Status of Xenon Ion Propulsion Technology

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This paper describes a working-model xenon ion propulsion subsystem (XIPS) designed for north-south stationkeeping (NSSK) of 2500-kg-class geosynchronous communications satellites. The XIPS consists of a 25-cm-diam laboratory-model thruster, a breadboard-model power supply, and a flight-prototype pressure regulator (the critical component of the pressure-regulated xenon feed system). With a thrust of 63.5 mN, specific impulse of 2800 s, and thruster efficiency of 65%, the XIPS performance is believed to be the highest ever reported for an ion thruster operated at 1.3-kW input power. The XIPS power supply accepts an input power of about 1.4 kW from a 28- to 35-V bus and converts it into the seven outputs required for startup and operation of the thruster. The simplified power supply contains only about 600 parts and has demonstrated an efficiency of 90% and a specific mass of about 8 kg/kW. The results of a highly successful wear-mechanism test in which the working-model XIPS was operated for 4350 h and 3850 on/off cycles are presented. These hours and cycles are equivalent to well over 10 years of NSSK on large communications satellites.

Nomenclature

F = thrust, mN
I_{sp} = specific impulse, s
J_A = accelerator electrode current, mA
J_b = beam current, A
J_{ck} = cathode keeper current, A
J_d = decelerator electrode current, mA
J_E = cathode emission current, A
J_{nk} = neutralizer keeper current, A
$\dot{m}_c$ = discharge cathode flow rate, mA
$\dot{m}_m$ = discharge plenum flow rate, A
$\dot{m}_n$ = neutralizer cathode flow rate, mA
P_T = thruster input power, W
P_{tk} = vacuum chamber pressure, Pa
r = radius, cm
r_b = beam radius, cm
V_A = accelerator electrode voltage, V
V_b = beam voltage, V
V_{ck} = cathode keeper voltage, V
V_D = discharge voltage, V
V_g = neutralizer coupling voltage, V
V_{nk} = neutralizer keeper voltage, V
η_e = thruster electrical efficiency, %
η_T = thruster efficiency, %

Introduction

THE most likely near-term use of ion propulsion is for north-south stationkeeping (NSSK) of geosynchronous communications satellites. An early study of that application[1] showed that onboard batteries (normally used to power the satellites during periods of eclipse) could be used to operate ion thrusters for about 1 h daily without incurring the mass penalty for supplying the electric power normally associated with the use of electric propulsion. More recent studies of ion propulsion for the NSSK application[2,3] have confirmed that a significant net performance improvement could be achieved by replacing, or even augmenting, chemical propulsion systems with high-specific-impulse ion propulsion. The performance improvement could be realized as a reduction in vehicle launch weight (lower launch cost), an increase in the amount of revenue-producing equipment (additional payload), or an extension of the maneuver lifetime of the spacecraft (added revenue).

For example, analyses have shown that the NSSK maneuver lifetime of Intelsat VI, the world's largest communications satellite, could be increased from its present 14 years to nearly 23 years by using xenon ion propulsion to augment the chemical-bipropellant propulsion system. The premise of the study was to replace about 200 kg of chemical bipropellant (about a 4-yr supply of NSSK propellant) with a fully redundant xenon ion propulsion subsystem (XIPS) of equal mass. The XIPS would consist of two thrusters, two power supplies, two propellant control units (with individual redundancy for the critical elements), and two propellant tanks filled with enough xenon to enable NSSK maneuvering for about 13 years.

The baseline XIPS and the status of the ion propulsion technology are described in the remainder of this paper. Though the NSSK application is emphasized, several recent studies[4,5] have shown that high-power versions of the baseline XIPS, or its derivatives, can offer significant performance advantages for other more demanding applications such as orbit raising and maneuvering.

Xenon Ion Propulsion Subsystem

A schematic diagram of the XIPS is shown in Fig. 1. This compact arrangement of a 25-cm-diam thruster, its power supply, and its propellant tankage and control unit is the baseline configuration of one-half of a fully redundant propulsion system designed for NSSK of large spacecraft, such as the Intelsat VI. The thruster produces 63.5 mN of thrust with an input power of 1.3 kW, resulting in a thrust-to-power ratio of 49 mN/kW and a thruster efficiency of 65%. With a specific impulse of 2800 s, the XIPS requires only about one-tenth of the propellant mass used by state-of-the-art chemical-bipropellant thrusters currently employed for NSSK.

Xenon propellant is stored as a high-pressure gas, with a density about twice that of water. The flow of xenon into the thruster is controlled passively, by use of a pressure regulator to maintain a constant pressure on the upstream side of flow

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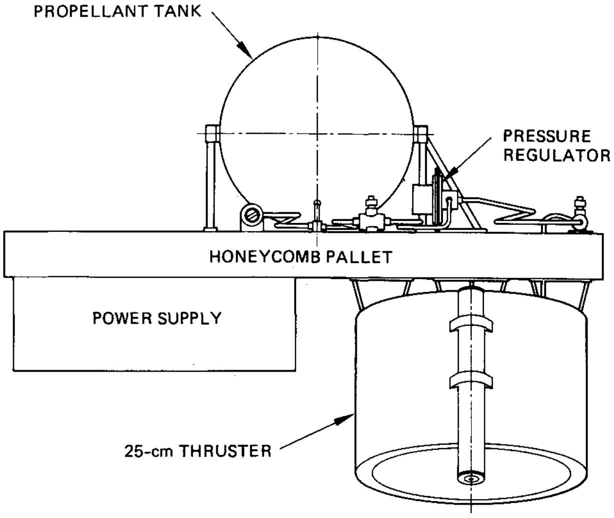

Fig. 1 Xenon ion propulsion subsystem (XIPS).

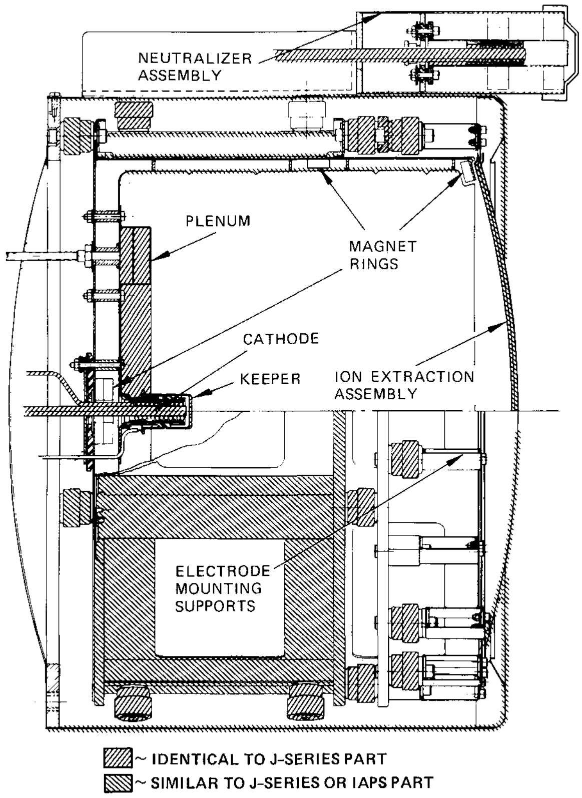

Fig. 2 25-cm-diam laboratory-model XIPS thruster.

restrictors located in the propellant lines leading to the discharge chamber, its cathode, and the neutralizer cathode.

The power supply requires an input power of about 1.4 kW and can operate over a spacecraft-bus-voltage range of 28–35 V. The unit is completely self-contained, including all of the timing and control mechanisms required to start, operate, and stop the thruster, as well as to detect current overloads in the screen or accelerator power modules and then to implement corrective action. The maximum output voltage of the power supply is provided by the screen module, which requires an output of only 750 V to give xenon ions an exhaust velocity equivalent to about 3300-s specific impulse (uncorrected for propellant utilization efficiency). Earlier mercury ion propulsion systems required a screen-module output of about 1.1 kV. The low output voltage of the XIPS simplifies spacecraft integration and voltage isolation.

A laboratory-model system containing the essential features of the XIPS shown in Fig. 1 was completed during 1985.[6] The following subsections describe the laboratory-model XIPS hardware along with the progress toward defining flight-prototype designs and architectures. In a later section, we describe the performance and operating characteristics of the laboratory-model XIPS in more detail and discuss the successful completion of a wear-mechanism test during 1987, in which this laboratory-model hardware was operated for over 4350 h and 3850 on/off cycles (the equivalent of a full mission lifetime in the Intelsat VI application).

Thruster

The laboratory-model XIPS thruster is shown in Fig. 2. The discharge chamber employs a ring-cusp magnetic-field geometry that was derived from the original ring-cusp configuration developed by Sovey.[7] The discharge and neutralizer cathodes have geometries that are similar or identical to those employed in the NASA/Hughes 30-cm-diam J-series thruster.[8] Ion extraction is accomplished with a three-grid arrangement consisting of screen, accelerator, and decelerator electrodes. The electrodes are attached to the thermally compliant mounting structure shown in Fig. 2. The lightweight structure minimizes temperature differences and thermal mismatch that could otherwise occur with J-series thruster-type electrodes and their stiffening rings during cyclic operation of the thruster. The unique arrangement of column-type supports allows for structural rigidity in the axial and transverse directions, while providing for nearly unrestrained thermal expansion of the electrodes in the radial direction.

The electrode aperture compensation is sufficient to provide near-paraxial ion flow from the spherical electrodes, as shown in Fig. 3. The thrust loss factor,[9] calculated from the beam dispersion data of Fig. 3, is 0.986. The high degree of beam collimation is reflected in far-field ($\simeq$14 beam diameters away) measurements of the ion beam current density, where a point-source approximation is valid.[10] Figure 4 shows that the entire beam is contained within a 21-deg half-angle and that about 95% of the beam is contained within a 14-deg half-angle. The high degree of beam collimation demonstrated with our three-grid ion-extraction assembly greatly facilitates the integration of XIPS onto both spin- and body-stabilized spacecraft.

The neutralizer cathode employs magnetic augmentation to enhance performance by minimizing its flow-rate requirement. The magnetic field tends to increase the ionization efficiency of the electrons emitted by the cathode, resulting in cathode flow-rate requirements that are comparable with those of mercury hollow cathodes. With comparable neutralizer keeper and coupling voltages, the neutralizer cathode flow rate of the XIPS is less than one-tenth that required to operate a J-series neutralizer on xenon.[11]

We anticipate that the following major design changes would be required in order to upgrade the laboratory-model XIPS thruster to a configuration suitable for flight: 1) the use of titanium and aluminum in place of stainless steel to reduce the thruster mass; 2) structural design improvements in the discharge chamber and the neutralizer assembly and its mounting; 3) positive retention of the magnet rings within the discharge chamber; 4) flake control on the discharge anode (this change simply incorporates the heritage of the 30-cm mercury ion thruster; the 4350-h XIPS thruster described in a later section did not definitize the need for flake control within the discharge chamber); 5) incorporation of propellant electrical isolators in the xenon feed lines; and 6) the use of a propellant manifold with integral flow restrictors. A flight-prototype XIPS thruster would be expected to achieve the same high level of performance and lifetime attained by the laboratory model, to have reduced thruster mass, and to possess the structural integrity required for launch vibration and shock.

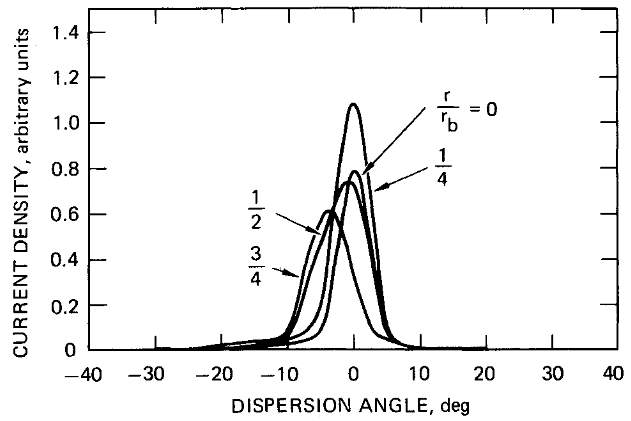

Fig. 3 Ion beam dispersion of laboratory-model XIPS thruster.

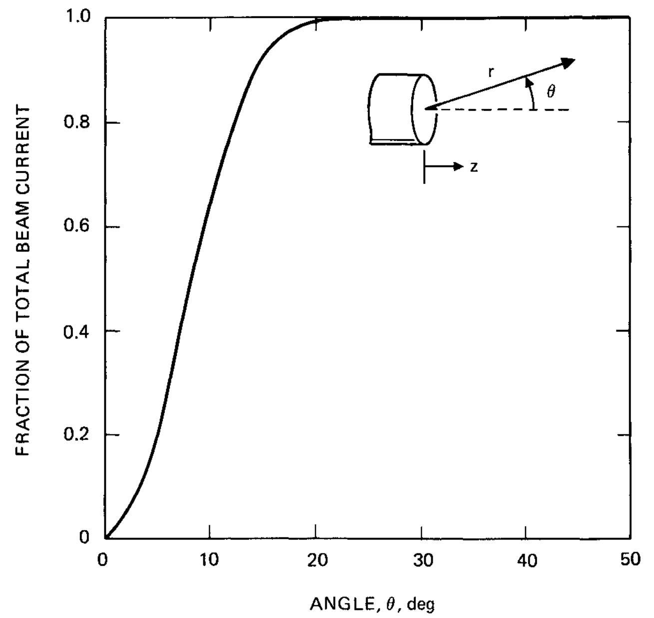

Fig. 4 Angular dependence of laboratory-model XIPS exhaust beam.

Power Supply

The XIPS power supply is highly simplified compared with earlier designs that were developed for mercury ion thrusters. The functional-model power processor unit (FM/PPU) that was developed for the J-series thruster[8] controlled the discharge voltage, beam current, and neutralizer keeper voltage by using complex active feedback to regulate the mercury flow rates through the cathode and main vaporizers. The feedback loops required isolated current and voltage sensing, in addition to sensitive high-gain feedback circuits. This design approach, along with requirements for numerous operating modes and set points (motivated by its intended application to solar electric propulsion, in which available power changes along spacecraft trajectories), made the FM/PPU very complex and costly.

The operating characteristics of the XIPS thruster (namely, its ability to operate with the discharge voltage, beam current, and neutralizer keeper voltage controlled in an open-loop manner), along with single-set-point operation and relaxed mission requirements (±10% thrust regulation), have allowed us to design a highly simplified power processor. The breadboard-model XIPS power supply contains approximately 600 parts, with no redundancy or telemetry. Addition of telemetry would require another 200 parts. Nevertheless, the 800 parts required for a nonredundant XIPS power supply with telemetry represents a factor-of-six reduction in parts count compared with the 4000 parts used in the partially redundant FM/PPU. (An improved, nonredundant FM/PPU design contained about 2500 parts, giving a factor-of-three reduction for the simplified XIPS design).

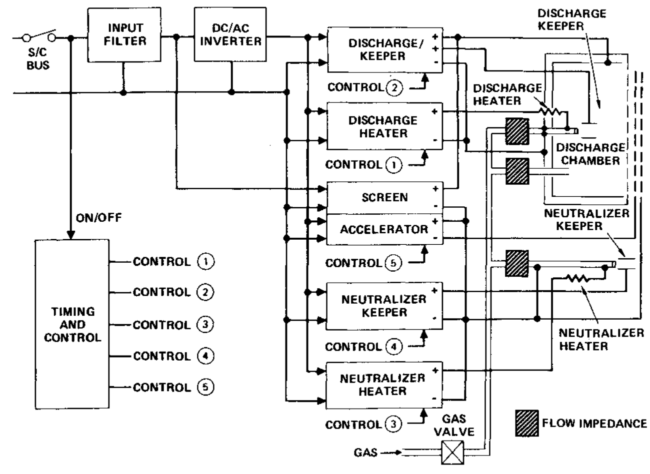

Fig. 5 Breadboard-model XIPS power supply.

A block diagram of the breadboard-model XIPS power supply is shown in Fig. 5. The power supply contains the seven power modules (screen, accelerator, discharge, 2 keepers, and 2 heaters) and simple control logic (no microprocessor) required to operate the thruster. When bus power is applied, the control logic automatically sequences the power modules to start the thruster, recycle the high voltages in case of a grid arc, and restart the thruster if one of the discharges should happen to go out.

The power supply employs a dedicated dc-to-dc inverter for the screen module (which processes about 90% of the total power). The inverter uses a two-choke buck regulator design similar to that of a 'Cuk inverter.[12] It produces near-zero input current ripple, which greatly reduces the size of the input filter necessary to meet electromagnetic interference (EMI) requirements. The remaining six modules operate from the output of a dc-to-ac inverter and are regulated by controlling their ac input voltage or current. In all power modules, current and voltage sensing for regulation and telemetry is performed on the primary side of the output transformers, resulting in simplification and higher reliability at the expense of slightly reduced accuracy. The output requirements of the seven power modules are presented in Table 1. The tabulated design regulation requirements are for bus voltage and load variations, whereas the measured regulations are for bus voltage variations only.

The overall efficiency of the power supply has been increased from approximately 87 to 90%, and its specific mass has been reduced from approximately 11 to about 8 kg/kW (compared with the FM/PPU). Table 2 lists the efficiency, mass, specific mass, size, and input power for the individual modules of the breadboard-model XIPS power supply.

Propellant Tankage and Control Unit

The baseline architecture for the propellant tankage and control unit (PTCU) is depicted in Fig. 6 for a typical redundant configuration of thruster and pressure regulator. Xenon is stored at moderate-to-high pressure [7.6–29 MPa (1100–4200 psia)], regulated to low pressure [69 kPa (10 psia)], and then expanded through flow restrictors that are sized to the flow-rate requirements of the discharge-chamber plenum and the discharge and neutralizer cathodes. The choice of gas storage pressure depends on several factors, including the spacecraft configuration, the propellant mass, and the availability of flight-qualified tanks.

Table 1 Output requirements of breadboard-model XIPS power supply

Power Module	Maximum output V	Maximum output A	Nominal output V	Nominal output A	Nominal output W	Regulation, % E or I	Regulation, % Design	Regulation, % Measured
Screen	750	1.6	750	1.45	1088	E	10	1
Accelerator	300	0.025	300	0.005	1.5	E	10	2
Discharge	50	9.0	28	6.5	182	I	10	4
Discharge keeper	30	1.0	14	1.0	14	I	20	20
Discharge heater	20	4.4	—	—	—	I	10	3
Neutralizer keeper	30	1.0	16	1.0	16	I	10	4
Neutralizer heater	20	4.4	—	—	—	I	10	3
Total power	—	—	—	—	1302	—	—	—

Table 2 Performance, power, and mass breakdown of breadboard-model XIPS power supply

Power module	Efficiency, %	Mass, kg	Specific mass, kg/kW	Size, cm	Input power, W
Screen	93	4.2	3.86	—	1170
Discharge	≈83	1.4	7.69	—	219
Low-power modules (total)	≈70	3.0	15.80	—	31
ac inverter	≈97	1.6	2.90	—	258
Total power supply	90 (92)[a]	10.2 (10)[a]	7.95 (7.8)[a]	45×60×15 (30×60×15)[a]	1428

[a]Estimate for flight packaging.

For example, on a spin-stabilized spacecraft such as the Intelsat VI, two interconnected tanks are necessary to minimize imbalance produced by propellant depletion. An existing flight-qualified tank can store one-half the xenon required to perform 13 years of NSSK at a pressure of 29 MPa (4200 psia), resulting in a tankage fraction of about 0.15. Design calculations indicate that, if the storage pressure is reduced to 7.6 MPa (1100 psia), the tankage fraction could be reduced to about one-half the value corresponding to 29 MPa (4200 psia) storage, with an increase in tank diameter of only about 12%.[13] Moreover, such a tank could be filled directly from commercially supplied xenon storage containers. Low-pressure storage would also simplify the design and safety requirements of the gas-handling components between the storage tank and the pressure regulator. However, the tank design modifications might be extensive enough to entail further qualification testing.

The laboratory-model XIPS employs the critical element of the flight-qualified PTCU architecture—the pressure regulator. The unit that we have been testing since 1985 is a modified version of a single-stage regulator that was used on the Viking spacecraft. The original design was modified to provide lower output pressure [69 kPa (10 psia)] at reduced flow rate (26.5 sccm). In tests using high-pressure argon as the working fluid, the regulated output pressure was found to remain at 67.91 kPa (9.85 psia) ± 0.36% over an input pressure ranging from 29 MPa (4200 psia) down to 3.5 MPa (500 psia). No change in regulator performance has been observed during nearly 2 years of daily use.

Performance and Lifetime

The nominal operating and test conditions of the XIPS thruster are summarized in Table 3. Thruster performance corresponding to those conditions is summarized in Table 4.

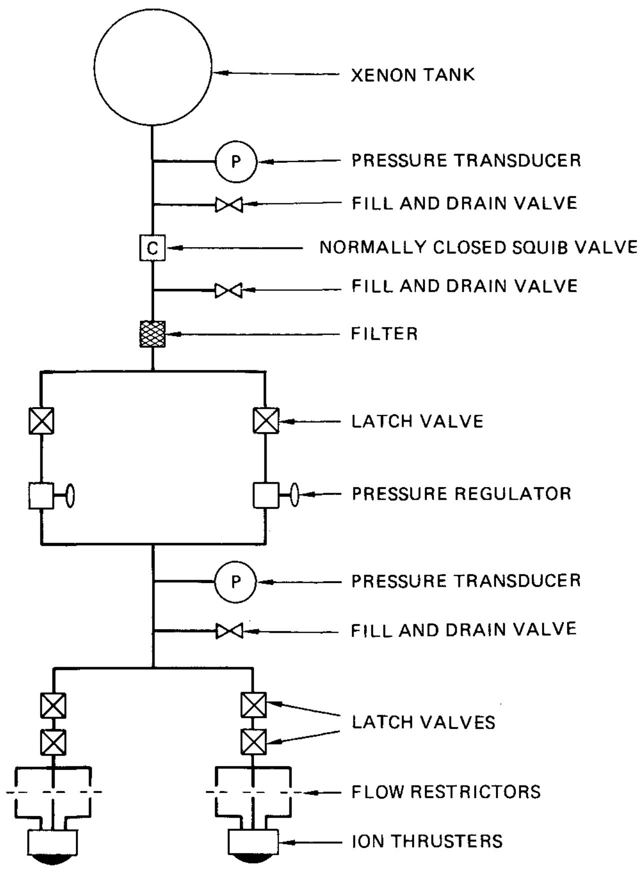

Fig. 6 Xenon propellant tankage and flow control system.

Sensitivity of thrust and specific impulse to variations in power supply outputs and xenon flow rate are listed in Table 5. Taking into account the power supply regulation and pressure regulator performance discussed earlier, the maximum deviation from nominal performance that can be predicted is about ±3% on thrust and specific impulse. The maximum off-nominal thrust is well within expectations for the NSSK application, requiring only infrequent adjustments in thrust duration to maintain communications satellites within ground-tracking capability.

A 15-month XIPS wear-mechanism test was conducted using the laboratory-model thruster, the breadboard-model power supply, and the flight-prototype xenon pressure regulator. The test was concluded in March 1987, after having accumulated 4350 h and 3850 on/off cycles—the equivalent of

Table 3 Nominal operating conditions of laboratory-model XIPS thruster

Operating parameter	Value
Beam	
J_b, A	1.45
V_b, V	750
J_A, mA	4.8
V_A, V	300
J_d, mA	6.4
Discharge	
J_E, A	6.3
V_D, V	28
Keeper	
J_{ck}, A	1.0
V_{ck}, V	14
J_{nk}, A	1.0
V_{nk}, V	16
V_g, V	22
Propellant flow rate	
$\dot{m}_m$, A	1.57
$\dot{m}_c$, mA	58.7
$\dot{m}_n$, mA	45.8
Tank pressure	
P_{tk}, Pa	1.23×10^{-3}

Table 4 Nominal performance of laboratory-model XIPS thruster

Performance parameter	Value
F, mN	63.5
I_{sp}, s	2800
P_T, W	1336
η_e, %	81.5
η_T, %	65.2

Table 5 Sensitivity of XIPS performance to variations in power supply output and xenon flow rate

Operating parameter	Performance sensitivity, %/% Thrust	Specific Impulse
	Power supply output	
V_b	0.8	0.8
V_A	0	0
J_E	1.2	1.2
J_{ck}	0	0
J_{nk}	0	0
	Xenon flow rate	
$\dot{m}_m$	0.3	−0.6
$\dot{m}_c$	−0.6	−0.6
$\dot{m}_n$	0	−0.1

over 10 years of NSSK on an Intelsat VI-class spacecraft and over 20 years of NSSK on smaller communications satellites. The values quoted are for failure-mode operation. In the normal operating mode, one-half the mission is performed using the redundant thruster, PPU, and PTCU. Therefore, the demonstrated hours and cycles correspond to 20 and 40 years of normal operation on a large and small spacecraft, respectively.

The primary thruster life-limiting wear mechanisms identified during the first few hundred hours of testing were cathode orifice erosion and elongation of the outermost apertures in the decelerator electrode. Minor configuration changes were incorporated into the test hardware to eliminate those wear mechanisms; the effectiveness of the solutions was confirmed by the successful completion of the test goals. One of the most significant results of the extended-duration test was the confirmation that thruster startup and transition to full-thrust operation could be accomplished throughout the required operational lifetime of the thruster using fixed flow rates to both cathodes and the propellant plenum.

The only long-term performance loss observed during the wear test was a gradual reduction in beam current, amounting to about 4% per thousand hours of operation. That anticipated performance degradation was the result of charge exchange ion erosion of the accelerator apertures, causing them to increase in diameter.[14] With fixed flow rates into the thruster, the effect of increasing the accelerator apertures is to lower the pressure in the discharge chamber. The pressure loss results in a reduction in the ion-production rate, which is manifested as a decrease in beam current. At the conclusion of the test, we confirmed that accelerator-electrode erosion was the major cause of the observed performance loss. By replacing the ion-extraction assembly with one that had pretest aperture dimensions, we regained all but about 7% of the observed 19% performance loss.

Though accelerator aperture enlargement due to charge exchange ion erosion is a natural consequence of the use of a three-grid ion-extraction assembly (as opposed to a two-grid configuration, in which the charge exchange ion erosion is concentrated on the downstream face of the electrode), we emphasize that the wear-mechanism test was conducted in a pressure environment of about 1×10^{-3} Pa (8×10^{-6} Torr). Short-term tests (in which lower facility pressures could be maintained) have shown that the charge exchange ion current to the accelerator electrode was about a factor of two higher during the wear-mechanism test than it would have been under ideal vacuum conditions. Therefore, the observed wearout rate is about twice as high as can be anticipated in a space vacuum environment, and the XIPS long-term performance loss should amount to no more than about 8% over a mission life in excess of 4000 h. During operation of the thruster, the facility pressure of about 1×10^{-3} Pa (8×10^{-6} Torr) was mostly due to inert xenon. Under no-flow conditions, the facility pressure drops to about 5×10^{-6} Pa (4×10^{-8} Torr), which is believed to be well below the point at which facility residual gases (such as nitrogen) could influence discharge-chamber and ion-optics wear rates.[15]

Conclusions

The technological feasibility of a simplified ion propulsion system for NSSK of geosynchronous communications satellites has been established. The major obstacle to prior use of cesium or mercury ion thrusters for that application has been eliminated by using chemically inert xenon as the propellant. The change to xenon also permits major simplifications in the design of the thruster, its power supply, and its propellant feed system. The lower atomic mass of xenon reduces the maximum output voltage of the power supply to 750 V, which simplifies spacecraft integration and voltage isolation.

In a relatively short period, a working model of a xenon ion propulsion subsystem has been developed that includes a 25-cm-diam laboratory-model thruster, a breadboard-model power supply, and a flight-prototype pressure regulator. A very high level of performance has been demonstrated with that hardware; the thrust subsystem produces 63.5 mN of thrust at a specific impulse of 2800 s, with an input power of about 1.4 kW. Thruster startup, shutdown, operation, and corrective actions are performed by a completely self-contained power supply that operates with an efficiency of about 90% and has a specific mass of about 8 kg/kW. The highly simplified power supply contains only about 600 individual parts. The pressure regulator has demonstrated its ability to regulate to within ±0.4% of its nominal output pressure, independent of its inlet pressure.

The working-model XIPS has completed a highly successful wear-mechanism test, the hours and cycles of which are equivalent to a full failure-mode mission lifetime for large communications satellites, such as the Intelsat VI. There are no known obstacles that would prevent this technology from demonstrating much longer operational lifetimes or higher power levels. The only long-term performance degradation mechanism has been identified as erosion of the accelerator apertures, leading to a projected performance loss of less than 2% per thousand hours of operation.

Acknowledgments

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