The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System for GEO Satellite Applications*†

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This paper summarizes the current program at General Dynamics Space Propulsion Systems (formerly Primex Aerospace Company) and Lockheed Martin to develop and qualify a 4.5 kW Hall Thruster Propulsion Subsystem. This subsystem is being developed to support geo-synchronous satellite applications. This paper describes the mission application, performance, program plan and current status of the development program. The overall system, including the Power Processor Unit, the Xenon Flowrate Controller, the Hall Thruster and Cathode and the Xenon Feed System is also described.

Introduction

Lockheed Martin Space Systems Company (LMSSC) and General Dynamics Space Propulsion Systems (GD-SPS) are pursuing development of a Hall Thruster Propulsion System (HTPS) for a wide range of applications on geosynchronous earth orbiting satellites. The system currently under development is planned to be used for both orbit insertion from an initial geosynchronous transfer orbit and on-orbit stationkeeping and repositioning maneuvers. The HTPS will take advantage of the dual-mode capabilities and wide operating power range of the GD-SPS' BTP-4000 Hall thruster (HT) to maximize efficiency for each mission phase. In addition, each Hall thruster will be mounted on a two-axis gimbal to provide flexibility in attitude control and thrust vector orientation under a closed loop control system.

GD-SPS is responsible for the development and qualification of the Hall thruster, Power Processor Unit (PPU) and Xenon Flowrate Controller (XFC) and all associated integration tasks between these components. LMSSC has responsibility for the xenon tanks, the Xenon Feed System (XFS) and all spacecraft level integration tasks. Moog Space Systems Division, under contract to GD-SPS, was selected to develop the XFC and will also be providing the XFS directly to LMSSC.

GD-SPS has been developing a family of Hall thrusters and PPUs since the mid 1990's. This development has included both 2 kW and 4 kW class HTs designated as the BPT-2000 and BPT-4000. Designs for both Hall thrusters have been fabricated and extensively tested at the GD-SPS thruster firing facility as reported in earlier publications [1] [2] [3]

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[4]. The HTPS Hall thruster design draws heavily from these previous efforts and is being optimized on the HTPS program for the stringent launch vehicle dynamic loads, thermal environments and performance requirements. The HTPS PPU design draws heavily from the Hall thruster RHETT PPU developed in 1997 by GD-SPS and successfully flown on the STEX satellite in 1998 [5] [6]. Since that time GD-SPS has developed higher power, more efficient, and lower cost HT PPUs under a multi-year internal technology development program. Breadboard PPUs developed on this program have been extensively tested with both the BPT-2000 and 4000 thrusters and various xenon flowrate control systems [3]. The HTPS PPU draws heavily from these previous designs and is being optimized for the HTPS specific command, telemetry, power and environmental interfaces.

This paper provides a design overview for each of the HTPS components, their current development status and demonstrated performance and planned future development and qualification activity. In addition, system level integration issues are discussed along with planned testing events.

HTPS Overview

The selected HTPS architecture is shown in Figure 1 and was based on extensive trade studies to optimize reliability, performance and scaleability. The results of these trades yielded a system that utilizes four (4) strings of PPUs, HTs and XFCs with each string capable of operating at up to 4.5 kW of discharge power. Only two of the four strings will fire simultaneously on the current design, however this approach could be scaled up to utilize six or eight strings if the mission warranted. This architecture provides 4 for 3 redundancy, allowing the loss of one string of hardware without degrading mission performance. The system is also designed to take advantage of the BPT-4000's ability to operate over a large range of discharge power and voltages. The system is designed to operate in a high thrust mode during orbit insertion. This mode combines a lower anode operating voltage with a higher power setting to maximize thrust and minimize the time required to achieve final orbit. The HTPS can be used in conjunction with conventional bipropellant engine apogee firings to optimize satellite mass to orbit within a given transfer orbit time constraint. Once the electric propulsion portion of transfer orbit has commenced, the Hall thrusters will operate almost continuously until the satellite reaches the desired final orbit.

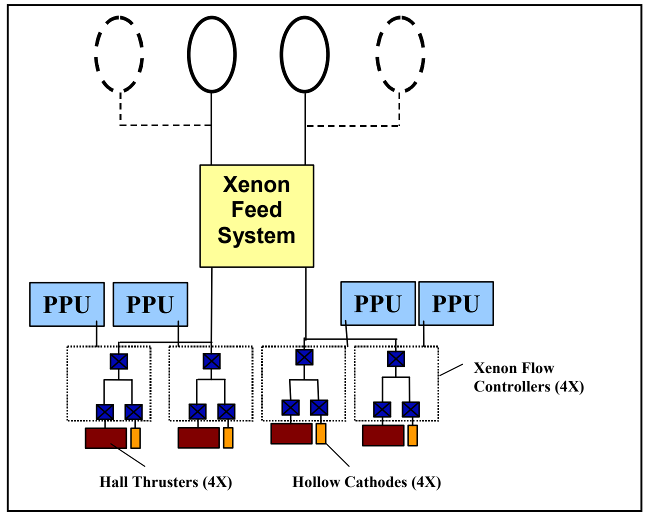

Figure 1 – HTPS Schematic

Once on-orbit, the gimballed HTs will be used to perform all stationkeeping activities. In this capacity, the thrusters will operate in a high-efficiency mode that utilizes a higher anode operating voltage to increase I_{sp} at all operating powers. Depending on the specific spacecraft configuration, a single thruster may be capable of both east/west (longitude control) and north/south (inclination control) stationkeeping, improving system level redundancy. In addition, repositioning maneuvers during life can be performed in either high-thrust or high-efficiency modes by flying the satellite in the same manner as transfer orbit. Finally, HTs may be used alone or in conjunction with chemical thrusters to improve the propellant efficiency of momentum unloading operations.

The HTs will be mounted on two-axis gimbals located external to the satellite, to facilitate the optimization of the thrust vector depending on the type of maneuver being performed. All other components will be mounted internal to the satellite on the equipment panels. All command and telemetry from the PPU, HT and XFC will be provided via a MIL-STD-1553 data link. In addition to the various on/off commands for each power supply, the level of current provided by the PPU can be controlled via the data link for the anode, magnet, cathode heater and cathode keeper supplies. The anode voltage can also be commanded between 150 V and 400 V in 50 V increments. There are approximately 30 channels of telemetry available to monitor various operating parameters for each HT/PPU/XFC string during maneuvers. All power is obtained from the satellite's regulated +70 V power bus, which directly connects to the PPU.

HTPS Development Program Plan

The HTPS development program, which builds upon previous development efforts at both LMSSC and GD-SPS, was formally kicked of in September of 2000. The overall development program incorporates an extensive test program using developmental hardware, followed by the formal qualification testing of each of the HTPS components. Two flight-weight engineering development model (EDM) HTs have been fabricated and are being used for vibration, shock and thruster performance testing, including a 1,000 hour thruster firing test that is currently in progress. This testing will culminate in a formal Critical Design Review (CDR) meeting followed by the fabrication and qualification testing of an Engineering Qualification Model (EQM) HT. This testing will include a 5,600-hour thruster life test. The PPU development program includes the fabrication and testing of both a breadboard and EDM PPU prior to the fabrication and formal qualification testing of the EQM PPU. The XFC development program includes the fabrication and test of an EDM XFC and the fabrication and formal qualification testing of the EQM XFC.

During the development program, multiple system level tests are planned that utilize a HT, PPU and XFC to demonstrate all interfaces and control methods. The first of these tests were performed in March of 2001 using the breadboard PPU, laboratory model of the BPT-4000 and an EDM XFC. In addition, system level tests are planned to ensure all spacecraft interactions are well characterized. These tests will include the characterization of radiated and conducted EMI, signal transmission compatibility, thermal balance between the HT and gimbals and plume characterization testing.

Hall Thruster Overview

A flight design BPT-4000 Hall thruster has been completed and two engineering model thrusters built and tested as shown in Figure 2. The thruster is a high performance, dual-mode design capable of both a high-thrust, orbit-raising mode and a high specific impulse, stationkeeping mode.

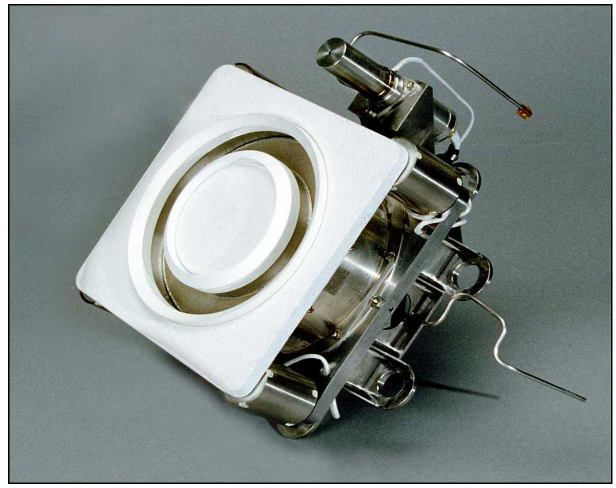

Figure 2 – BPT-4000 EDM Hall Thruster

Two flight-weight engineering development model (EDM) thrusters, including cathodes, have been assembled. One unit has successfully passed qualification level sine vibration, random vibration and shock testing and is currently undergoing a 1,000-hour risk mitigation life test. The design life of the thruster is projected to be at least 7,000 hours at 4,500 watts. The second EDM thruster assembly is being used for additional performance characterization, unit-to-unit repeatability testing, and system integration testing.

The flight-weight BPT-4000 design is based on the successful 130mm mid-diameter BPT-4000 lab thruster [1] [2]. It also leverages work done under funding from NASA-GRC on the development of multi-mode Hall thrusters to provide extended life capability and improved performance over a wide range of voltages [7]. Unlike previous Hall thrusters which are qualified for a single design point, as part of the HTPS program, the BPT-4000 will be qualified to operate at power levels from 3.0 to 4.5 kW and at both 300 and 400 V discharge voltages. This multi-mode capability provides maximum flexibility at the satellite level. It also provides maximum mass and cost savings by allowing low voltage, high thrust operation for reduced trip times during orbit raising and high voltage, high I_{sp} operation for stationkeeping to minimize propellant usage.

Thruster Performance and Test Results

The performance and plume characteristics of the EDM thrusters have been measured during extensive testing. Primary testing was conducted at GD-SPS in the Chamber 2 test facility. EDM #1 was also tested at the Aerospace Company to verify the GD-SPS facility and also to obtain additional plume characteristic data. At both facilities, the performance showed good agreement with published performance on the laboratory BPT-4000 and was above the minimum HTPS specification requirements at all four target operating conditions. Vacuum corrected efficiencies exceeded 57% at the 4.5 kW level and measured thrust was 294 mN at 4.5 kW, 300 V.

Extensive plume and performance characterization of the accelerator design has been conducted, and is described in detail elsewhere [8].

The EDM #2 thruster assembly (with cathode) successfully passed qualification-level random vibration, sine vibration and shock testing in July 2001. The EDM #2 thruster assembly is currently undergoing a 1,000-hour life test intended to provide risk mitigation for the upcoming qualification life test.

Planned Activity
The 1,000-hour life test on EDM #2 is scheduled to be completed in October 2001. The Critical Design Review (CDR) for the thruster is currently scheduled for 2002, followed by the start of the qualification test program, which includes a 5,600-hour life test.

Cathode Overview

General Dynamics has designed and built hollow cathodes since 1994 to support testing with the GD-SPS 30-cm Ion Engine [9], the TsNIIMASH TAL D-55, and most recently, GD-SPS's BPT-4000 Hall thrusters. The technical basis for all of the designs is the NASA hollow cathode for the space station plasma contactor [10], which has demonstrated over 28,000 hours of life. To maintain the heritage of this demonstrated long life capability, GD-SPS has maintained the dimensions and materials of the components critical to cathode operation. The cathode tube and orifice plate configurations have been maintained, as has the same 4:1:1 ratio of $BaO:CaO:Al_2O_3$ impregnant in the porous tungsten base of the emitter insert.

To reduce manufacturing cost, the NASA cathode design was subjected to an aggressive design-for-manufacturing analysis, which resulted first in a prototype cathode, and then was refined to the current qualification unit [11]. The current design has a reduced parts count, has a minimum of threaded fasteners, and minimizes the risk of poisoning the emitter during fabrication. The cathode is shown here in Figure 3.

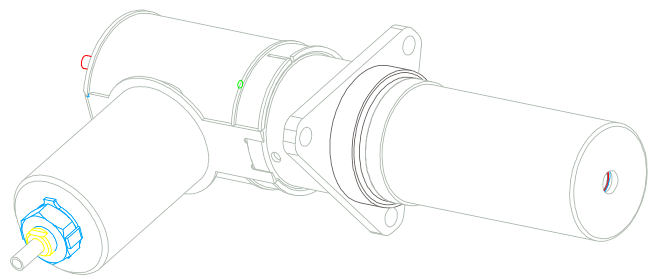

Figure 3 - GD-SPS Hollow Cathode

The cathode tube is a brazed and welded assembly that extends from the cathode orifice plate to the propellant isolator. The cathode tube and installed heater are mounted in an insulator body that provides both electrical isolation and a mechanical connection to the keeper and the cathode mounting flange. To protect the cathode from sputtering and to provide structure for the propellant isolator, the upstream side of the cathode is housed in a cathode cover that also covers the propellant isolator. In testing at GD-SPS, the propellant isolator has held off electrical potentials in excess of 3 kV over a pressure range of 0.2 to 60 Torr of xenon.

Test Results
To-date, three flightweight EDM cathodes have been built and tested. Two were built and assembled into the EDM #1 and EDM #2 thrusters as shown in Figure 4, and one was built as a program spare and to support cathode level EDM testing. As part of the EDM test programs, the cathode has successfully passed all performance requirements; qualification-level sine vibration, random vibration, and shock, and is currently undergoing a 1,000-hour life test.

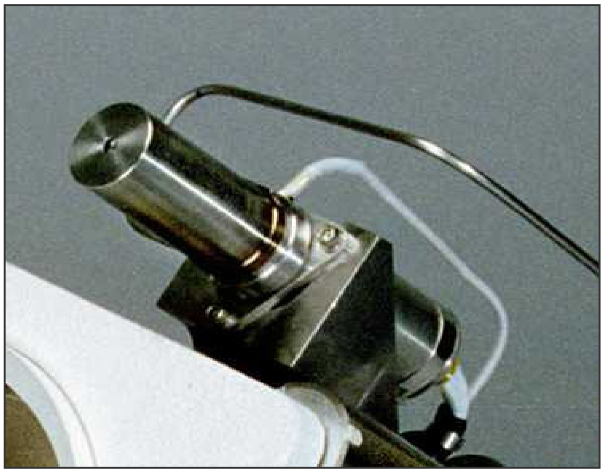

Figure 4 – BPT-4000 EDM Cathode Assembly

Planned Activity

As part of the thruster assembly, the cathode will complete the 1,000-hour life test in October 2001. The Critical Design Review (CDR) for the thruster and cathode is currently scheduled for early 2002, followed by the qualification test program. A more detailed review of the BPT-4000 Hall thruster and cathode design is presented in IEPC-01-11 [12].

Power Processor Unit Overview

The PPU is designed to provide all command, telemetry and power interfaces between the spacecraft and the BPT-4000 HT and XFC. The PPU provides regulated power to the HT for both startup and steady state operations. Commands and telemetry are communicated with the spacecraft utilizing a MIL-STD-1553B data link. Discharge power can set using data link commands to operate between 2 kW to 4.5 kW at voltages between 150 to 400 Volts. Commandable power is also provided to the thruster coils, cathode heater and cathode keeper. In addition, the PPU drives two solenoid-holding valves in the XFC and utilizes closed loop control to operate the Proportional Flow Control Valve (PFCV) to regulate the level of xenon provided to the thruster which controls the discharge to the commanded level. The design of the PPU is largely based on technology developed under General Dynamic's internal development programs during the 1990s.

The functional block diagram of the PPU is shown in Figure 5 and illustrates each of the key elements of the PPU. The PPU directly interfaces with a regulated 70-Volt spacecraft power bus and incorporates input power relays and EMI filtering. Two paralleled anode supplies are utilized, each capable of providing up to 2.25 kW of power to the thruster anode.

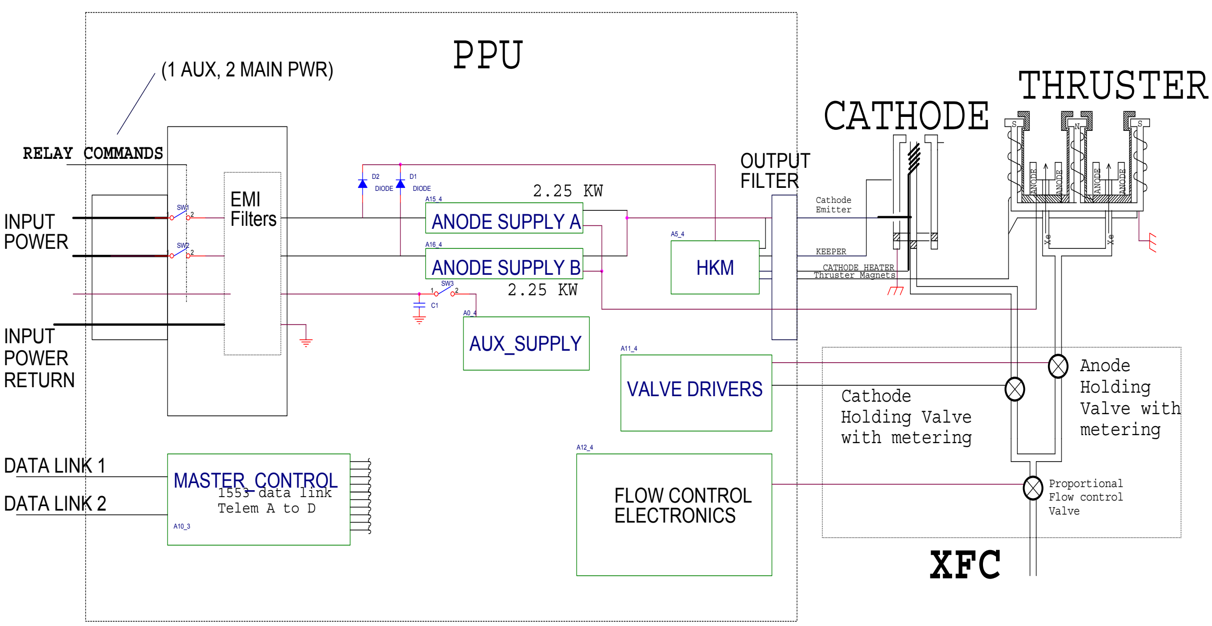

Figure 5 - HTPS PPU Block Diagram

The supplies utilize a current fed topology and have an operating efficiency of greater than 94%. Operational power for the cathode heater, keeper, and thruster magnets are provided by a single power supply with multiple outputs. This unique, patented [13] design, significantly reduces the number of components required to provide these functions compared to the traditional approach of utilizing separate supplies for each function. The PPU also includes the valve driver circuitry for operating the two solenoid-holding valves in the XFC and utilizes a closed loop control circuit to command the PFCV to provide the appropriate amount of xenon to the thruster for the commanded power level. An auxilliary power supply is also included that provides all house keeping power for the digital logic circuitry. A MIL-STD-1553 interface circuit is incorporated into the PPU and is used to transmit all command and telemetry information. A Field Programmable Gate Array (FPGA) is utilized for decoding the data link commands and to provide various command sequences that require precision timing. Radiation hardened S-Level components are being utilized to be compatible with the predicted natural radiation environments and to provide maximum reliability.

The mechanical design of the PPU is shown in Figures 6 and 7 and has been optimized for electrical and thermal performance, mass and manufacturability. The overall PPU has dimensions of 43 cm x 40 cm x 11 cm (17"w x 15.5"l x 4"h) and has a mass of approximately 12.75 kg. A more detailed description of the PPU design can be found in IEPC-01-333 [14].

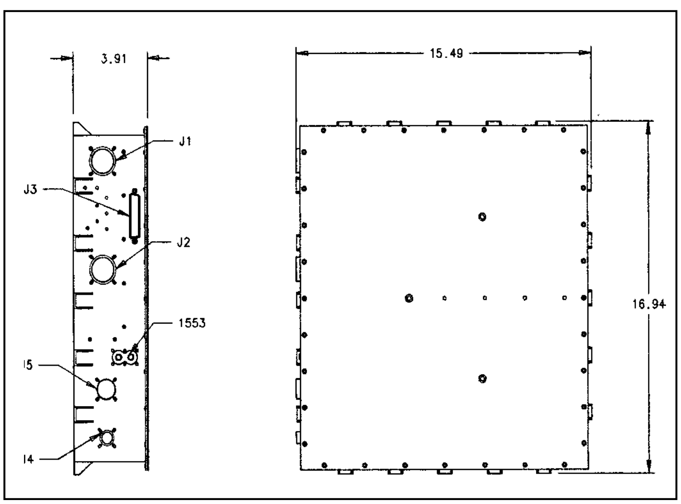

Figure 6 – HTPS PPU Envelop

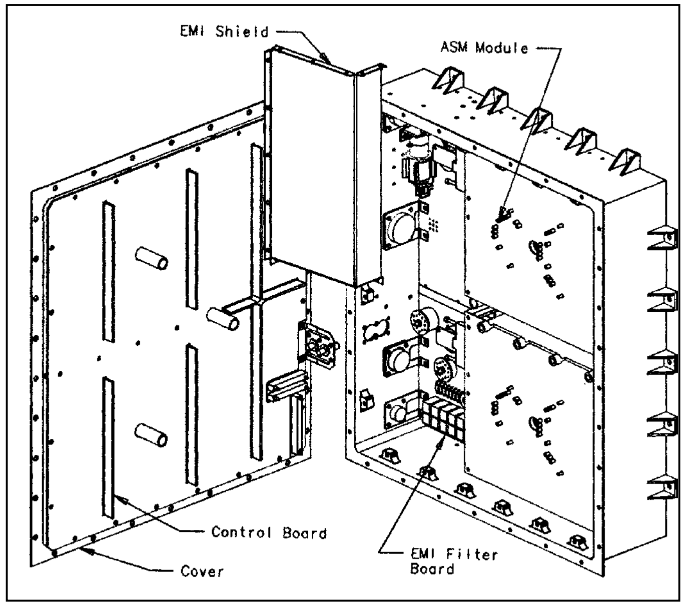

Figure 7 – HTPS PPU Mechanical Design

PPU Design and Analysis Status

At the time of this writing, the PPU has completed the preliminary design phase of the development program. This phase included the design, fabrication and testing of a complete PPU bread board that is electrically identical to the flight PPU. Testing included bench level performance testing, elevated temperature testing and system testing with a BPT 4000 thruster and a flight like XFC. Initial analyses have also been completed including thermal, structural, parts derating, radiation/survivability, reliability and Failure Modes, Effects, Criticality Analysis (FMECA). This phase was culminated with a preliminary design review meeting, held in March of 2001. Since that time printed wiring board designs and the detailed drawings of the flight like engineering development model (EDM) PPU have been completed. Fabrication of the EDM PPU is approximately 90% complete with testing of the individual circuit cards in progress.

PPU Performance and Test Results

PPU testing has successfully demonstrated all functional elements of the PPU design, using both resistive loads and flight like thruster and XFC components. Bench level testing has demonstrated all command and telemetry interfaces including start up, throttling and shut down sequences utilizing our custom MIL-STD-1553 interface test equipment developed to support this product. In addition, the overall operating efficiency of the PPU (total power in - total power out) has been characterized at both room and elevated temperatures and has been demonstrated at greater than 93% at full power operation of 4.5 kW of discharge power at 300 volts output.

System level testing was successfully completed in March of 2001 and demonstrated startup, operation over the full power and voltage range and shut down of the system. Testing was performed utilizing a laboratory version of the BPT-4000 thruster, an EDM version of the XFC and the breadboard PPU as shown in Figure 8. Testing was performed at General Dynamics Hall Thruster Firing facility and validated the startup sequence set points and timing along with confirming the XFC control loop parameters and thruster stability.

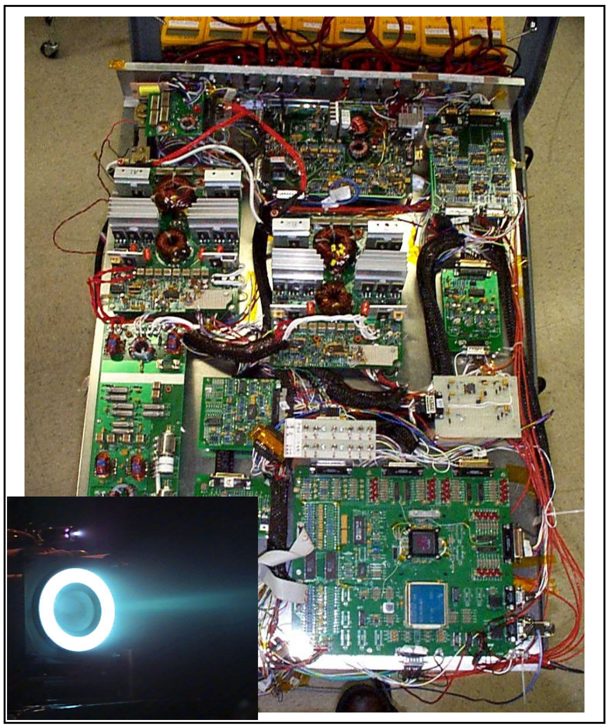

Figure 8 - Breadboard of PPU Electronics

Planned Activity

In September 2001, a second system level demonstration test will be performed using the breadboard PPU in conjunction with the flight configuration EDM thruster and EDM XFC. The objectives for this testing is to validate the PPU's compatibility with the flight configuration EDM thruster. At the end of 2001 the EDM PPU will be subjected to the same test that will be performed during formal qualification testing. This includes random and sine vibration, mechanical shock, EMI/EMC, ESD, thermal vacuum temperature cycling and system level testing using a flight configuration thruster and XFC. CDR for the PPU is planned in 2002, followed by the fabrication and qualification testing of the EQM PPU. Following component level qualification testing, the EQM PPU will be utilized to support the remainder of the thruster life test.

Xenon Flowrate Controller Overview

The Xenon Flowrate Controller (XFC), supplied by Moog Space Systems Division, regulates the flow of xenon propellant to the anode and cathode of the HT system, based on the anode demand. The XFC provides appropriate flow over the range of operating conditions and has significant margin to provide more or less flow if desired.

The XFC includes a Proportional Flow Control Valve (PFCV) and two solenoid valves that isolate the cathode and anode. The cathode isolation solenoid valve is fitted with an orifice to provide precise flow control. Other components are: the electrical connector; the mounting structure; the bracketing hardware that attaches the PFCV and solenoid valves to the mounting structure; the stainless steel tubing that carries the propellant; and the electrical wiring. Figure 9 illustrates the general XFC layout and Figure 10 provides top-level interface dimensions.

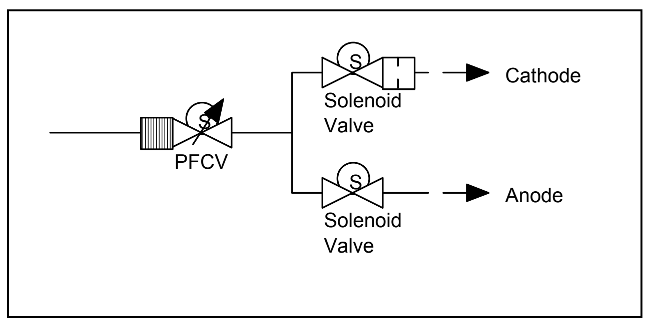

Figure 9 – XFC Schematic

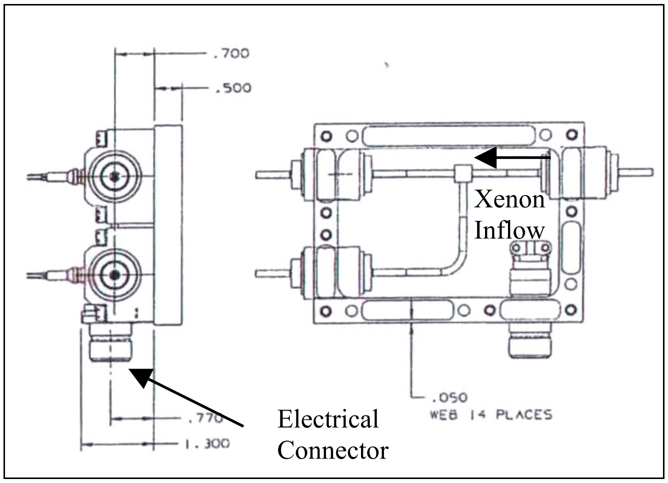

Figure 10 - XFC Layout

The majority of the selected components of the XFC has flight heritage or are very similar to components that have flight heritage:

- The solenoid isolation valves were used on the JPL DS1 and DASA Artemis programs [15].
- Development of the PFCV began at Moog in late 1997 as an internal research and development effort. The solenoid component of the PFCV is the same as the isolation solenoids. The PFCV design has undergone extensive testing at Moog [16]. Valves of the same design have been successfully operated for several hundred hours with Hall thrusters during NASA tests [17].
- The 0.318 cm outer-diameter electro-polished stainless steel tubing is welded using TIG orbital butt welding techniques. Similar weld joints were present on the JPL DS1 and Loral ISTI programs [18] [19].

XFC Performance

The XFC was designed to minimize power consumption and weight in a device that can provide optimal xenon flow to the anode and cathode of the HT system. The key performance parameters of the XFC are listed in Table 2.

Table 2. XFC Performance Parameters

Parameter	Nominal Value
Inlet Pressure to PFCV	255 kPa +/- 21 kPa
Anode Flow Rate	8.4 – 14.8 mg/s
Cathode Flow Rate	0.42 – 1.33 mg/s
Cathode Flow as Percentage of Anode Flow	5 – 9 %
Max Power Dissipation	4.1 Watts
Total Weight	~670 grams

The PFCV will be qualified to perform at temperatures ranging from -34 to +71^{o} C. Heat conduction to the spacecraft will be less than 5 Watts.

Planned Future Activity

Fabrication of the qualification hardware is complete as shown in Figure 11. Qualification testing is currently underway and will complete in the 4th quarter of 2001. Following component level qualification testing of the EQM XFC, it will be used in the 5,600 hour HT life test.

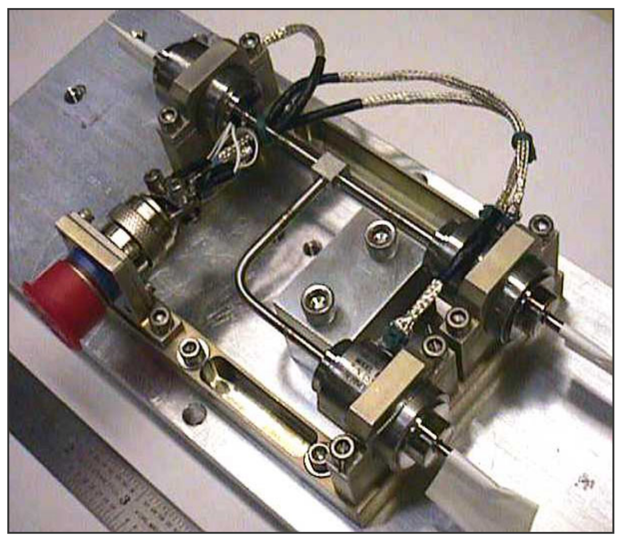

Figure 11 - EQM XFC Assembly

Xenon Feed System Overview

In conjunction with the development of the thruster, power processor, and flowrate controller, Lockheed Martin has begun the requirements definition for the xenon propellant storage and feed system elements of the HTPS. The system is currently envisioned to consist of two or four composite overwrapped pressure vessels for storage of xenon propellant at pressures up to 2,700 psia, and a feed system manifold which would provide isolation, filtration, and regulation of propellant flow from the tanks to the individual XFCs. The manifold would also provide service access for pressure testing and propellant loading.

The xenon tanks will be sized to fit the current Lockheed Martin A2100 spacecraft bus. The quantity of tanks will be mission dependent, with the maximum capacity corresponding to sufficient propellant to provide the qualified throughput of eight GD-OTS HTs.

The primary component of the feed system manifold will be a Xenon Feed System (XFS) module, to be supplied by Moog Space Systems Division. This unit will incorporate the primary feed system components, including the propellant line filters, isolation valves, and xenon pressure regulators. The feed system will manage propellant to provide a regulated propellant pressure of 37+/-3 psia over the full range of tank pressures throughout the mission, consistent with the XFC design. Draft requirements have been written, and design and qualification are planned to begin early next year.

System Integration Overview

System integration efforts have been an integral part of the development program. Efforts underway are addressing key integration issues between the HT, XFC, and PPU. These integration issues include the interactions between PPU and HT plume to ensure stable operation over the entire power and voltage operating range. This includes the stability of the control loop in the PPU that commands the PFCV in the XFC that regulates the amount of xenon flow to the HT. Another key issue includes the startup, transition to full power and shutdown sequences that have been developed to minimize power transients to the spacecraft's power bus [3].

In addition, external interfaces with spacecraft power, thermal, and mechanical systems are under investigation and are factored into the HTPS design. The HTPS operation represents a substantial draw on the satellite power bus, and poses the potential of power transients, which must be limited by design to prevent unacceptable loads on the spacecraft. The thermal dissipation from the XFC must be adequately managed during thruster operation. Finally, the HTs will be mounted on gimbals to maximize efficiency and flexibility of operation, requiring a robust mechanical interface design. While this is not an exhaustive description of the integration issues associated with Hall thrusters, significant activities that have been completed in these areas are discussed below to highlight the efforts currently underway.

Analysis Activities and Results

Extensive system level simulation and testing is being used to ensure stable operation of the HT over the entire power, voltage and flowrate operating range. Analytical models of the system have been developed that account for the electrical interfaces between the PPU and HT, the fluid dynamics of the xenon flow as controlled by the PFCV and influenced by the overall feed system and the gains and amount of damping in the control loop utilized to regulate the anode current. These analytical models are being used to simulate both nominal and off-nominal conditions and are being correlated to actual performance obtained during system level testing. The results to date have yielded highly stable system and thruster plume performance during all operating points and transitional phases.

To address the power transient issue for the high power HTPS, measured electrical performance characteristics of the ETM PPU and predicted performance for the EDM unit have been used to analyze the impacts of thruster activation and shutdown on the standard A2100 satellite power bus. Results indicate compatibility with the current bus has been achieved through the controlled transient power characteristics of the power processor. The startup of the HT was found to be no more stressing than that of the Arcjet system currently flying on seventeen A2100 spacecraft, in spite of the much higher maximum operating power (4.5 kW vs. 2 kW) of the HT.

The XFC utilizes continuously powered solenoid valves during thruster operation, and the power dissipated by these valves must be accommodated by conduction to its mounting interface. Thermal modeling of the XFC and various mounting locations has shown that the XFC can be readily accommodated on Lockheed Martin's A2100 and A2100 derivative spacecraft without overheating the valve coils. This is true even though the thrust of HT systems requires long maneuver times. Similar thermal models have been developed for the HT and PPU and have been integrated with thermal models of the spacecraft to ensure that the overall thermal design is adequate.

Test Activities and Results

As previously discussed, extensive system level testing is in progress to address a wide range of system integration issues. Testing performed to date includes HT plume characterization testing, HT EMI testing and PPU/XFC/HT system level testing. The results of the testing to date indicate all key parameters are well understood and well within the levels of compatibility with the overall system. Details of these tests are being reported in other papers prepared for this conference [12] [14].

The baseline implementation of Hall thrusters will mount one or two thrusters on a two-axis gimbal currently being qualified for commercial Lockheed Martin spacecraft applications. This implementation permits maximum efficiency in performing thruster maneuvers over the entire range of mission phases, from initial orbit acquisition through station maintenance and end-of-life repositioning. The mounting interface in this configuration results in higher dynamic environments input to the thruster over the full frequency range, which have been addressed through the use of a vibration isolation system.

Conclusions

General Dynamics Space Propulsion Systems and Lockheed Martin are jointly developing and qualifying a 4.5 kW Hall Thruster Propulsion System for a wide range of applications on geosynchronous earth orbiting satellites. Flight configuration engineering models of the HT, PPU and XFC have been fabricated and are in various stages of development and qualification testing. This includes the successful testing of the HT to qualification level vibration and shock environments to address the dynamic environments during launch and early orbit of an HTPS equipped satellite. The thruster was subsequently operated across its expected range with no performance degradation, and is currently in a 1,000-hour risk mitigation life test. A complete breadboard version of the PPU has been fabricated and fully tested with both resistive loads and a HT and XFC in system level testing and has successfully demonstrated all command, telemetry and performance requirements. Testing is currently in progress on a flight configuration EDM version of the PPU. The XFC is currently in qualification testing and will be used to support the HT's 5,600-hour life test. System integration analysis and testing activities are currently in progress to address all system integration issues. The results of the testing to date indicate all key parameters are well understood and within the levels of compatibility with the overall system. The mechanical integration of the thruster continues to be a high priority development task, with continuing work directed at completing the thermal interface and optimizing the routing of mechanical and electrical connections. Qualification testing of the HTPS components is projected to continue through the first quarter of 2003 and will be reported on in subsequent technical conferences.

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