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Space Station Cathode Design, Performance, and Operating Specifications

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A plasma contactor system was baselined for the International Space Station (ISS) 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 efforts on ion thruster systems. The plasma contactor includes a hollow cathode assembly (HCA), a power electronics unit, and a xenon gas feed system. Under a pre-flight development program, these subsystems were taken to the level of maturity appropriate for transfer to U.S. industry for final development. NASA's Lewis Research Center was subsequently requested by ISS to manufacture and deliver the engineering model, qualification model, and flight HCA units. To date, multiple units have been built. One cathode has demonstrated approximately 28,000 hours lifetime, two development unit HCAs have demonstrated over 10,000 hours lifetime, and one development unit HCA has demonstrated more than 32,000 ignitions. All 8 flight HCAs have been manufactured, acceptance tested, and are ready for delivery to the flight contractor. This paper discusses the requirements, mechanical design, performance, operating specifications, and schedule for the plasma contactor flight HCAs.

Introduction

The International Space Station (ISS) power system is designed with high voltage solar arrays which operate at output voltages of typically 140-160 volts. The ISS grounding scheme electrically ties the habitat modules, structure, and radiators to the negative tap of the solar arrays. This electrical configuration and the plasma current balance would cause the habitat modules, structure, and radiators to float to voltages as large as -120 V with respect to the ambient space plasma without some active charge control method.[1]

As a result of these large negative floating potentials, there exists the possibility for deleterious interactions of ISS with the space plasma. These interactions may include arcing through insulating surfaces and sputtering of conductive surfaces due to acceleration of ions by the spacecraft plasma sheath. To eliminate arcing and sputtering a plasma contactor system was baselined on the ISS.[2] The sole requirement for the system is contained within a single directive: "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."[3] NASA is developing this plasma contactor as part of the ISS electrical power system.

For the ISS application, efficient and rapid emission of high electron currents is required from the plasma contactor system under conditions of variable and uncertain current demand. A hollow cathode plasma source is well suited for this application, and was therefore selected as the design approach for the station plasma contactor system.[4]

In addition to the plasma source, referred to here as a hollow cathode assembly or HCA, the plasma contactor system includes two other subsystems. These are the power electronics unit and the xenon gas feed system.

The Rocketdyne Division of Boeing North American is responsible for the design, fabrication, assembly, test, and integration of the plasma contactor system. Based on technical and schedule considerations, NASA's Lewis Research Center (LeRC) was requested to manufacture and deliver the engineering model, qualification model, and flight HCA units for the plasma contactor system as government furnished equipment. To date, all deliverable HCAs have been manufactured and tested, and the engineering and qualification units have been delivered. This paper describes the plasma contactor HCA requirements, its mechanical design, performance, operating specifications, and the flight hardware delivery schedule.

Requirements

The major requirements for the ISS plasma contactor system which flow down to the HCA include clamping voltage, emission current, and lifetime.

Clamping Voltage

The HCA must emit an electron current to the space plasma at least matching the net electron current collected on the station solar arrays at a clamping voltage of ≤ 20 volts between HCA common and local space plasma potential. The 20 volt "allocation" for the HCA, combined with the induced structure voltage due to the Earth's magnetic field (estimated to be ≤ 20 volts), ensures that the structure floating potential at all points on the station is within ± 40 volts of the ionospheric plasma potential.

Emission Current

The HCA is required to emit up to 10 A of electron current in a self-regulating manner under dynamic conditions. The electron emission current to the space plasma is required to match the net electron current collected on the station solar arrays (referred to as "clamping" mode) for a portion of the station orbital period. This period includes approximately one-third of the orbit, from dawn through noon when the solar arrays are illuminated, generating power, and facing the ram direction. During the remainder of the orbital period the HCA may be either operated in an "idle" mode or turned off.

Lifetime and Cycling

The required operational lifetime for the HCA is a minimum of 18,000 hours of operation, or approximately 2 years of continuous operation. This represents the plasma contactor system lifetime, based on selected xenon tank size.

The option exists to extend the plasma contactor system lifetime by operating the HCA only during periods in which the space station is actively charging. In this manner, the xenon consumption rate can be reduced and hence the system life can be increased. To accommodate this option, a requirement for the HCA to be capable of a minimum of 6000 ignitions with a minimum ignition reliability of 99% was imposed.

Mechanical Design

Although several alternative hollow cathode plasma source designs were investigated, including ring cusp sources,[5] the design selected for the HCA is an enclosed-keeper geometry operated on xenon gas, shown in Figure 1. The considerations in HCA design selection were to satisfy the potential control requirement and maximize expectations for long life. HCA attributes are summarized in Table I.

The primary components of the HCA include a hollow cathode, an anode, a heater, and an electrical isolator. The hollow cathode consists of a refractory alloy tube with an orifice plate welded on one end. An electron emitter located within the hollow cathode serves as a low-work function electron source. A heater surrounds the downstream end of the cathode tube, and is used to raise the temperature of the cathode during conditioning and ignition. The HCA incorporates a cylindrical anode which surrounds the hollow cathode in close proximity. Upstream of the cathode tube is an electrical isolator which isolates the HCA from ISS structure, allowing HCA emission current to be monitored.

HCA mass, including power cable, gas line, and mounting bracket, is approximately 0.250 kg. The overall length (including gas line) is approximately 21.1 cm and maximum diameter (at the mounting bracket) is approximately 7.6 cm. The HCA has three interfaces to the plasma contactor system. These include a mounting flange for mechanical attachment to the plasma contactor system, a single xenon gas line for coupling to the gas feed system, and a 3-conductor electrical cable for electrical connection to the plasma contactor power electronics.

A total of 29 HCAs have been manufactured and assembled at LeRC for the ISS application. The 29 HCAs include 15 development units, used for performance and life testing, and 1 quality-control unit, fabricated with the flight HCA batch. An additional 11 deliverable HCA's have been built and these include 1 mass-thermal-acoustic mockup (MTAM), 1 engineering model unit, 1 qualification unit, and 8 flight units. Figure 1 shows 9 of the 11 deliverable HCAs.

Operating Considerations and Characteristics

Conditioning

The conditioning sequence consists of heating the HCA electron emitter with a series of time-at-temperature steps to remove contaminants and prepare the low-work function insert material for emission. It is performed after each HCA air exposure, prior to ignition.

Ignition

The HCA must be capable of at least 6000 ignitions with a reliability of ≥99%. In addition, a minimum of 10 ignitions in 6.0 minutes or less must be demonstrated.

The HCA is considered ignited when the anode current reaches its nominal 3.0 ampere value. Typically, HCA ignition takes less than 6.0 minutes, measured from the time the heater is energized.

To define and verify conditions for HCA ignition, preliminary tests were performed on a prototype (pre-development unit) HCA.[6] A long-duration cyclic ignition test was subsequently conducted using the prototype HCA to validate the ignition requirements. More than 3300 sequential HCA ignitions were demonstrated without a single ignition failure, and the test was voluntarily terminated.[6]

Subsequently, life tests were initiated using development unit HCAs. These HCAs included HCA.014, which has completed over 32,000 ignitions,[7] and HCA.010, which has completed approximately 4,360 ignitions.[8] An analysis was performed on the distribution of ignition times over the life of these two units. For HCA.014, the ignition durations which capture 99%, 95%, and 90% of the total number of ignitions are 5.8, 5.0, and 4.9 minutes, respectively. For HCA.010, these percentages correspond to 3.9, 3.8, and 3.8 minutes. The cause for the difference in distributions between the two units is presently unknown. However both units are operating well within acceptable limits.

Figure 2 shows ignition time versus ignition number for the first several ignitions performed during acceptance testing of the qualification and 8 flight units. As indicated the first 2 ignitions take substantially longer than 6 minutes for some units. Subsequent ignitions occur within 6 minutes.

Tests were performed on a development unit HCA to characterize its ignition behavior starting from space environment temperatures. Eleven ignitions were performed over a range of HCA starting temperatures (measured on the external surface of the HCA anode) from approximately -56 deg. C to +212 deg. C. The ignition times over this temperature range varied from about 3.6 minutes to 5.2 minutes. The ignition that occurred from -56 deg. C was indistinguishable from ignitions starting from room temperature.

Idle Mode Operation

During idle mode, the HCA operates at the fixed anode current of 3.0 A, with no net emission current to the space plasma. The xenon flow rate to the HCA in flight will be in the range of 5.80 sccm to 7.50 sccm. The lower bound flow rate ensures a clamping voltage of less than 20 volts at all emission currents, while the upper bound simply reflects the flow-control bandwidth delivered by the flight gas feed system.

In idle mode operation, the static and dynamic impedance of the HCA anode discharge are evaluated at xenon flow rates and anode currents which bound the operating envelope for the HCA. These tests were performed on development unit HCAs to characterize the power electronics and gas feed system interface specifications and stability envelope, and were then repeated on the flight units to verify similarity to the development units and to quantify unit-to-unit dispersions.

Figure 3 shows the variation in HCA anode voltage with variation in the xenon gas flow rate at 3.0 A anode current, for several flight units. As indicated, the anode voltage decreases from about 18 volts at 4.50 sccm to about 13 volts at 9.00 sccm, and good unit-to-unit repeatability was measured (typically within 1 volt) between 5.80 and 7.50 sccm.

At flow rates above 4.50 sccm, the HCA operates in a quiet spot mode, with a peak-to-peak anode voltage noise of less than 1 V at frequencies above 1 MHZ. The HCA would transition into plume[9] mode for flow rates at or below this value; a flow rate considerably below the flight specification. In plume mode, anode voltage noise was ≥ 1 volt peak-to-peak at a frequency of about 500 kHz.

HCA input power varies with flow rate. Over the range of flow rates that will be seen in flight, input power varies from a maximum of about 41-45 watts to a minimum of about 37-39 watts in idle mode.

Clamping Mode Operation
During clamping mode, the HCA must emit an electron current to the space plasma matching the net electron current collected on the station at a potential difference of $\leq$ 20 volts (between HCA cathode and space plasma potential) at all emission current levels up to 10 A. Figure 4 shows the typical measured clamping voltages at several emission currents and several xenon flow rates. As indicated, the HCA exhibits clamping voltages less than 20 volts for emission currents up to 10 A.

Demonstrated Life
Several lifetests of development unit HCAs to establish the HCA lifetime capability are on-going. These include the lifetest of 3 units in a nominal mission profile, with accumulated operating times to date of approximately 10,900, 10,300, and 7,800 hours.[9] The objective of these tests is demonstrate 1.5X the mission-required life (i.e. 27,000 hours).

The lifetest of a fourth development unit was voluntarily terminated after 8000 hours of accumulated operating time. This was done so that a destructive physical analysis could be performed prior to committing to fabrication of the flight units. The results of the analysis indicated that the HCA lifetime is in excess of that required for the space station application.[9]

A cyclic ignition lifetest of a fifth development HCA continues. To date, this unit has demonstrated more than 32,000 ignitions. This test is scheduled to continue until failure.

The aforementioned HCA lifetests were preceded by several component lifetests. These included several hollow cathode life tests of varying duration to identify requirements for long-life operation, such as cathode conditioning and gas feed system cleanliness. One of these hollow cathode life tests demonstrated approximately 28,000 hours of operation at a 12 A emission current.[10]

Other component lifetesting included cyclic-testing of the HCA heater to assess alternative heater materials and ultimate life. Over the course of this work, several heaters were tested to failure. Heater life test results using the same materials used in the HCA flight units established a B_{10} life (the cycles at which 10% of the population would have failed) of approximately 6700 cycles.[11]

Operating Specifications

This section summarizes the major operating specifications imposed on the HCA. The operating specifications include hardware limitations and constraints, ground test requirements, on-orbit environments, and associated verification plans necessary to satisfy the ISS plasma contactor system requirements. Table II, HCA verification matrix, lists all of the specifications and associated verification plans.

Handling and Atmospheric Exposure
The HCA flight hardware is transferred to the plasma contactor system contractor for integration and system qualification. Handling requirements are imposed on the system contractor to ensure HCA reliability and life. The HCA performance, reliability, and life are believed to be sensitive to exposure to the ambient ground environment. As such, limits to the total atmospheric exposure time, maximum temperature, and maximum dew point are imposed. To accommodate HCA protection, the HCA will be purged during ground processing and through launch.

Tests to relax present environmental exposure restrictions are on-going on development unit HCAs. The intent is to establish ultimate HCA exposure limits. To date, these tests have resulted in the elimination of any active environmental control requirement during the nominal 26 day shuttle launch pad operations.

On-Orbit Environments
The HCA must meet performance requirements during exposure to ambient operating temperatures of -43 deg. C to +91 deg. C, and after exposure to dormant temperatures of -43 deg. C to +82 deg. C. Testing on a development unit HCA verified that the HCA can be ignited at temperatures as low as -56 deg. C.

To demonstrate compliance with the dormant exposure requirements, the performance of a development unit HCA was characterized and then thermally cycled between -54 deg. C and at +60 deg. C for 8 cycles with one-hour dwells times at each temperature. The HCA was inspected after the test and its performance was recharacterized. Its condition and performance were found to be nominal.

Verification that the flight deliverable HCAs satisfy the thermal operating and dormant thermal environments is by analysis. Other on-orbit environmental requirements, including pressure, ionizing radiation, and cold soak space storage, are listed in Table II.

Vibration
The HCA must meet its performance requirements following a 0.5 G sine sweep from 5 Hz to 2000 Hz through all three axes at 1 octave per minute, and a 16.5 G_{rms} random sweep through all three axes for 60 seconds. Two vibration tests of development unit HCAs were performed under these conditions.

The first vibration test identified a resonance frequency in all three axes at approximately 1000 Hz and a large resonance at 250 Hz in the radial directions. This HCA was subsequently inspected, performance characterized, and then put into lifetest. To date, this unit has accumulated approximately 10,900 hours of operation.[9] While the first vibration test was successful, changes were made to the HCA to reduce its resonance response and to accommodate changes made to the system mechanical interface.

A development unit HCA with these design changes was vibration tested. A resonance frequency in all three axes of 1000-1200 Hz was observed, with resonances occurring beginning at about 600 Hz in the radial direction. This unit was subsequently inspected, its performance was characterized, and a destructive physical analysis was then performed. Results from these tests indicated that the HCA condition and performance were nominal. These design changes were implemented on all subsequent development units and on all the flight HCAs. Verification that the flight deliverable HCAs satisfy the vibration specification is by analysis.

Flight Hardware Testing

An acceptance test procedure is performed on all flight HCAs prior to delivery. The procedures include a heater confidence test and a plasma test. The heater confidence test includes a 150-cycle burn-in to verify heater function and check workmanship.

The plasma test includes characterizing idle mode performance over a range of xenon flow rates and currents. This is followed by a clamping mode test to verify 10 A emission at $\leq$ 20 volts. Also, a series of ignitions followed by operation in idle mode are conducted to demonstrate a minimum of 10 ignitions in 6.0 minutes or less. Qualification of the flight HCAs are performed at the system level.

Hardware Schedule

The HCA development program was initiated in 1992. This activity included design definition, development tests, and hollow cathode life tests.

In May 1993, the enclosed-keeper geometry was selected for the ISS HCA application. The preliminary design review for the HCA was completed in July 1994, and the critical design review was completed in September 1995.

Fabrication of the deliverable HCAs was initiated in February 1996. The MTAM, engineering model, and qualification unit HCAs were delivered in February 1996, June 1996, and May 1997 respectively. All of the flight unit HCAs have been fabricated and have completed acceptance testing. The first two flight units are scheduled for delivery in October 1997 to accommodate the launch of the first plasma contactor systems in 1998.

Conclusions

A hollow cathode assembly is under development in support of the space station plasma contactor system. Based on technical and schedule considerations, NASA was requested to manufacture and deliver the engineering model, qualification model, and flight HCA units for the plasma contactor system as government furnished equipment to the plasma contactor system contractor Rocketdyne.

To date, an HCA cathode has demonstrated approximately 28,000 hours lifetime, two development unit HCAs have demonstrated over 10,000 hours lifetime (in on-going tests), and one development unit HCA has demonstrated more than 32,000 ignitions. A full set of tests (e.g. vibration, thermal vacuum) have been completed to verify the design. All of the flight unit HCAs have been fabricated and have completed acceptance testing. The first two flight units are scheduled for delivery in October 1997 to accommodate the launch of the first plasma contactor systems in 1998.

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[2]Moorehead, R.W., Deputy Director, Space Station Freedom Program and Operations, communication to Work Packages 1-4 Directors, dated April 3, 1992.
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[9]Kaufman, H.R., Advances in Electronics and Electron Devices, Vol. 36, Academic Press Inc., 1974.

[10]Verhey, T.R., "28,000 Hour Xenon Hollow Cathode Life Test Results," IEPC Paper No. 97-168, August 1997.

[11]Personal communication, Zampino, E., NASA-LeRC, January 1996.

Table I - Space Station HCA Attributes

Design - • Enclosed-keeper geometry • Hollow cathode with low-work funtion electron emitter Performance - • electron emission current: 10 A when biased 20 volts wrt external anode • input power (typical) conditioning/heater power: 10.6 W and 54.7 W ignition/heater power: ≤ 76 W steady-state operation/anode power: ≤ 44 W 'idle' mode • gas: xenon, high-purity • xenon consumption rate (typical): ≥ 5.80 sccm • ignition time: ≤ 6.0 minutes (typical) • lifetime: >18,000 hours, continuous-operation • ignitions: ≥6000 requirements; >32,000 demonstrated • thermal operating: -43 deg. C to +91 deg. C • thermal dormant: -43 deg. C to +82 deg. C	Mechanical Characteristics - • mass: approximately 0.25 kg • parts count: 30 • size: 15.0 cm (less gas line) x 3.2 cm dia. (7.6 cm dia. at flange) • vibration: 16.5 G_{rms} random, all 3 axes, 60 seconds Interfaces - • mounting interface flange to ISS plasma contactor system • single gas line to xenon gas feed system • 3-wire harness to power electronics unit Development Status - • development unit lifetesting on-going • MTAM, engineering, and qual. unit HCAs delivered • flight HCAs fabrication and testing completed

Table II - Space Station HCA Requirements and Verification Matrix

Requirement or Specification	Capability	Verification Method[1]				Level[2]		Comment
		D	A	I	T	C	S	
Lifetime: 18,000 hours, continuous-operation	>18,000 hours							verified via similarity analysis, and results of lifetests on development HCAs
Emission: up to 10 A electron current	>10 A							verified via flight HCA acceptance test
Clamping voltage: 20 volts, at 10 A emission	15 volts							verified via flight HCA acceptance test
Ignitions - 6000 cycles with 99% ignition reliability 10 ignitions within 6.0 minutes	 32,000 ignitions >4,000 ignitions							verified via similarity analysis, and results of lifetests on development HCAs verified via flight HCA acceptance test
Flow rates: 5.80 sccm to 7.50 sccm xenon	5.80 sccm							verified via flight HCA acceptance test
Handling: HCA-imposed procedures								requirement imposed on system
Storage/Environmental Exposure: HCA-imposed limits	1250 hours atm. exp.							requirement imposed on system; exposure log kept
On-Orbit Environments - Thermal operating: -43 deg. C to +91 deg. C Thermal dormant: -43 deg. C to +82 deg. C Pressure: <5.0×10^{-6} torr Ionizing radiation: 20 krads (Si) total Cold-soak storage: 5 years in space environment	 -56 deg. C -54 deg. C >5.0×10^{-6} torr >20 krads >5 years							 verified via similarity analysis and develop. HCA test verified via similarity analysis and develop. HCA test; flight HCA thermal cycling at system level verified via similarity analysis and develop. HCA test
Materials and Processes: per SSP 30233								verified via materials documentation
Vibration - 0.5 G sine, all 3 axes, 1 octave per minute and 16.5 G_{rms} random, all 3 axes, 60 seconds	same							verified via similarity analysis, and results of vibration tests on development HCAs; flight HCA vibration tests at system level
Contamination releases: per SSP 30426								
Weight: 0.27 kg	0.25 kg							

[1]Verification methods: D=design; A=analysis; I=inspection; T=test. [2]Level: C=component; S=system.

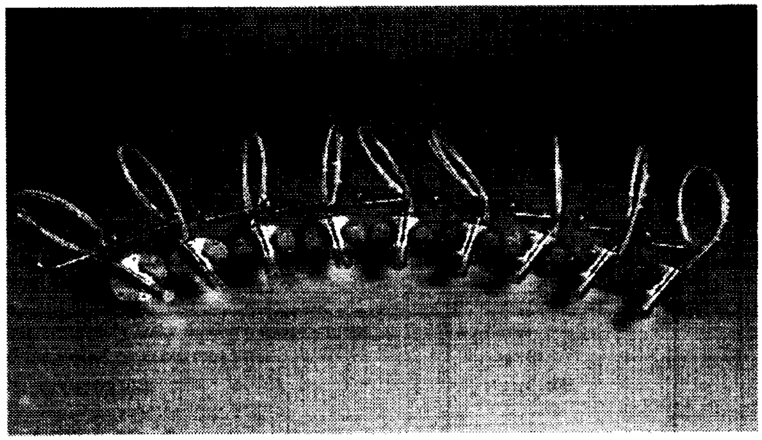

Figure 1. Qualification and flight HCAs.

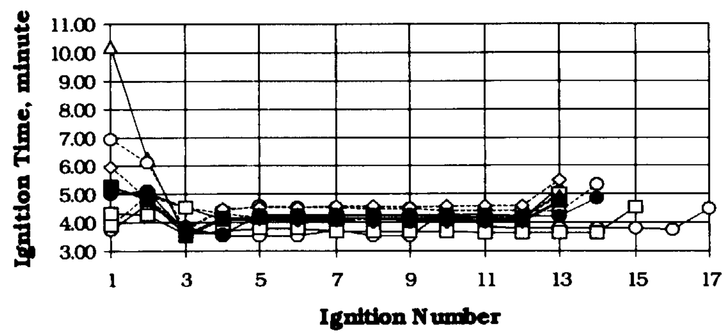

Figure 2. Ignition time versus ignition number, for all flight HCAs.

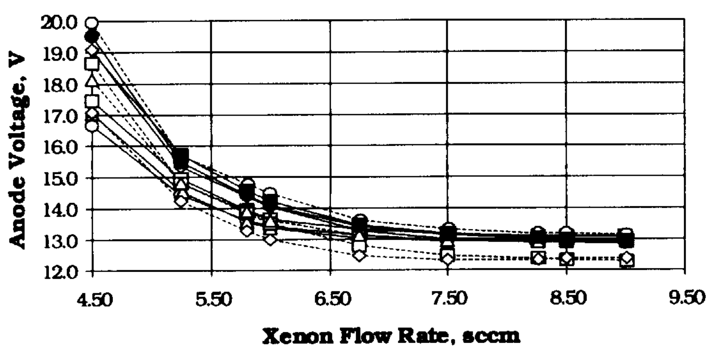

Figure 3. Anode voltage versus xenon flow rate for all flight HCAs.

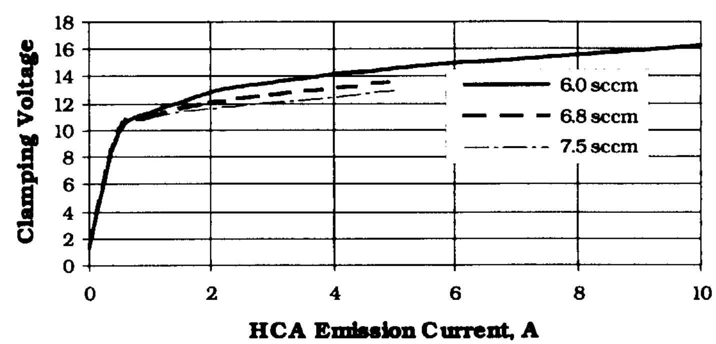

Figure 4. Clamping voltage versus emission current for several flow rates.

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13. ABSTRACT (*Maximum 200 words*)

A plasma contactor system was baselined for the International Space Station (ISS) 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 efforts on ion thruster systems. The plasma contactor includes a hollow cathode assembly (HCA), a power electronics unit, and a xenon gas feed system. Under a preflight development program, these subsystems were taken to the level of maturity appropriate for transfer to U.S. industry for final development. NASA's Lewis Research Center was subsequently requested by ISS to manufacture and deliver the engineering model, qualification model, and flight HCA units. To date, multiple units have been built. One cathode has demonstrated approximately 28,000 hours lifetime, two development unit HCAs have demonstrated over 10,000 hours lifetime, and one development unit HCA has demonstrated more than 32,000 ignitions. All 8 flight HCAs have been manufactured, acceptance tested, and are ready for delivery to the flight contractor. This paper discusses the requirements, mechanical design, performance, operating specifications, and schedule for the plasma contactor flight HCAs.

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