THE DEVELOPMENT AND QUALIFICATION OF A 4.5 KW HALL THRUSTER PROPULSION SYSTEM FOR GEO SATELLITE APPLICATIONS – STATUS UPDATE

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ABSTRACT

This paper provides an updated status of the 4.5 kW Hall Thruster Propulsion Subsystem development and qualification program at Aerojet (formerly General Dynamics Space Propulsion System) and Lockheed Martin. This subsystem is being developed to support geosynchronous satellite applications for both commercial and military 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 the Xenon Feed System is also described. 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 takes advantage of the dual-mode capabilities and wide operating power range of the Aerojet BPT-4000 Hall thruster to maximize efficiency for each mission phase.

INTRODUCTION

Lockheed Martin Space Systems Company (LMSSC) and Aerojet are pursuing development of a Hall Thruster Propulsion System (HTPS) for a wide range of applications on geosynchronous earth orbiting satellites as previously reported.[1-3] The system currently under development is planned to be used for orbit insertion from an initial geosynchronous transfer orbit, on-orbit stationkeeping and repositioning maneuvers. The HTPS will take advantage of the dual-mode capabilities and wide operating power range of the Aerojet's 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.

Aerojet 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 Aerojet, was selected to develop the XFC.

Aerojet 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 Aerojet thruster firing facility as reported in earlier publications.[4-7] 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 Aerojet and successfully flown on the STEX satellite in 1998.[8, 9] Since that time Aerojet has developed more efficient, higher power, 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.[6] The HTPS PPU draws from these previous designs and is being optimized for the HTPS specific command, telemetry, power and environmental interfaces.

HTPS OVERVIEW

The HTPS architecture is shown in Figure 1 and was based on extensive trade studies to optimize reliability, performance and scalability. 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 any number of strings 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 the transfer orbit has commenced, the Hall thrusters will operate almost continuously until the satellite reaches the desired final orbit.

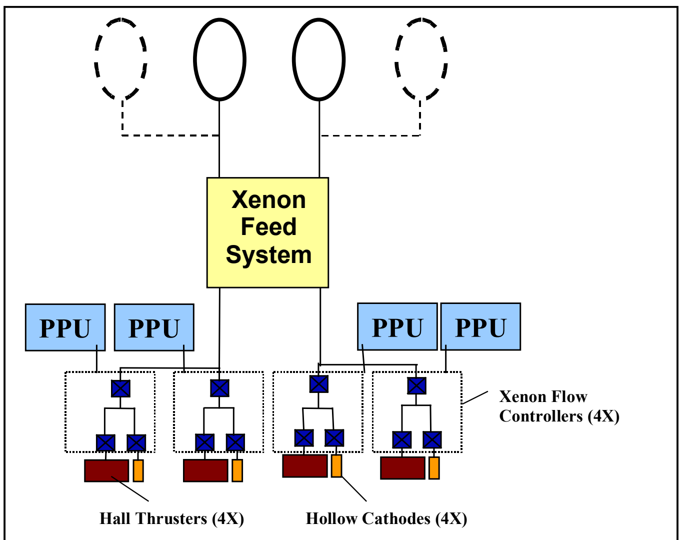

Figure 1 – HTPS Schematic

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 specific impulse 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, thereby improving system level redundancy. In addition, repositioning maneuvers during life can be performed in either high-thrust or high-specific impulse 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 was formally kicked off in September of 2000 and incorporates an extensive test program using developmental hardware, followed by the formal qualification testing of each of the HTPS components as shown in Figure 2. The HT and PPU development programs include the fabrication and testing of both laboratory/breadboard and Engineering Development Model (EDM) HTs and PPUs prior to the fabrication and formal qualification testing of the Engineering Qualification Models (EQMs). The XFC development program includes the fabrication and test of an EDM XFC and the fabrication and formal qualification testing of the EQM XFC. Both Preliminary and Critical Design Review meetings have now been successfully held for each of the three components, along with completion of the qualification hardware fabrication.

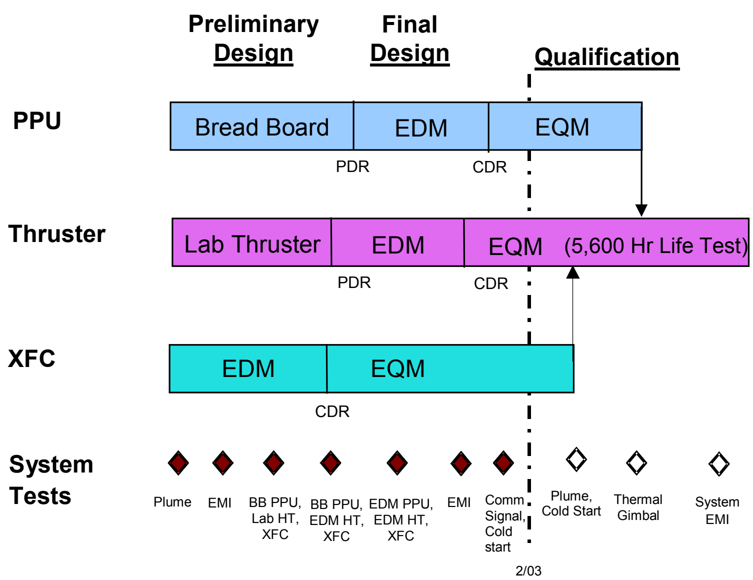

Figure 2 - HTPS Development Plan

During the development program, multiple system level tests have been performed that utilize a HT, PPU and XFC to demonstrate all interfaces and control methods. These included the use of both the breadboard and EDM PPUs in conjunction with both laboratory and EDM HTs. In addition, system level tests are included in the plan to ensure all spacecraft interactions are well characterized. These tests have included the characterization of radiated and conducted EMI, signal transmission compatibility, thermal balance between the HT and gimbals and plume characterization testing.

HALL THRUSTER OVERVIEW

Over the past two years, since the initiation of the HTPS program, Aerojet has completed a full EDM program on the flightweight BPT-4000. This program has included the completion of the flightweight engineering model design, fabrication of two flight-like HT units as shown in Figure 3, and a comprehensive test program on these units.

The highly successful initial performance and environmental testing included demonstration of greater than 59% efficiencies and the successful completion of qual-level sine vibration, random vibration and pyroshock testing.[10] It also included cyclic component level temperature and power testing of the cathode heater and magnet coils to demonstrate long term survivability over the full range of operating environments. After meeting the environmental requirements, the second portion of the test program included over 2,000 hours of life testing to validate a life capability of greater than 7,000 hours. The thruster test program was culminated with a successful formal Critical Design Review meeting held in April of 2002.

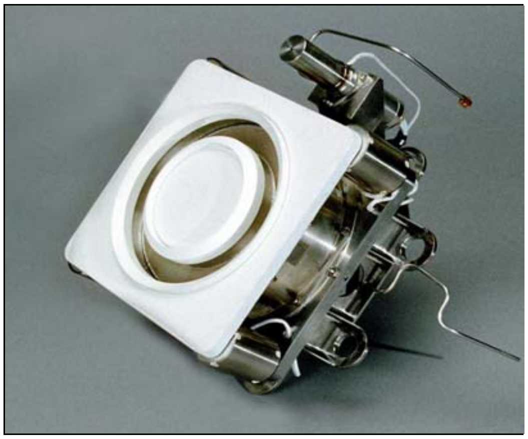

Figure 3 – BPT-4000 EDM Hall Thruster

The flight-weight BPT-4000 design is based on the successful 130mm mid-diameter BPT-4000 lab thruster[4, 5] that was extensively tested and characterized in 1998 and 1999. 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.[11] Unlike previous Hall thrusters, which are qualified for a single design point, 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 optimizes 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.

The hollow cathode design is based on Aerojet's previous cathode development experience, which includes the design and build of hollow cathodes beginning in 1994 to support testing with the Aerojet 30-cm Ion Engine[12], the TsNIIMASH TAL D-55, and most recently, Aerojet's BPT-2000 and BPT-4000 Hall thrusters. The technical basis for all of the designs is the NASA hollow cathode for the space station plasma contactor[13], which has demonstrated over 28,000 hours of life. To maintain the heritage of this demonstrated long life capability, Aerojet has maintained the dimensions and materials of the components critical to cathode operation.

THRUSTER PERFORMANCE AND TEST RESULTS

As part of the initial portion of the EDM test program and prior to beginning the life test, the EDM #2 thruster was subjected to extensive performance characterization testing which established the baseline performance of the thruster and again is discussed in detail in References 2 and 10. Characterization included performance measurements at each of the four corners of the operational voltage and power design box. The results of this characterization are shown in Table 1.

Table 1: BPT-4000 Performance

POWER (kW)	VOLTAGE (V)	THRUST (mN)	I_{SP} (sec)	EFFICIENCY (%)
4.5	300	299	1798	59
4.5	400	262	2059	59
3.0	300	203	1728	57
3.0	400	176	1982	57

In addition, the thruster was subjected to and successfully passed qual-level environmental testing including pyroshock, sine and random vibration.

1,200 HOUR LIFE TEST

Extensive life testing was conducted on the BPT-4000 EDM#2 thruster to validate the greater than 7,000 hour life capability of the EDM design. The bulk of this life testing was a 1,200 hour extended duration life test conducted on the EDM#2 thruster between December 2001 and June of 2002. Results of these tests demonstrated stable performance and ring erosion rates consistent with a >7000 hour thruster life. Prior to the 1,200 hour life test, two shorter duration life blocks (300 and 200 hours) were also conducted on the EDM #2 thruster, to investigate the effect of power and voltage on insulator ring erosion rates. The results of all of these tests are described in greater detail in Ref 10. The entire life test was conducted in the Chamber 2 Hall Thruster Test Facility at Aerojet. Chamber 2 is a 2.1 m dia. x 7.2 m stainless steel vacuum chamber shown in Figure 4. The chamber is equipped with four cryopumps, two 48 inch tubs and two nude head pumps, which yield a combined pumping speed of 75,000 L/sec on xenon yielding a back pressure of ~$3x10^{-5}$ Torr at the highest tested flow rate of 16.7 mg/s.

Figure 4 - Aerojet's Hall Thruster Test Facility

PLANNED ACTIVITY

The EQM Hall thruster has completed fabrication and assembly and has started formal qualification testing. Qualification testing, which includes sine and random vibration, pyroshock, cold start demonstration and a 5,600-hour life test, is scheduled to complete in 2004.

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 be 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 Aerojet'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.

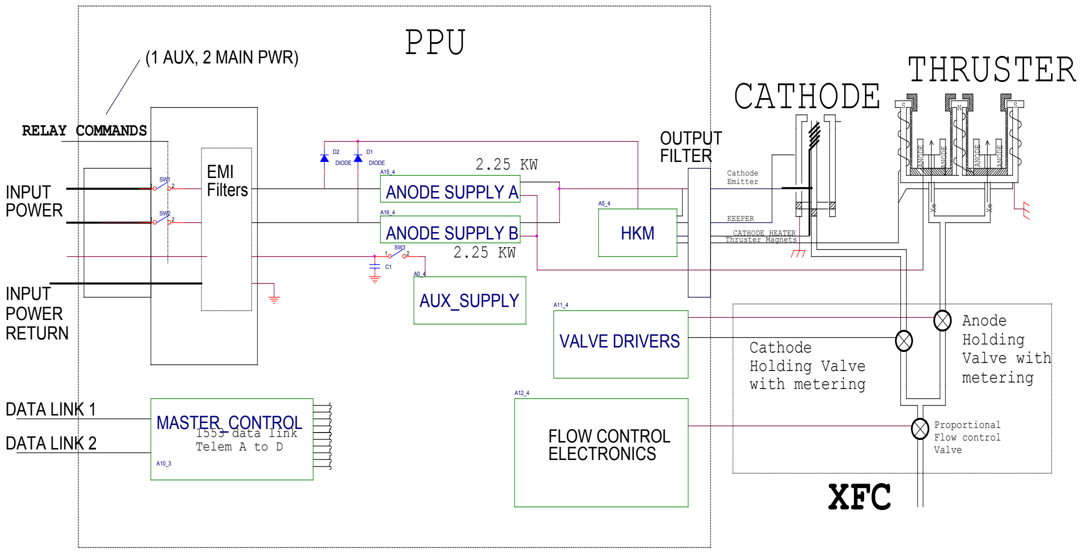

Figure 5 – HTPS PPU Block Diagram

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[14] 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. 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 Figure 6 and 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 Ref 14.

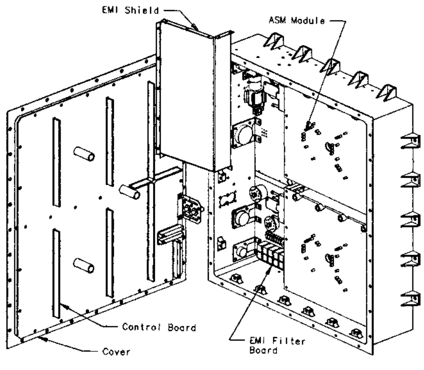

Figure 6 – HTPS PPU Mechanical Design

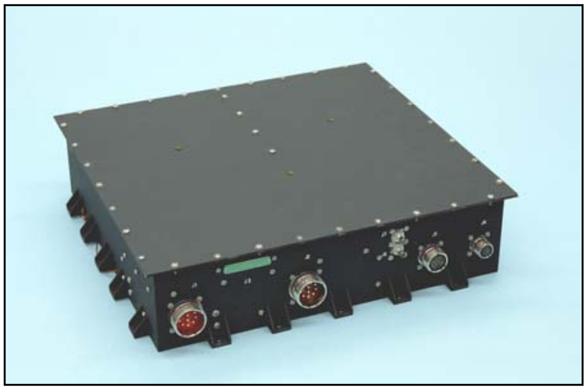

Figure 7 – HTPS EDM PPU

PPU DESIGN AND ANALYSIS STATUS

At the time of this writing, the PPU has completed the design phase of the development program and is entering qualification testing. This phase included the design, fabrication and testing of both a breadboard and flight like EDM PPU. Both units are electrically identical to the flight configuration design, with the EDM PPU also being mechanically identical as shown in Figure 7. Bread board and EDM PPU testing has been completed and included sine and random vibration, pyroshock, EMI, thermal vacuum temperature cycling, and thruster firing. This phase was culminated with a Critical Design Review meeting, held in April of 2002.

PPU PERFORMANCE AND TEST RESULTS

EDM PPU testing has successfully demonstrated all functional elements and environmental compatibility 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 over the full qualification temperature range and has been demonstrated at greater than 93% at full power operation of 4.5 kW of discharge power at 300 volts output.

Four separate system level test series were successfully completed over the last year and demonstrated startup, operation over the full power and voltage range and shut down of the system. Testing was performed utilizing the EDM BPT-4000 thruster, EDM XFC and the EDM PPU as shown in Figure 8. Testing was performed at the Aerojet Cell 2 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 – System Testing with EDM PPU

PLANNED ACTIVITY

At this time the PPU design has been updated to incorporate minor design changes as a result of the EDM PPU test program. The EQM PPU has completed fabrication and initial bench level functional testing and is ready to begin formal qualification testing. Qualification testing will include random and sine vibration, pyroshock, EMI/EMC, ESD, thermal vacuum temperature cycling and system level testing using the EQM Hall thruster and XFC. 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 layout of the XFC.

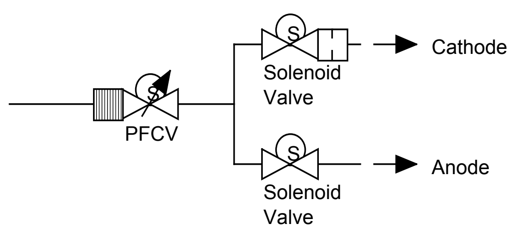

Figure 9 - XFC Layout

XFC PERFORMANCE

The XFC was designed to minimize power consumption and weight, and provide optimal xenon flow to the anode and cathode. 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	~500 grams

The PFCV is being qualified to perform at temperatures ranging from -34 to +71° C. Heat conduction to the spacecraft will be less than 5 Watts. Additional design detail can be found in IEPC-01-315.[16]

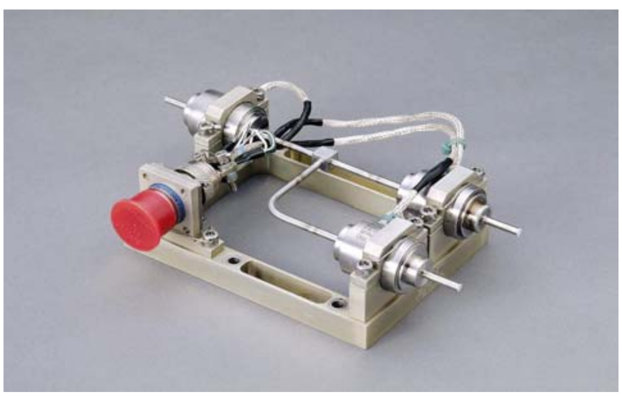

Figure 12 - EQM XFC Assembly

PLANNED FUTURE ACTIVITY

Fabrication of the qualification hardware is complete as shown in Figure 12. Qualification testing is currently underway and will complete in 2003. Following component level qualification testing of the EQM XFC, it will be used in the 5,600 hour HT life test.

XENON FEED SYSTEM OVERVIEW

In conjunction with the Aerojet development of the thruster, power processor, and flowrate controller, Lockheed Martin has begun the development 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 Aerojet HTs. The primary component of the feed system manifold will be a Xenon Feed System (XFS) module. 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. Specification requirements have been written, and design and qualification are planned to begin later this 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, PPU and the spacecraft. These integration issues include the interactions between PPU, XFC and HT to ensure stable operation over the entire power and voltage operating range. In addition, external interfaces with spacecraft power, thermal, and mechanical systems have been completed and are factored into the HTPS design. While this is not an exhaustive description of the integration issues associated with the HTPS, significant activities that have been completed in these areas are discussed below to highlight these efforts.

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 have been correlated to actual performance obtained during system level testing. The results to date have yielded highly stable system and thruster performance during all operating points and transitional phases.

TEST ACTIVITIES AND RESULTS

Extensive system testing has been performed using both laboratory and EDM HT, PPU and XFC hardware at Aerojet and two other test facilities. Testing to date has included plume characterization, EMI, communications signal compatibility and cold start testing (-40 C). The results of the system level testing indicate all key parameters are well understood and well within the levels of compatibility with the overall system. Details of these tests have been reported in other papers.[10, 15, 17] Additional system level tests planned going forward include plume characterization, cold start and EMI testing at the Aerospace Corporation using the EQM hardware and a thermal balance test with the HT and the two-axis gimbal.

CONCLUSIONS

Aerojet 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 extensively tested and demonstrated to meet all performance requirements. This includes the successful testing of the HT to qualification level vibration and shock environments and over 2,000 hrs of life testing that validated a life capability of more than 7,000 hours. A flight-like EDM PPU was fabricated and successfully passed all functional and environmental testing required for formal qualification testing. All three components are currently in qualification testing and will be used to support the HT’s 5,600-hour life test. Extensive system integration analysis and testing activities have been completed that address all system integration issues. The results of the testing indicate all key parameters are well understood and within the levels of compatibility with the overall system. Qualification testing of the HTPS components is projected to continue into 2004 and will be reported on in subsequent technical conferences.

REFERENCES

[1] Fisher, J., et al., "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System for GEO Satellite Applications," International Electric Propulsion Conference Paper 01-010, October 2001.

[2] de Grys, K., et. Al., "Extended Duration Life testing Testing of BPT-4000 Flightweight Thruster", JANNAF Proceedings, November 2002.

[3] Fisher, J., et al., "The Development and Qualification of a 4.5 kW Hall Thruster Propulsion System", JANNAF Proceedings, November 2002.

[4] King, D., et al., "Development of the BPT Family of U.S.-Designed Hall Current Thrusters for Commercial LEO and GEO Applications," 1998 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings, July 12-15, 1998.

[5] Wilson, F., et al., "Development Status of the BPT Family of Hall Current Thrusters," 1999 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Paper 99-2573, June 1999.

[6] Meyer, S., et al., "Development Status of the BPT Hall Thruster Power Processor," 1999 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings, June 20-24, 1999.

[7] de Grys, K., et al., "BPT Hall Thruster Plume Characterization," 1999 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings, June 20-24, 1999.

[8] Lynn, P., et al., "Electric Propulsion Demonstration Module (EPDM) Flight Hall Thruster System," International Electric Propulsion Conference Paper 97-109, 1997.

[9] Skelly, P. and Kay, R. "RHETT/EPDM Power Processing Unit," 1997 International Electric Propulsion Conference Paper 97-104, August 1997.

[10] de Grys, K., et al., "Development and Testing of a 4500 Watt Flight Type Hall Current Thruster and Cathode," International Electric Propulsion Conference Paper 01-011, October 2001.

[11] King, D. and de Grys, K. "Multi-mode Hall Thruster Development," 2001 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Paper 01-3778, July 2001.

[12] King, D., et al., "Design for Manufacturing Improvements and Demonstration of 30 cm Ion Thruster," AIAA-2000-3271, 2000 AIAA/ASME/SAE/ASEE Joint Propulsion Conference Proceedings, July 2000

[13] Patterson, M., et al., "International Space Station Cathode Life Testing," IEPC-97-166, 1997 International Electric Propulsion Conference Proceedings.

[14] Meyer, S., "Method and Apparatus for Selectively Distributing Power In a Thruster System," U.S. Patent No. 6031334, February 29, 2000.

[15] Kay, R., et al., "The Development of a 4.5KW Hall Thruster Propulsion System Power Processing Unit,", IEPC Paper 01-333, October 2001.

[16] Bushway, D., et al., "A Xenon Flowrate Controller for Hall Current Thruster Applications," International Electric Propulsion Conference Paper 01-315, October 2001.

[17] Beiting, E., et. al., "Electromagnetic Emissions to 60 GHZ from a BPT-4000 EDM Hall Thruster," International Electric Propulsion Conference Paper 0129, March 2003.