints.

The heater design used in the PCU hollow cathode assembly has also undergone a series of lifetests.[13] The first of several engineering-model units has been tested in a cyclic on/off mode, completing nearly 6000 thermal cycles, simulating 6000 PCU restarts. Because the SS PCU will be operated in a continuous mode, this total accumulated number of cycles is approximately 100 times greater than that required for qualifications and acceptance testing of the protoflight and flight units. To date, two additional heaters are undergoing cyclic lifetesting, each having accumulated more than 2500 on/off thermal cycles.

SS EMI Compatibility

The baseline prototype PCU was tested in conjunction with the breadboard PEU to characterize the PCU radiated and conducted electromagnetic emissions. These tests were performed to obtain a first look at the magnitude of the PCU emissions and its compatibility with space station EMI requirements. An additional goal was to determine the influence of the test configuration (isolation versus exposure of the antennas to the PCU plasma) to define appropriate EMI test procedures that would be implemented in characterizing the protoflight and flight hardware.

The EMI tests were conducted with the enclosed-keeper prototype PCU operating in the tank 5 vacuum facility at background pressures of approximately 2.0×10^{-6} torr. The procedures used for the EMI tests were based on MIL-STD-462. An array of 9 antennas covering the frequency range of 14 kHz to 18 GHz was used, with the antennas positioned in a semi-circle located one meter behind the PCU with the PCU plume directed away from the array. Three operating conditions were investigated (zero emission current idle mode, and 0.5 A and 2.0 A emission current clamping modes), using each of two EMI antenna configurations (with and without plasma shielding over the antennas). The results indicate:

With the antennas covered, the measurements over a 14 kHz - 18 GHz range show that the enclosed-keeper PCU emissions for both idle mode and clamping modes are within the SSP 30237 exterior equipment EMI specification for frequencies $\geq$ 30 MHz.

Broadband noise and PEU switching harmonics exceed the SSP 30237 specifications by up to 20 dB and 30 dB respectively, for frequencies $\leq$ 4 MHz. (noise and switching harmonics within specifications in 4 - 30 MHz frequency range)

The exposure of the measurement antennas to the PCU plasma was found to substantially increase the indicated low frequency emission levels by up to 40 dB, especially for the clamping mode.

PCU optical emissions in the 3000 - 9000 Angstrom wavelength range were quantified to evaluate the PCU source as an astronaut ocular hazard, and to assess its potential to interfere with SS navigational aids and space experiments. The schematic for this emission spectroscopy test and associated hardware specifications are shown in Figure 15.

The emission scans were obtained using a 0.5 meter scanning monochromator and a photomultiplier tube. Data were taken from a side-on viewing direction across the exit plane of the PCU. Phase sensitive detection was employed to discriminate plasma emission from other background emission. Emissions were obtained with 200 μm monochromator slit widths which resulted in an estimated spectral resolution of 3.2 Angstroms.

Initial tests were conducted with the baseline enclosed-keeper type PCU and it was found that even at 10 A contactor emission current conditions, the signal intensities were too low to obtain good quantifiable emission spectra. Subsequent measurements were conducting with a ring-cusp type PCU. This source, operating typically at 50% higher input power levels, was observed to have a significantly higher plume intensity in the visible spectra. Measurements were therefore obtained with the ring-cusp source and are interpreted as an absolute upper-bound on the baseline enclosed-keeper contactor emissions.

Spectra were obtained at both the idle mode zero emission current condition, and at a clamping mode of 2.5 A emission. Figure 16 shows a typical emission spectra for the PCU in a 2.5 A emission current condition, with signal intensity, in Watts per steradian-Angstrom, versus wavelength. Almost without exception the emission was due to excited state transitions of Xe(I) or Xe(II), with 160 Xe(I) lines and 70 Xe(II) lines identified. The dominant visible emission was found in the blue wavelengths. The extrapolated total emissive power (side view) for these conditions is estimated to be $<$ 1 mW in idle mode, and approximately 20 mW in clamping mode. The uncertainty in the values of absolute intensities are estimated to be less than an order of magnitude, and with an in situ calibration, this uncertainty could be reduced to approximately 10%. Based on these results, it appears that the PCU source is unlikely to pose an ocular hazard or to interference with SS navigational aids or experiments.

PCU Development Status

An engineering model (EM) version of the enclosed-keeper plasma contactor unit design has been completed and is under fabrication, with the first units scheduled for completion in Fall 1993. The design and performance specifications for this version are detailed in Table VI.

Typical steady-state input power for this 10 A contactor design is estimated at 36 W, with a xenon consumption rate of ≤ 19 kg/yr, or approximately 6 sccm. The contactor mass, less power cable and connector, is estimated to be ⟨ 150 g (⟨ 5.3 oz.), with a length of approximately 11.5 cm and maximum diameter of approximately 2.8 cm, and it has a total of 24 parts. A CAD-based drawing package for the EM PCU has also been completed, which consists of 29 drawings, and associated procurement specifications and fabrication, assembly, and inspection procedures.

The next testing phase of PCU subsystem development is to initiate functional (performance and lifetime) testing of the EM PCU. The performance tests will examine the transportability of results obtained with prototype PCU's, verify unit-to-unit repeatability, and conduct sensitivity analyses. Upon completion of these tests a second series of performance tests will be conducted concurrent with an EM PCU lifetesting program. The additional performance tests will examine PCU subsystem integration. These include evaluating the EM PCU electrical load characteristics to define the PCU-PEU interface, defining and verifying the PCU ignition requirements to define the PCU-EMU interface, and quantifying the PCU temperatures for lifetime assessments and for ORU-level thermal analyses. Concurrently, lifetesting of the EM PCU's will be initiated under emission current and environmental conditions simulating on-orbit SS operations, and will continue through the flight hardware development program. Environmental tests will also be done in concert with the functional testing to verify EM PCU design compliance with SS structural (primarily launch loads) and thermal requirements.

Concluding Remarks

Space Station has baselined plasma contactor systems for potential control of space station structures to mitigate possible damaging interactions with the space plasma. NASA-LeRC/Work Package 4 has been directed to initiate a plasma contactor development program as an integral part of the SS electrical power system. In support of this activity, a hardware definition and testing program is being conducted to establish design requirements for the SS plasma contactor system and acquire performance and endurance data for components of the PCS. Under this program, the plasma contactor unit is being developed to engineering model status and the PEU and EMU to breadboard models.

Progress in the development of the plasma contactor unit has been made in key areas. A xenon hollow cathode plasma source was selected for the SS PCU and it will be operated in a continuous mode. The PCU hollow cathode assembly design was completed and validated via performance tests and long-duration wear tests of hollow cathodes and heaters. Prototype plasma contactor units were built and tested over the required emission current ranges, and several have met the performance requirements for the SS contactor under operating conditions expected to allow meeting the 17,500 hour required operating lifetime. Several new cryopumped test facilities have been developed to support characterizations and life testing of PCU components and systems.

Based on the results of these prototype tests, an enclosed-keeper design PCU was baselined for the space station. Typical performance for this PCU is a maximum steady-state input power of 30 to 36 W in idle mode, and clamping voltages less than 20 volts for contactor emission currents up to 10 A. The observed current-voltage characteristics of this PCU indicate that the contactor emission current contributes to the ionization of xenon gas within the PCU. Electromagnetic emissions in the 14 kHz to 18 GHz frequency range and optical emissions in the 3000 to 9000 Angstrom wavelength range radiated by the PCU were measured and appear to pose no major compatibility issues with SS systems.

A design for an engineering model (EM) version of the enclosed-keeper PCU was completed and is under fabrication, with the first units scheduled for completion in Fall 1993. Typical steady-state input power for this 10 A contactor is estimated to be 36 W, with a xenon consumption rate of about 19 kg/yr (≤ 6 sccm). The contactor mass, less power cable and connector, is estimated to be less than 150 g, with a length of approximately 11.5 cm and diameter of approximately 2.8 cm.

The next testing phase of PCU subsystem development is to initiate functional (performance and lifetime) testing of the EM PCU. In addition to verifying the transportability of performance data obtained with prototype hardware and demonstrating unit-to-unit repeatability, the performance tests will also examine PCU subsystem integration. Concurrently, lifetesting of the EM PCU's will be initiated under emission current and environmental conditions simulating on-orbit SS operations, and will continue through the flight hardware development program.

Acknowledgements

The support of the SS Plasma Contactor Office/Photovoltaic Power Module Division, and specifically Robert Corrigan, Program Manager, is gratefully acknowledged. Additionally the authors would like to express their appreciation to the modeling and analysis team lead by Dr. Carolyn Purvis, Chief of the NASA-LeRC Space Environment Effects Branch, for many helpful discussions. Fabrication and test support provided by Robert Butler, George Jacynycz, Fred Jent, David Lilly, Bernard Loyer, Craig Nelson, Mike Pastel, Eugene Pleban, Mike Perez, Gerald Schneider, Larry Schultz, David Wolford, and Peggy Yancer is gratefully acknowledged.

References

[1]Personal communication, Katz, I., S-Cubed Division of Maxwell Labs, San Diego, CA, October 1992.

[2]Moorehead, R.W., Deputy Director, Space Station Freedom Program and Operations, communication to Work Packages 1-4 Directors, dated April 3, 1992.

[3]Ijichi, K., Harada, H., and Koricki, K., "MPD Arcjet System for Space Experiment with Particle Accelerator (SEPAC)," AIAA Paper No. 79-2072, October 1979.

[4]Beattie, J.R., et al., "System Performance of ATLAS Plasma Contactor," AIAA Paper No. 90-2568, July 1990.

[5]Sarver-Verhey, T.R., "Extended-Testing of Xenon Ion Thruster Hollow Cathodes," AIAA Paper No. 92-3204, July 1992.

[6]Directive SSCBD: BM003057, paragraph 3.1.3.2.1.8 to SSP 30000, dated December 4, 1992.

[7]Personal communication, Katz, I., S-Cubed Division of Maxwell Labs, San Diego, CA, August 1992.

[8]Personal communication, Corrigan, R., NASA-Lewis Research Center, Cleveland, OH, December 1992.

[9]Personal communication, Katz, I., S-Cubed Division of Maxwell Labs, San Diego, CA, December 1992.

[10]Personal communication, Jongeward, G., S-Cubed Division of Maxwell Labs, San Diego, CA, May 1993.

[11]Patterson, M.J., et al., "Plasma Contactor Technology for Space Station Freedom," AIAA Paper No. 93-2228, June 1993.

[12]Sarver-Verhey, T., "Results of an Extended Test of a Xenon Hollow Cathode for a Space Plasma Contactor," IEPC Paper No. 93-020, September, 1993.

[13]Soulas, G.C., "Hollow Cathode Heater Development for the Space Station Plasma Contactor," IEPC Paper No. 93-042, September, 1993.

[14]Hamley, J.A., et al., "Development of a Power Electronics Unit for the Space Station Plasma Contactor," IEPC Paper No. 93-052, September 1993.

[15]Duncan, W., et al., "Final Report Ad Hoc Orbiter Charging Committee for the TSS-1 Mission," Universities Space Research Association Report, Nov. 8, 1985.

[16]Kolecki, J.C., "Electrodynamic Interactions, Executive Summary," Proceedings of the 2nd Biennial Workshop, Applications of Tethers in Space, Venice, Italy, Oct. 15-17, 1985.

[17]Burch, J.L., Southwest Research Institute Letter Conveying Charge Neutralization Workshop Resolution, Sept. 9, 1985.

[18]Patterson, M.J. and Wilbur, P.J., "Plasma Contactors for Electrodynamic Tether," NASA TM-88850, September 1986.

[19]Olsen, R.C. and Whipple, E.C., "Active Experiments in Modifying Spacecraft Potential: Results from ATS-5 and ATS-6," NAS 5-23481 Final Report, May 1977.

[20]Jones, S.G., Staskus, J.V., and Byers, D.C., "Preliminary Results of SERT II Spacecraft Potential Measurements Using Hot Wire Emissive Probes," AIAA Paper No. 70-1127, August 1970.

[21]McPherson, D.A., Cauffman, D.P., and Scheber, W.R., "Spacecraft Charging at High Altitudes: SCATHA Satellite Program" *Journal of Spacecraft and Rockets*, Vol. 12, Oct. 1975, pp. 621-626.

[22]Cohen H., et al., "The Sounding Rocket Flight of a Satellite Positive Ion Beam System," AIAA Paper No. 79-2068, Oct. 1979.

[23]Kerslake, W.R. and Ignaczak, L.R., "Development and Flight History of SERT II Spacecraft," *Journal of Spacecraft and Rockets*, Vol. 30, May-June 1993, pp. 258-290.

[24]Sovey, J.S., "Improved Ion Containment Using a Ring-Cusp Ion Thruster," *Journal of Spacecraft and Rockets*, Vol. 21, Sept.-Oct. 1984, pp. 488-495.

[25]Personal communication, Katz, I., S-Cubed Division of Maxwell Labs, San Diego, CA, December 1992.

Appendix

The following test stands were built for testing components and subsystems of the PCS. All the facilities employed for life or wear testing can operate autonomously for periods of several months in duration.

Hollow cathode wear test stand - This facility is presently operational and is used for long-duration wear tests of xenon hollow cathodes to evaluate contamination control requirements for the EMU. Testing with this facility also has obtained cathode temperature information critical to lifetime assessments and to cathode sizing requirements for the PCU. The facility has a single test port (to accommodate the hollow cathode) which is attached to a six-way vacuum cross evacuated with a helium refrigerator cryopump (see Figure A1). The facility has a xenon pumping speed of approximately 1100 ℓ/s and can be operated for several thousands of hours before regeneration of the cryogenic pumping surface is required. The facility has a base pressure of approximately 1.3×10^{-5} Pa (1.0×10^{-7} torr) and an operating pressure of 1.5×10^{-2} Pa (1.1×10^{-4} torr) under typical cathode operating conditions.

Heater test stand - This facility is designed for testing the performance and cyclic-life of the PCU hollow cathode's heater assembly. The vacuum chamber consists of a 0.3 m diameter by 0.3 m long stainless steel cylinder evacuated with a turbomolecular pump. The typical base pressure of the facility is 1.3 x 10^{-4} Pa (1.0 x 10^{-6} torr). The stand is designed to accommodate concurrent life testing of up to 3 heaters.

Hollow cathode and PCU life test stand - This facility is presently operational and in use to conduct life testing of both hollow cathodes and plasma contactors. Fully automated life testing of up to six hollow cathodes or four plasma contactors can be concurrently conducted in it. The vacuum chamber is approximately 1 m in diameter by 1.5 m in length and has two 0.3 m test ports which can be isolated from the main chamber by gate valves. The vacuum chamber is equipped with a 0.9 m diameter helium refrigerator cryopump attached to one end, providing a xenon pumping speed of approximately 15,000 ℓ/s. The facility's base pressure is approximately 1.3 x 10^{-6} Pa (1.0 x 10^{-8} torr).

Plasma contactor wear test stand - This facility is presently under construction and will be used to define and verify conditions for PCU hollow cathode ignition. Its design and pumping train are similar to those of the hollow cathode wear test facility shown in Figure A1, and it will accommodate up to three plasma contactors for cyclic ignition tests.

Plasma contactor and system integration stand - This new vacuum chamber facility, fabricated of aluminum, is 2.1 m in diameter and 4.3 m long (see Figure A2). Presently under construction, the facility will be used to conduct detailed PCU-PEU integration tests and PCS performance and lifetime assessments. The pumping train includes a two-stage blower system backed up by a roughing pump. The chamber is equipped with four 0.9 m diameter helium refrigerator cryopumps which will provide a xenon pumping speed of approximately 60,000 ℓ/s. The chamber has 2 test ports, one a 0.9 m diameter port with a 1.1 m long spool piece and an isolation valve, and the other a 0.3 m diameter port with a 0.5 m long spool piece and an isolation gate valve. The facility also has multiple 0.3 m and 0.6 m apertures for electrical penetrations, windows, and additional test ports.

Plasma contactor performance stand - The existing tank 5 facility, which is used primarily for electric propulsion research, is also being utilized for performance tests of the plasma contactor, and for assessing PCU-SS integration issues. The vacuum chamber is approximately 4.6 m in diameter by 18.3 m long and has a xenon pumping speed of approximately 230,000 ℓ/s, provided by twenty 0.9 m diameter oil diffusion pumps and a 15 K helium cryosurface of approximately 40 m^2 area.

Table I Plasma Contactor Hardware Definition and Testing Task

plasma contactor system component	function	key technology issues	development target*
plasma contactor unit {PCU}	• provides electron return current to control SS potential	• lifetime • environmental effects on performance • uncertainties in key parameters - range and variation in electron current ion production • issues of scale	engineering model
power electronics unit {PEU}	• provides command/control/ and telemetry interface to contactor system ORU • converts 120 VDC SS power to levels needed by PCU and EMU • activates, ignites, and maintains PCU operation • detects and resolves faults	• critical interfaces • EM compatibility • fault detection and resolution	breadboard model
expellant management unit {EMU}	• provides regulated flow of xenon gas to PCU	• contamination control • flight integration • flow control approach	breadboard model
orbit replaceable unit {ORU}	•provides mechanical, electrical, command/control/ telemetry,and thermal interface between contactor system and SS • provides micrometeroid protection	-	-

*Indicates highest hardware development status that will be completed under existing definition and testing task.

Table II SS Plasma Contactor System Operational Requirements

attribute	requirement
potential control	clamping voltage* ≤ 20 volts at all emission currents
emission current	• electron current levels up to 10 A to space plasma • dynamically variable
lifetime	17,500 h
performance	minimize power and expellant consumption
system reliability	single-fault tolerant
interfaces	• compatible with all SS utilities - power, data management, thermal, etc. • robotically serviceable
instrumentation	• health monitoring • measurement of plasma return current

*Clamping voltage refers to potential difference between cathode common of PCU and ambient space plasma potential.

Table III Considerations in Expellant Selection

consideration	comment
PC system perspective - non-contaminating and non-reactive with SS systems - compatibility with hollow cathode operation	- inert gases - argon, krypton, xenon
PCU perspective - knowledge base - starting requirements - electrode voltages/lifetime - minimum clamping voltage	- xenon optimal
PEU perspective - input power and thermal rejection requirements - SS drain power	- xenon optimal (input power to PCU 50% and 75% higher, respectively, with krypton and argon)
EMU perspective - total expellant mass - tankage fraction	- xenon optimal

Table IV First-Order Considerations for the SS PCU

consideration	approach
PCU type	hollow cathode plasma source
expellant	xenon gas
operating/control mode	continuous, steady-state, single-set-point, with no active feedback loops on operating parameters
electrical connection	cathode common of PCU connected to SS single-point-ground, with electrical isolation for measurement of emission current

Table V Selection Criteria for SS PCU

attribute/criteria	ring-cusp type	enclosed-keeper type
endurance potential {life} - number of welds and brazes - sputtering	- sputtering probable; flake-control required	✓ - negligible sputtering
development effort & risk - simplicity - parts count - ignition - development time/parameters to optimize - knowledge base	- tight control of parameters required - large test matrix, number of parameters, to optimize geometry: single prototype has not satisfactorily demonstrated all performance/lifetime criteria simultaneously	✓ - (25% of RC type - straight-forward, multiple options - small test matrix to optimize geometry
operational risk - flow control - ignition - number of commands and operating parts {number of failure modes} - stability	- ± 4% of full-scale	✓ - ± 20% of full-scale
system mass - hardware - xenon	✓	- 5-10% higher
impact on other subsystems - EMU - - complexity - # of lines/parts - flow control requirements - PEU - - thermal control - ignition - EMU interface	- 50% higher dissipated power - additional commands & valve drivers	✓ - factor of 2-3 lower

✓ implies advantage

Table V (continued) Selection Criteria for SS PCU

attribute/criteria	ring-cusp type	enclosed-keeper type
cost - development - recurring - xenon - launch mass		✓
on-orbit resources - power - thermal - volume - mass - data management services	- ≥ 56 W	✓ - ≤ 36 W
performance {device characteristics} - clamping voltage		✓
integration - stray fields - susceptibility to external contaminants - metal efflux - optical/EMI signature		✓

✓ implies advantage

Table VI SS Engineering Model PCU Attributes

Design

- enclosed-keeper geometry, no magnetic augmentation
- hollow cathode with low-work function insert

Performance

- maximum electron emission current: 10 A
- input power {typical}
  - ignition/heater power:
    53.8 W {7.0 A @ 7.7 V}
  - steady-state operation/keeper power:
    36 W {2.0 A @ 18 V} idle mode
- expellant: xenon, $\leq$ 1 ppm O_2 and H_2O
- xenon consumption rate {typical}: $\leq$ 18.6 kg/yr; 6.0 sccm
- lifetime: 17,500 h expected

Mechanical Characteristics

- mass: ⟨150 g (⟨5.3 oz.)
- parts count: 24
- shape: cylindrical
- size/vol.: 11.5 cm length x 2.8 cm dia./71 cm^3

Interfaces

- mechanical attachment to ORU box
- single expellant feed line to EMU
- 3-pin electrical connector to PEU

Development Status

- prototype PCU test program completed
- engineering model components under fabrication and lifetesting
- engineering model PCU under fabrication

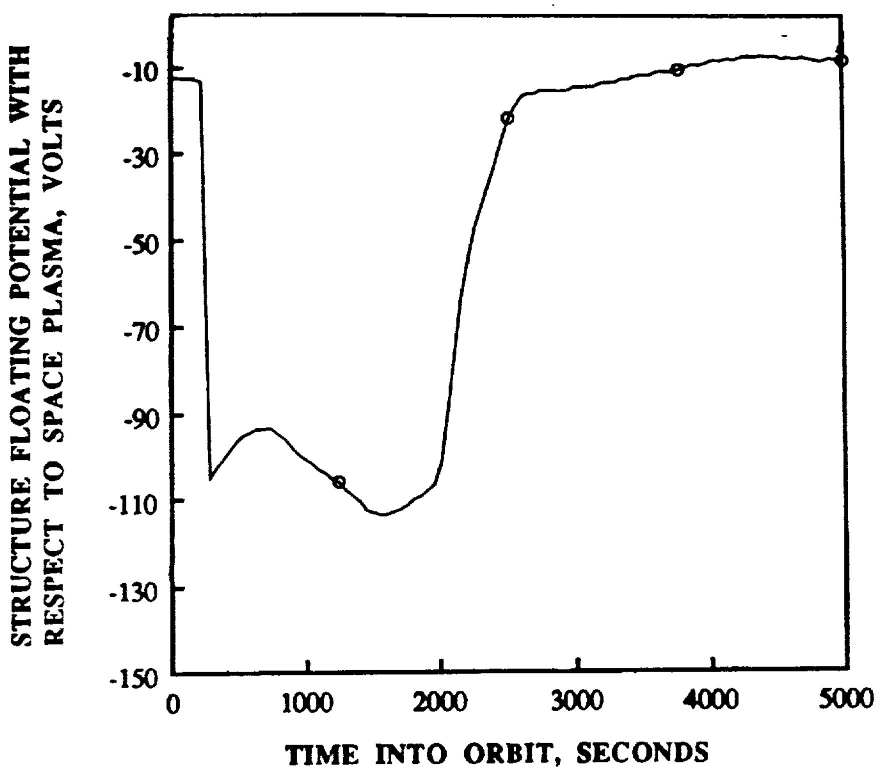


Fig. 1 Predicted negative floating potentials of SS structure during mission build 5 {without plasma contactor system}, from Ref. 1.

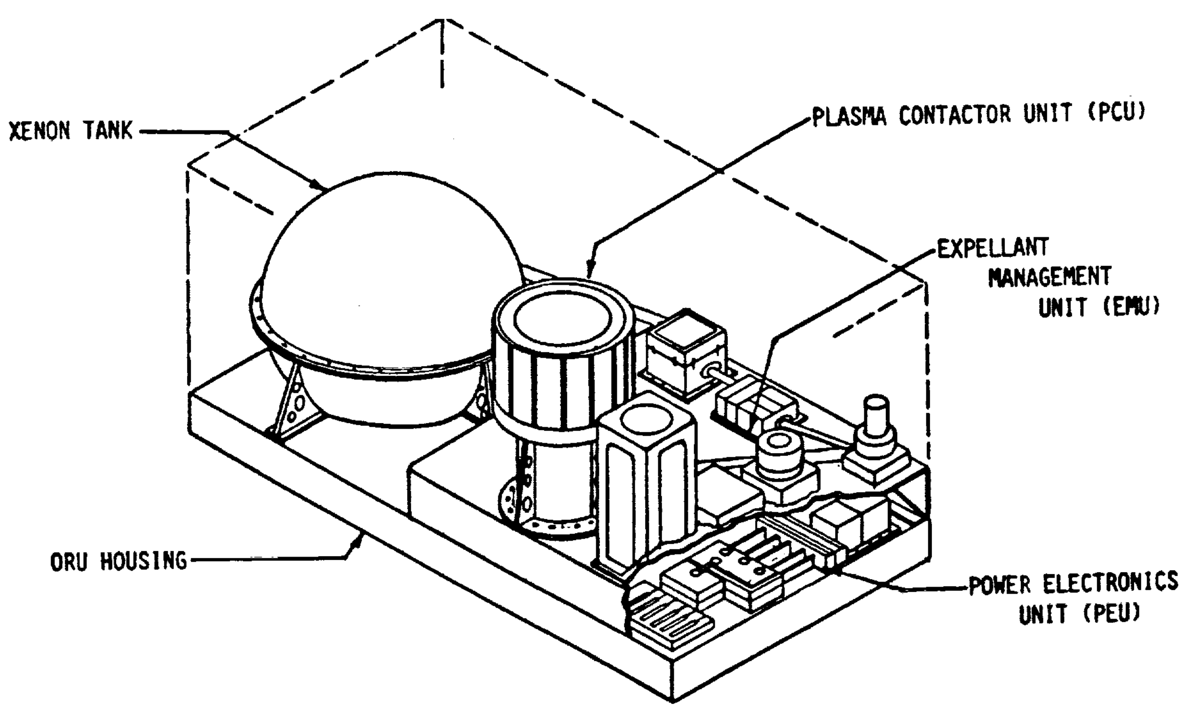


Fig. 2 Plasma contactor system conceptual design.

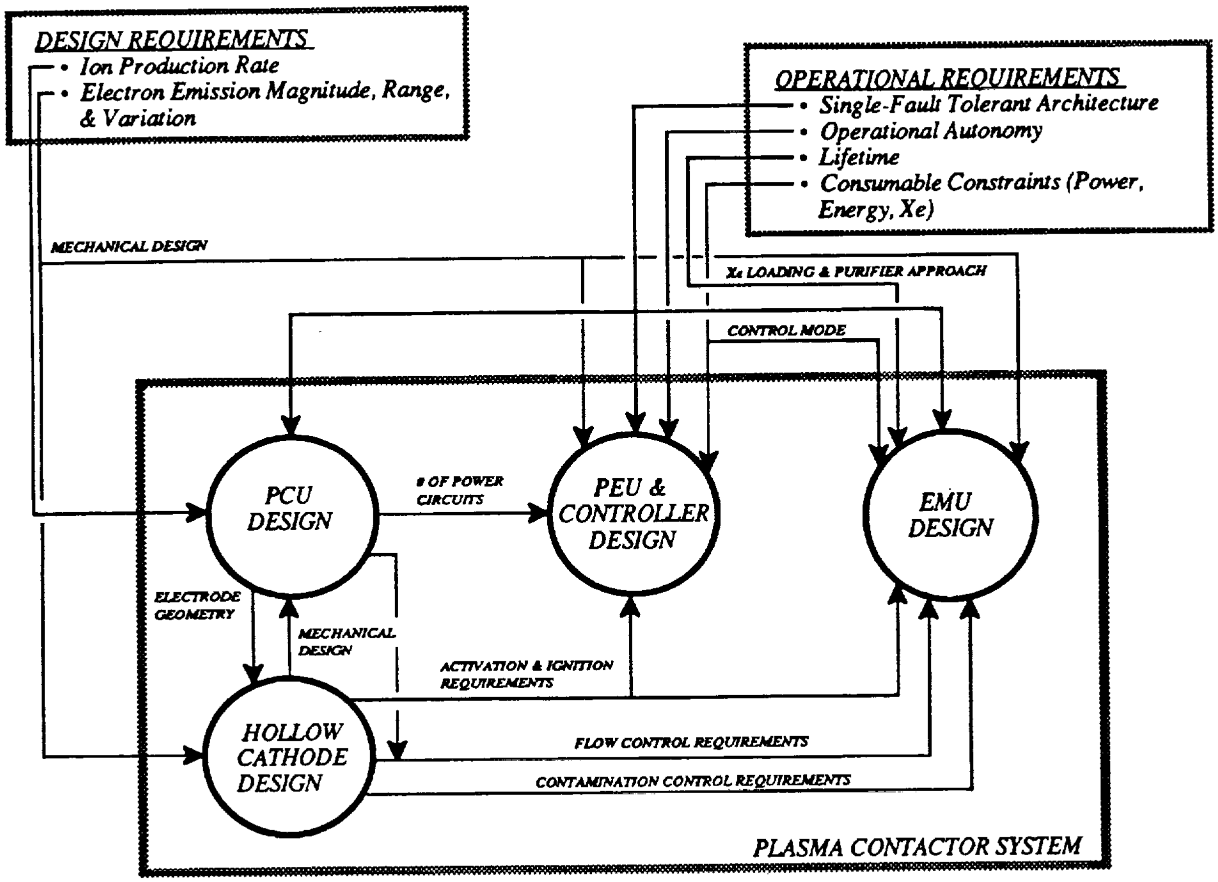


Fig. 3 Plasma contactor subsystem interdependency.

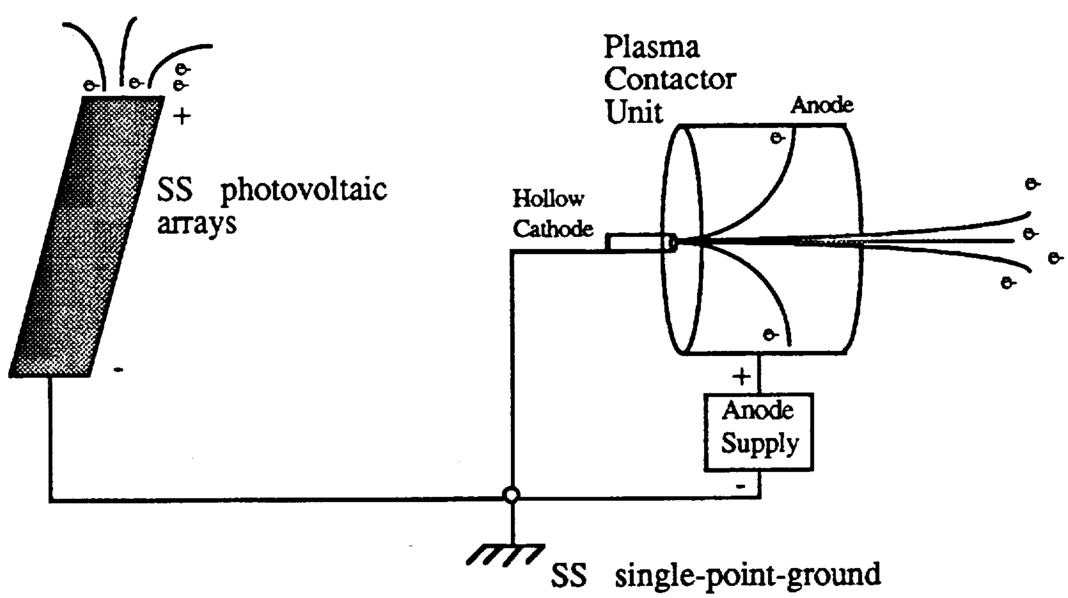


Fig. 4 Simplified plasma contactor/SS electrical schematic.

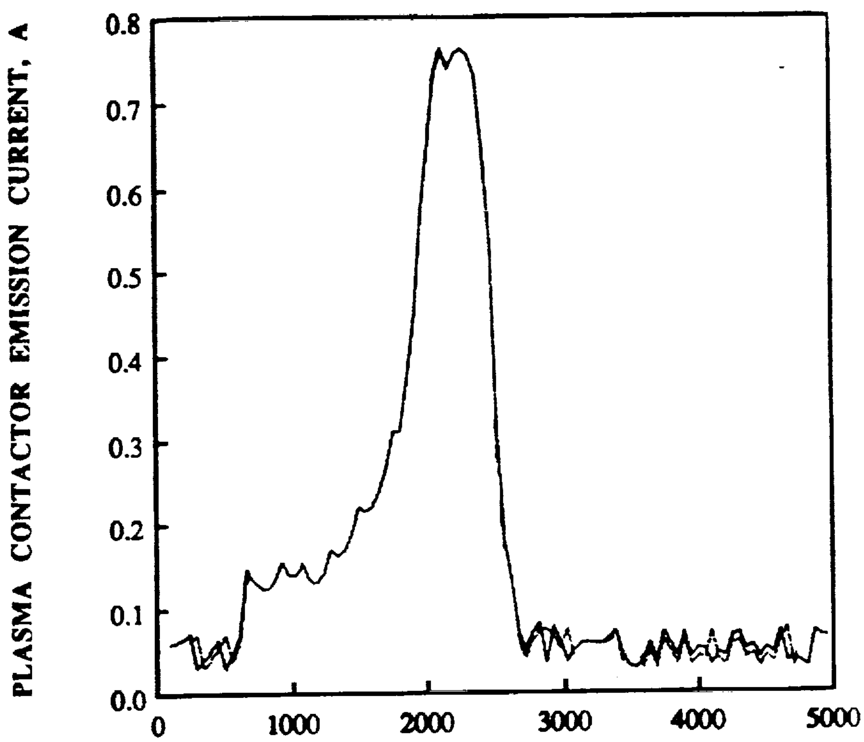


Fig. 5 Predicted contactor emission current required for single-orbit during mission build 6 {solar maximum conditions, from Ref. 10}.

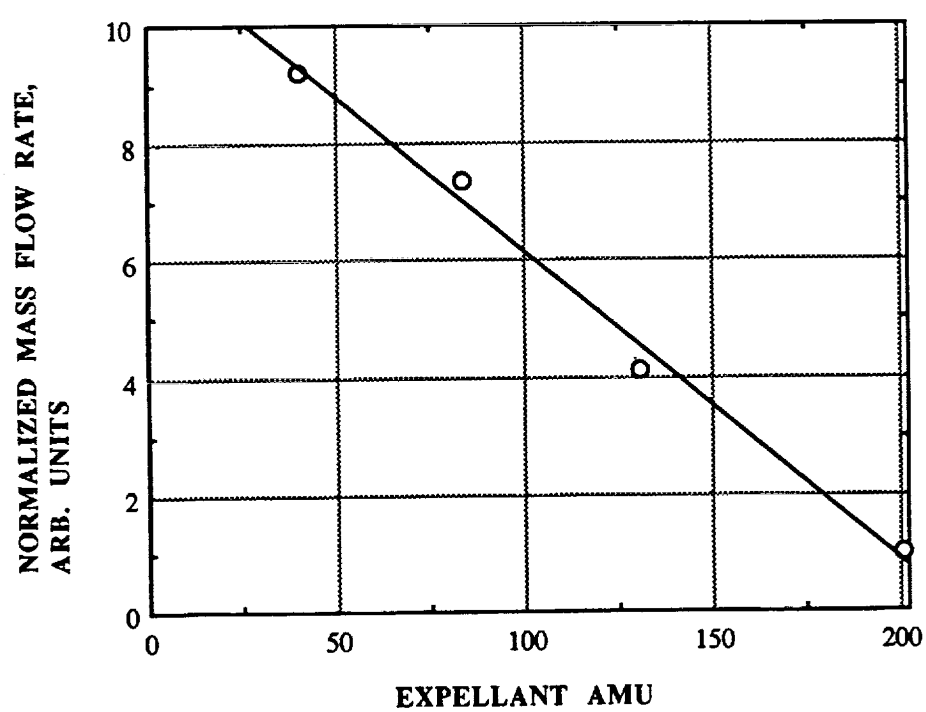


Fig. 6 Typical variation in minimum mass flow rate versus expellant AMU, for a hollow cathode plasma source.

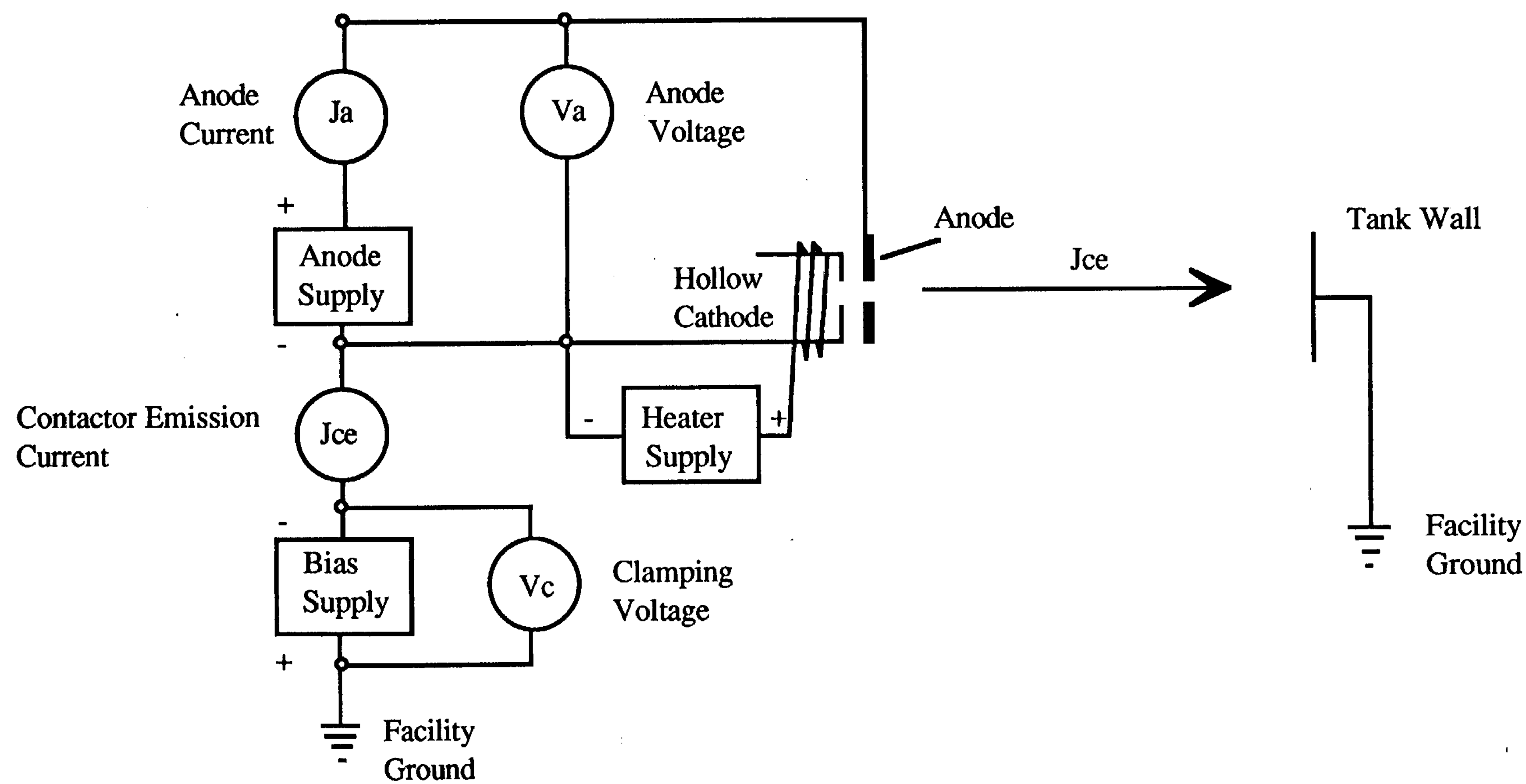


Fig. 7 Electrical test schematic.

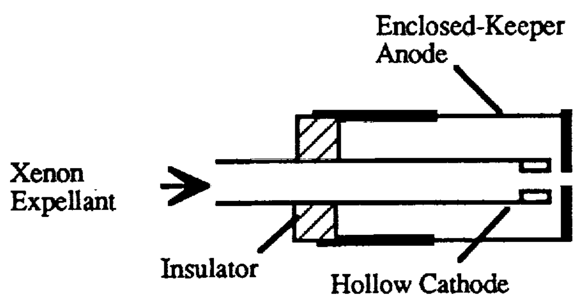


Fig. 8 Enclosed-keeper type hollow cathode PCU.

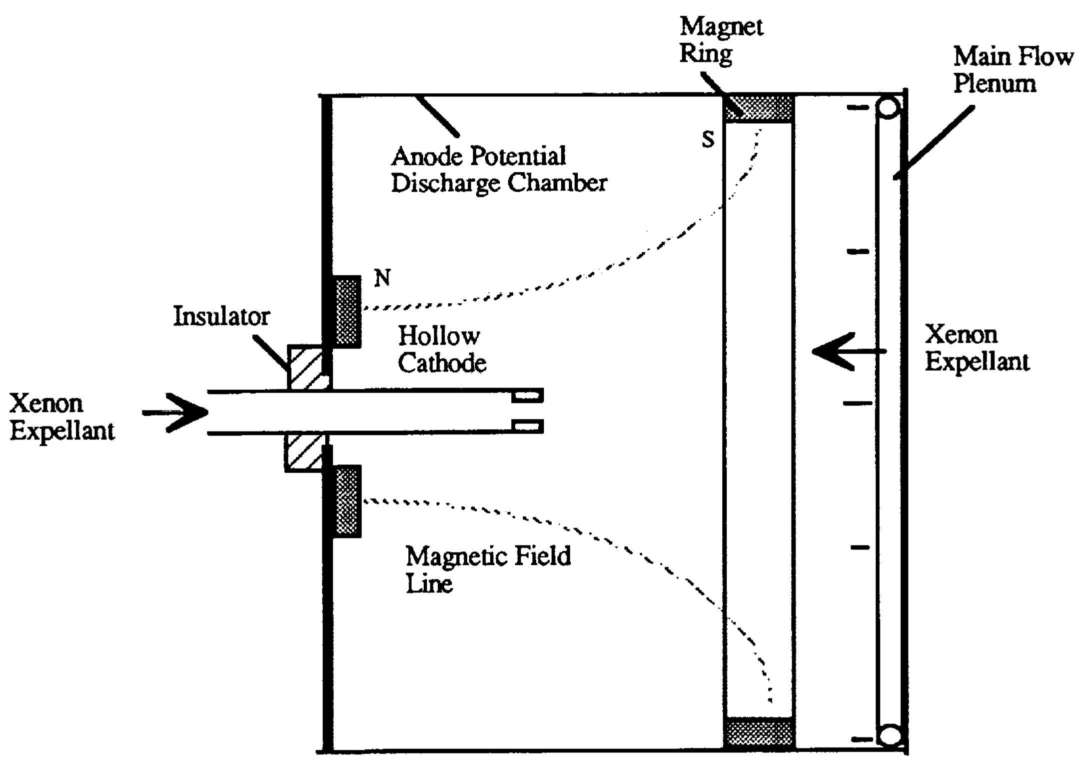


Fig. 9 Ring-cusp type hollow cathode PCU.

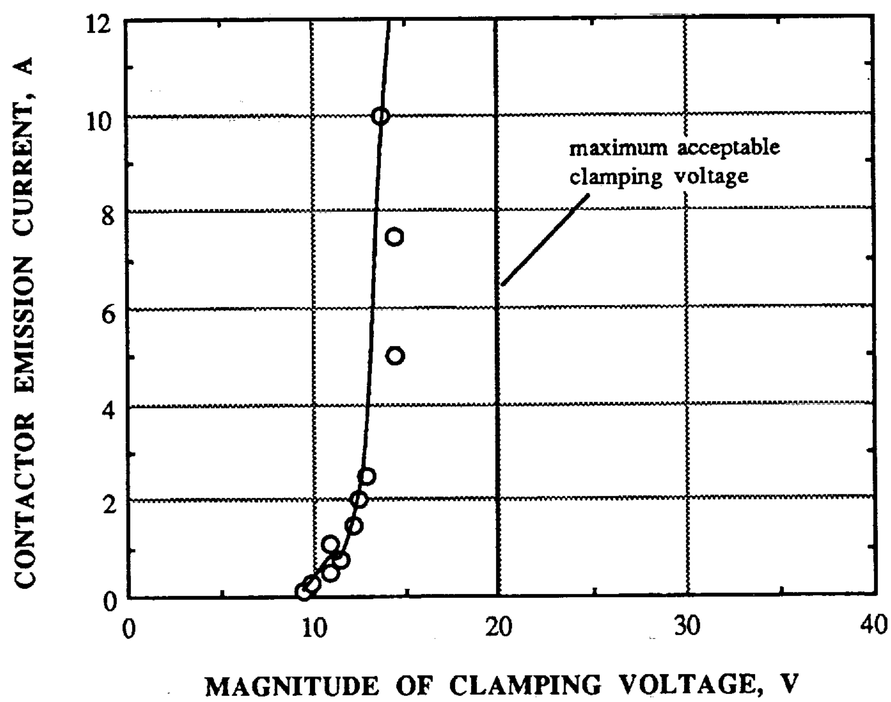
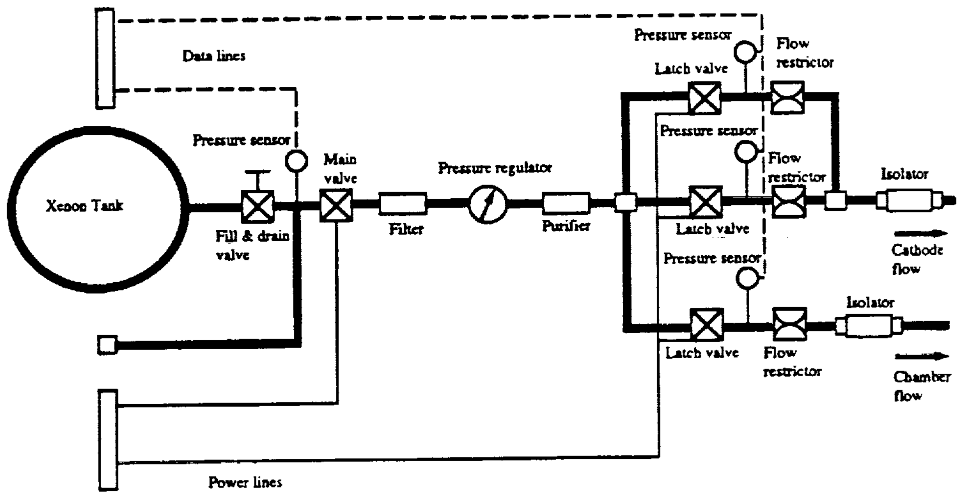
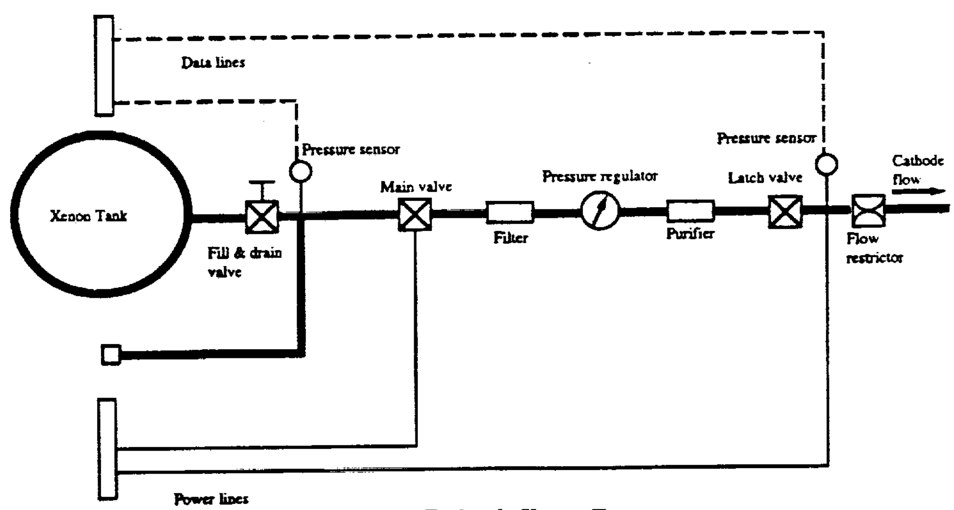


Fig. 10 Typical prototype PCU performance characteristic.



Ring Cusp Type



Enclosed - Keeper Type

Fig. 11 Comparison of EMU designs for ring -cusp and enclosed-keeper type PCU's.

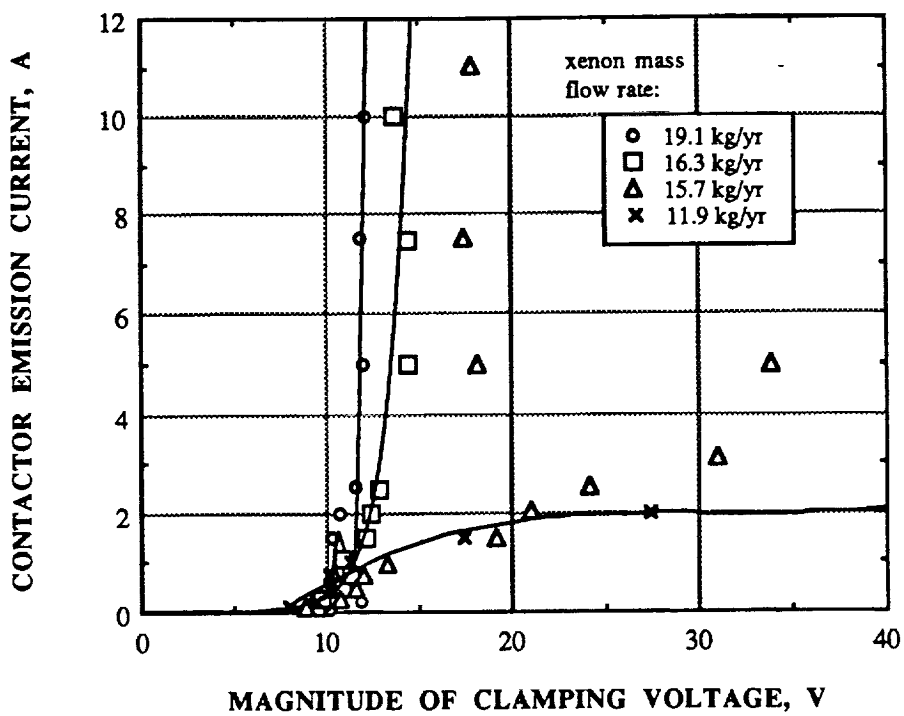


Fig. 12 Typical performance for baseline enclosed-keeper design PCU.

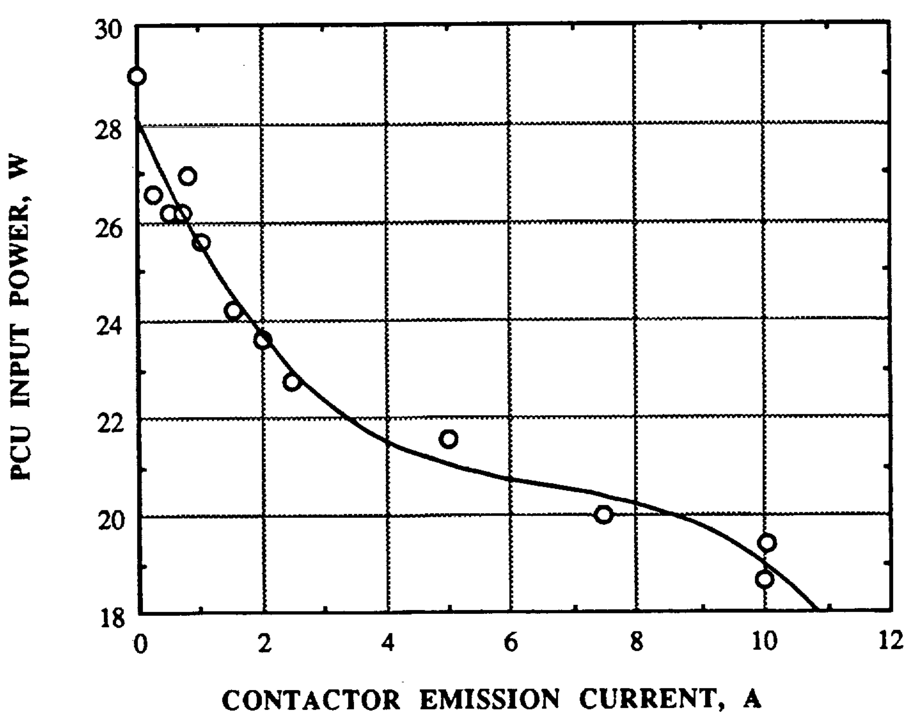


Fig. 13 Variation in PCU input power with contactor emission current.

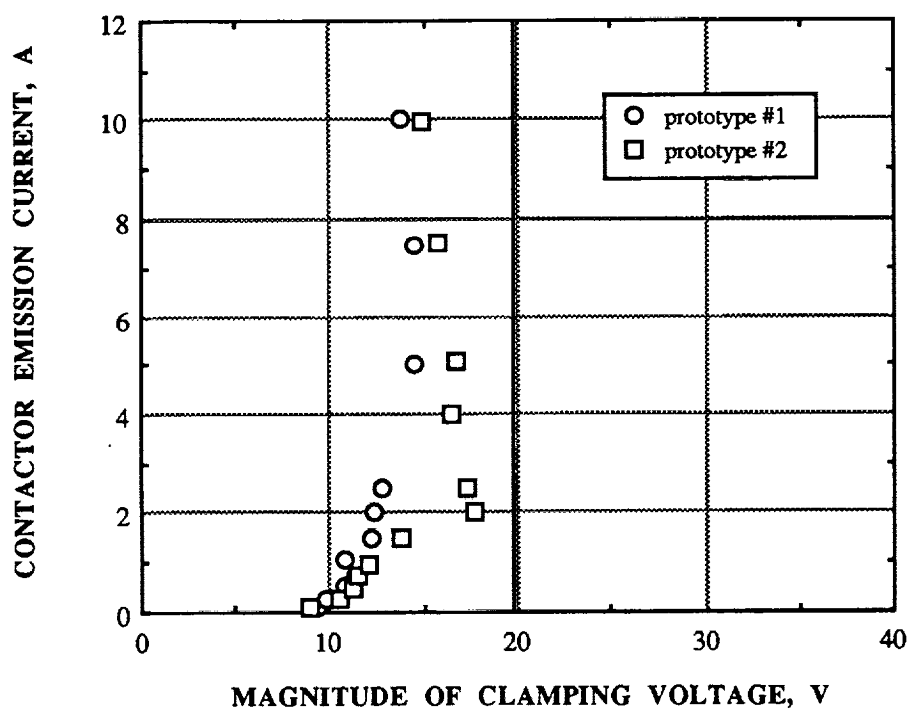


Fig. 14 Comparison of PCU performance data.

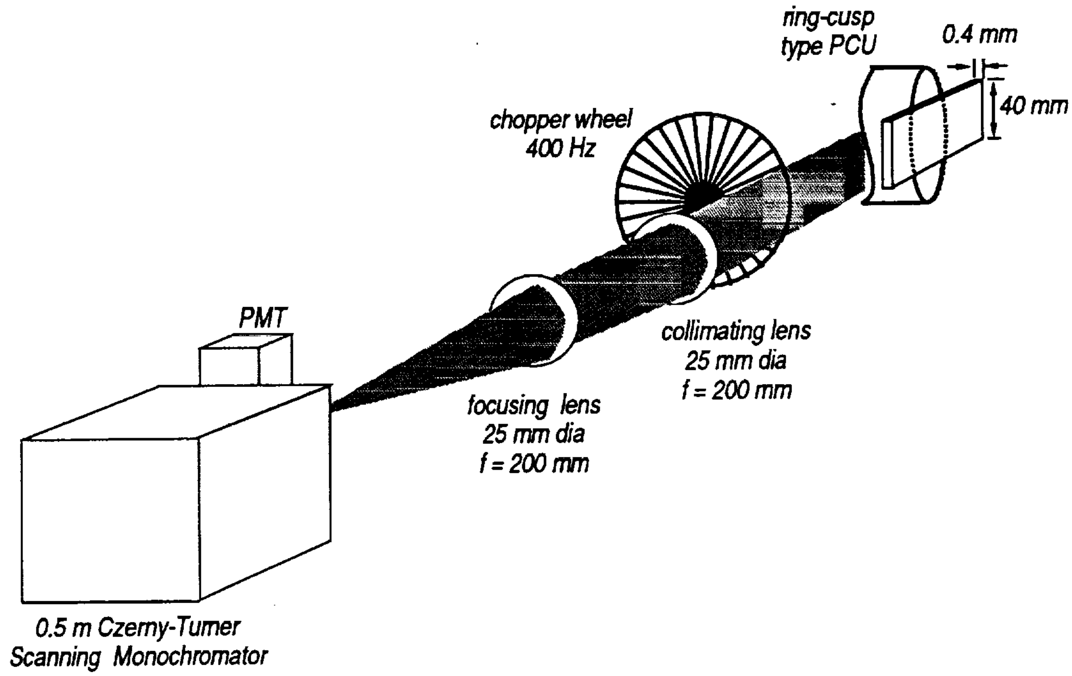


Fig. 15 Emission spectroscopy test schematic.

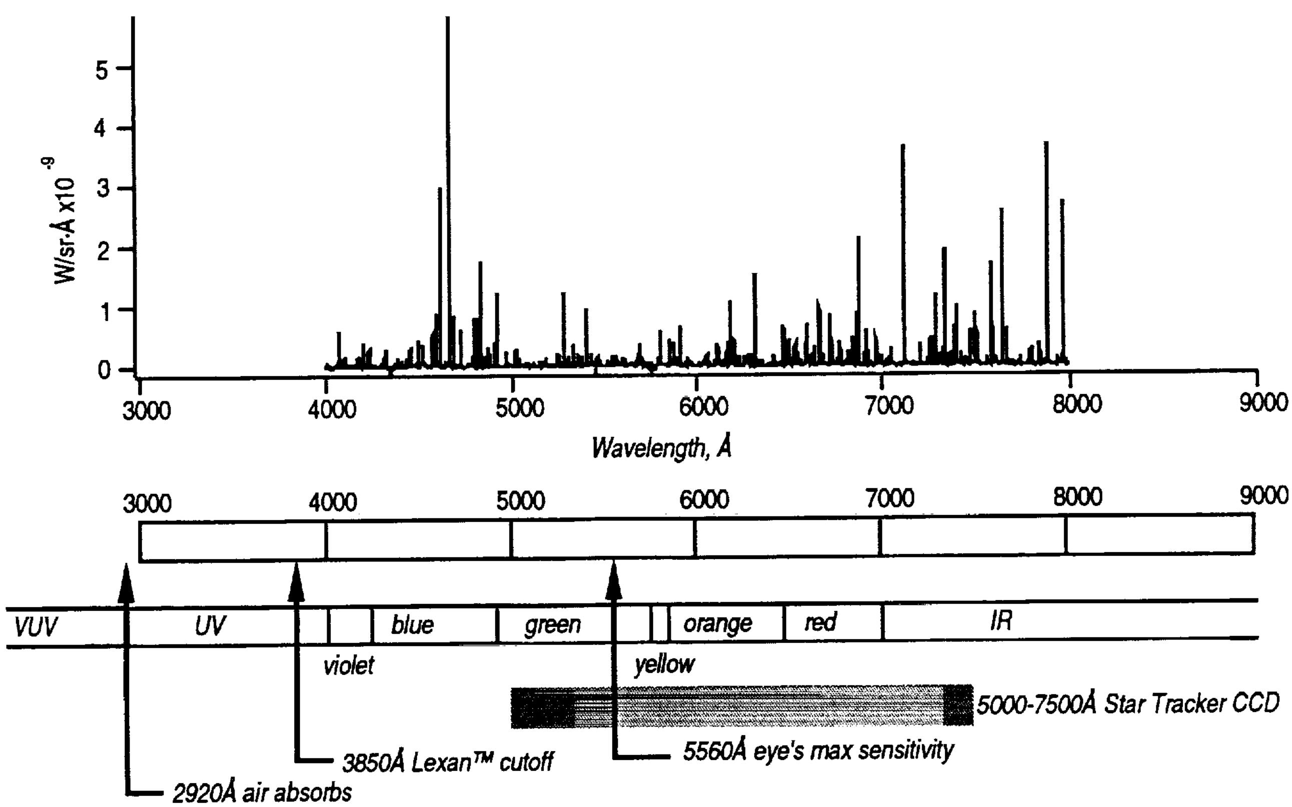


Fig. 16 Typical PCU emission spectra; 2.5 A contactor emission current.

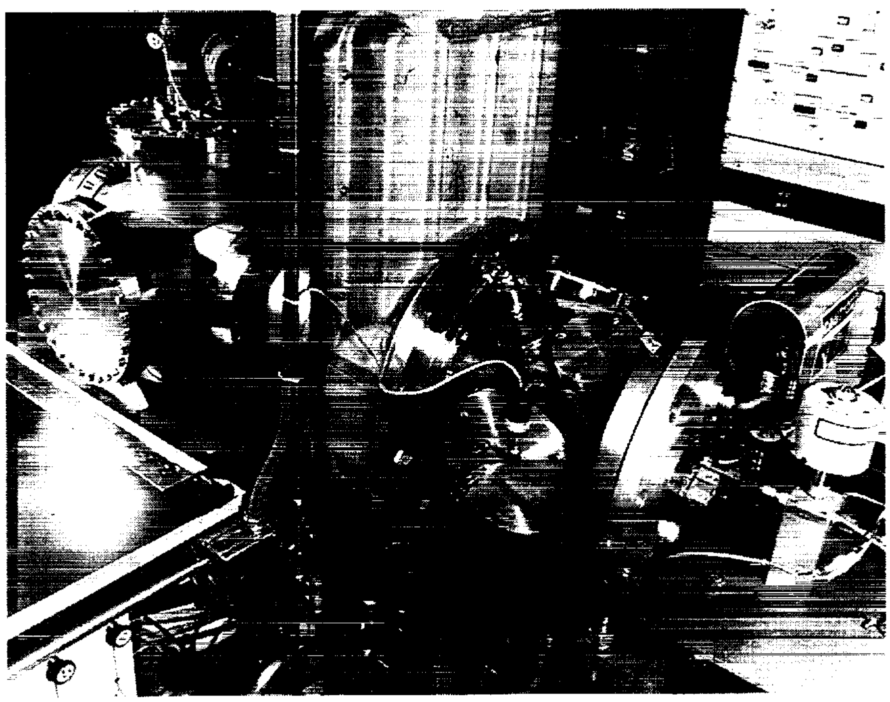


Fig. A1 Hollow cathode wear test stand.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

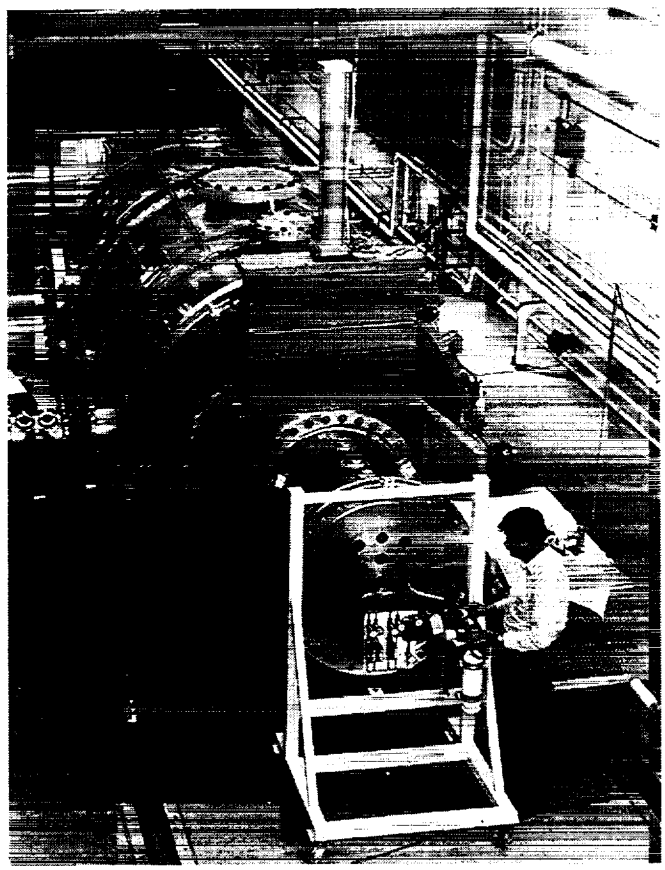


Fig. A2 Plasma contactor and system integration stand.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
December 1993

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Plasma Contractor Development for Space Station

5. FUNDING NUMBERS
WU–474–46–10

6. AUTHOR(S)
Michael J. Patterson, John A. Hamley, Charles J. Sarmiento, David H. Manzella, Timothy Sarver-Verhey, George C. Soulas, and Amy Nelson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–8267

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–106425
IEPC–93–246

11. SUPPLEMENTARY NOTES
Prepared for the 23rd International Electric Propulsion Conference, cosponsored by the AIAA, AIDAA, DGLR, and JSASS, Seattle, Washington, September 13–16, 1993. Michael J. Patterson, John A. Hamley, and Charles J. Sarmiento, NASA Lewis Research Center; David H. Manzella, Timothy Sarver-Verhey, and George C. Soulas, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3–25266), and Amy Nelson, Department of Physics, Purdue University, West Lafayette, Indiana 47907. Responsible person, Michael J. Patterson, (216) 433–7481.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 75

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

Plasma contactors have been baselined for Space Station (SS) to control the electrical potentials of surfaces to eliminate/mitigate damaging interactions with the space environment. The system represents a dual-use technology which is a direct outgrowth of the NASA electric propulsion program and in particular the technology development effort on ion thruster systems. The plasma contractor subsystems include the plasma contactor unit, a power electronics unit, and an expellant management unit. Under this pre-flight development program these will all be brought to breadboard or engineering model status. Development efforts for the plasma contactor unit include optimizing the design and configuration of the contactor, validating its required lifetime, and characterizing the contactor plume and electromagnetic interference. The plasma contactor unit design selected for SS is an enclosed keeper, xenon hollow cathode plasma source. This paper discusses the test results and development status of the plasma contactor unit subsystem for SS.

14. SUBJECT TERMS
Space station; Plasma contactor

15. NUMBER OF PAGES
30

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	