Demonstration of the XR-12 Hall Current Thruster

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Abstract: Aerojet Rocketdyne, a member of the Lockheed Martin/Northrop Grumman Transformational Satellite Communications System (TSAT) Space Segment team, completed in 2009 a successful demonstration of its new generation 12 kW xenon Hall current thruster (XR-12) electric propulsion system. The target application at the time was the U.S. Air Force's TSAT constellation. Developed by Aerojet Rocketdyne and Lockheed Martin, the Hall thruster propulsion technology provides significantly improved specific impulse and flexibility over conventional chemical propulsion systems. The Hall thruster system was developed to satisfy both orbit transfer and on-orbit station keeping propulsion needs of large communications satellites. Performance goals included high thrust at high power for orbit transfer and moderate specific impulse at low power for station keeping. Since the cancellation of the TSAT program, Aerojet Rocketdyne and NASA Glenn Research Center have explored the use of the XR-12 for NASA missions. Leveraging lessons learned from the flight qualified Zero-Erosion™ XR-5 (formerly BPT-4000), High Power Propulsion System subscale thruster development, and Hall thruster design knowledge, Aerojet Rocketdyne developed the XR-12 Hall thruster propulsion system to a TRL 4-5 that could achieve the demanding performance goals of the TSAT program and as well as long life through the zero-erosion design technique. Aerojet Rocketdyne estimates, depending on the system requirements, that a XR-12 propulsion system could be available in 33 months.

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Nomenclature

AEHF = Advanced Extremely High Frequency communications system
BOL = beginning of life
CMM = coordinate measurement machine
EOM = end of mission
EP = electric propulsion
GEO = geostationary orbit
HCT = Hall current thruster
HPPS = High Power Propulsion System
LVDT = linear voltage displacement transformer
NASA = National Aeronautics and Space Administration
PEPL = Plasmadynamics and Electric Propulsion Laboratory
PPU = Power Processing Unit
I_{sp} = Specific Impulse
T/P = thrust-to-input power ratio
TSAT = Transformational Satellite Communications System
XFC = Xenon flow Controller

I. Introduction

HALL thruster propulsion systems provide significantly improved on-station payload mass for commercial satellites, military communications satellites and NASA cargo and exploration missions when compared to chemical systems. Aerojet Rocketdyne's Redmond Operations facility has been developing Hall thruster propulsion systems since 1994. Aerojet Rocketdyne's systems typically include a thruster, xenon flow controller, power processing unit and cable harness. Aerojet Rocketdyne's Hall thruster programs cover a wide range of technology readiness levels. On the research and development end of the range, the sub-scale model High Power Propulsion System (HPPS) demonstrated significant performance improvement over state of the art thrusters.[1] On the mature end of the technology readiness spectrum, the two ship sets of Zero-Erosion™ XR-5 (formerly BPT-4000) 4.5 kW Hall thrusters have successfully propelled Air Force's Advanced Extremely High Frequency (AEHF) communications spacecraft 1 and 2 into geostationary orbit and currently perform station keeping duties for each spacecraft. One additional ship set has been delivered to Lockheed Martin Space Systems Company in preparation for launch of the third spacecraft in the AEHF series.

The technology readiness of the 12 kW Hall current thruster (XR-12) lies between that of the HPPS and the XR-5 at a TRL 4-5. The XR-12 is part of a propulsion system originally designed to support the Lockheed Martin space segment team's Transformational Satellite or TSAT development efforts. Other components developed for the Hall thruster propulsion system include a power processing unit, xenon flow controller and cable harness.

The XR-12 is larger and more efficient than the XR-5 and it incorporates design improvements validated on the HPPS program. This paper presents the performance demonstrated and analyses accomplished during development of the laboratory model XR-12. Included are program background and status, a description of the test facility, hardware and software, results of performance, system compatibility and wear testing, analysis accomplishments, future work and conclusions.

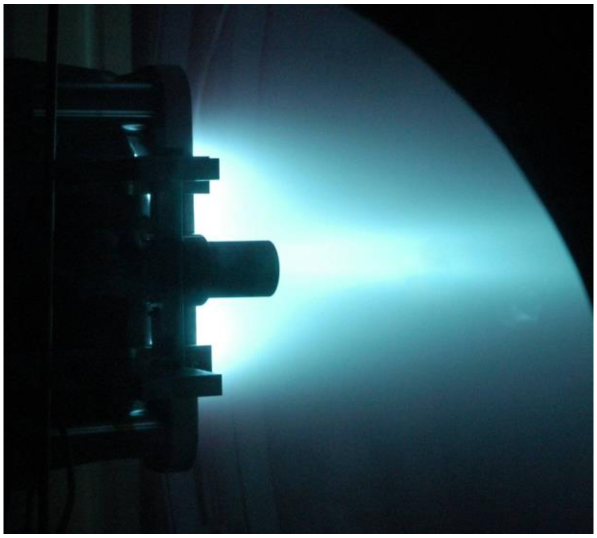

Figure 1. Photograph of Aerojet's XR-12 Hall current thruster during operation with cathode and cathode mounting structure in the foreground.

II. Background

Development of the XR-12 started in 2005, with the goal of providing specification compliant performance, life, and environmental robustness for the TSAT mission. Design of the laboratory–weight thruster took into account the launch and operation environments to facilitate later evolution into a flight model. Vibration, shock, thermal management and wear were carefully considered during the initial design and throughout the laboratory model development effort.

Electric Propulsion (EP) devices, including Hall thrusters, have traditionally been used for station keeping and disposal maneuvers. Lower powered EP systems typically have not been considered for initial orbit insertion in the commercial sector, because of their low thrust would result in longer trip times. Instead, chemical thrusters provide the majority of the required velocity increment for orbit insertion because of stringent spacecraft insertion time requirements. However, as spacecraft power levels and EP capabilities increase, Hall thrusters are being used and/or considered for part, or all, of the orbit transfer due to the large mass benefits associated with the higher I_{sp} and thrust-to-power that advanced Hall thrusters can achieve. In fact, the XR-5 thrusters played a critical role in placing the AEHF-1 satellite in orbit.[2] Although the XR-5 engines are fully capable of performing orbit transfer maneuvers, the time required to complete them exceeds the time allotted for most spacecraft operators. Major spacecraft primes, such as Boeing, have begun work towards all-electric propulsion system spacecraft design that eliminates the heavy chemical propulsion systems in favor of the more efficient EP systems. Boeing’s all-electric platform, the 702SP, in its initial configuration will incorporate four ion thruster based XIPS thrusters to achieve increase in dry mass ratio of 85% and enables Boeing to launch two spacecraft on the same launch vehicle that could only accommodate one of Boeing chemical based 702 platforms.[3] Boeing just recently passed the critical design review of the 702SP and plans the first launch of their all-electric platform in 2015.[4]

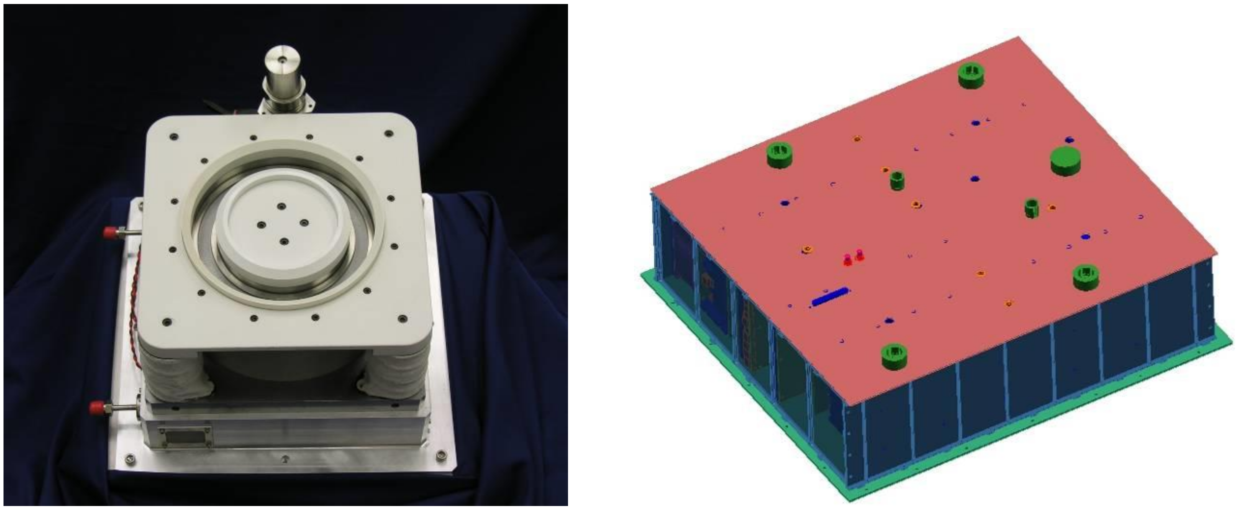

Figure 2. Photograph of the XR-12 (left) and model of the high power PPU (right)

The XR-12 is a 10 kW class thruster capable of throttling over a 2.7x range in power and a 3.4x range of thrust at total efficiency levels exceeding 55% over the full range. Like its predecessor, the XR-5, the XR-12 will be capable of supporting high-impulse missions requiring both orbit transfer and station keeping. Sized for larger missions, the XR-12 demonstrated operation up to 12 kW and a peak total efficiency of 65% (up from 57% measured on the XR-5 at beginning of life). This increase in performance and capability enables new missions that lower performance engines cannot support.

The XR-12 was designed to meet the orbit transfer and station keeping needs of future geostationary (GEO) communications spacecraft. The XR-12’s high thrust capability allows mission designers to use EP for a larger percentage of the orbit insertion maneuver, because a greater fraction of the required delta-V can be performed within the specified insertion time. Each increment in thrust delivered by the Hall thruster allows additional chemical fuel and oxidizer to be replaced by a smaller amount of xenon, which decreases the spacecraft mass. Once on orbit, the thruster can operate efficiently at 4.5 kW or 38% of its maximum rated power. This allows the spacecraft payload to operate simultaneously with the thruster providing uninterrupted communications capability. High specific impulse (I_{sp}) minimizes fuel required for on-orbit station-keeping. This efficient use of both power and fuel further minimizes the required spacecraft mass.

III. Mission Applications

Although the XR-12 was designed specifically for the TSAT program, the high performance achievements and wide throttling range make this Hall thruster well suited to a broad range of mission applications. The high thrust-to-power ratio (T/P) and efficiency can reduce transfer times or solar array size. Alternatively, higher performance enables larger and more capable satellites to reach orbit in the same transfer window. The paragraphs below describe applications where the XR-12 may provide mission benefits.

Byers and Dankanich[5] state that trip times associated with EP have been an impediment to its acceptance. They show that trip times are reduced with higher spacecraft power-to-mass ratios and lower I_{sp}. It may be more intuitive to state that trip times are reduced with higher T/P, which is inversely related to I_{sp} for a given thruster efficiency. Most spacecraft currently in orbit do not produce sufficient solar power to fully capitalize on the XR-12's capabilities. However, trends in Ref. 5 suggest that the rising spacecraft power and mass of GEO commercial communication satellites will be able to support 10 kW to 20 kW Hall thruster propulsion systems within a few years. Aerojet Rocketdyne's XR-12 has demonstrated T/P levels 18% higher (at a given I_{sp}) than currently qualified Hall thrusters. This allows mission planners to reduce trip times and allows payloads to start operation sooner.

The European Space Agency and the Centre National d'Études Spatiales are developing the Alphabus for high capacity geostationary telecommunications spacecraft. Lyszyk and Garnero state that the requirements for EP orbit raising include a thrust range of 500 to 1500 mN at a I_{sp} of 1500 to 2500 seconds and a power level of 10 to 20 kW.[6] Performance measurements published in Section IX of this paper show that the XR-12 can meet all of these requirements.

The wide throttling range of the XR-12 allows communications satellite mission planners to tailor the propulsion system operation depending upon the power available. This flexibility may also help NASA deep space missions. Oh[7] found that the best propulsion system performance generally came from the EP system that best utilized the available solar array power over the course of the mission. For those missions that stay within the inner solar system, a commercially available Hall thruster system with wide throttling capability may provide the highest delivered payload at an acceptable cost.

Researchers at the Jet Propulsion Laboratory have found that EP may be cheaper than aerobraking for orbit insertion around planets with atmospheres. Hofer, et al.[8] found that the cost of using the Deep Space Network (DSN) during aerobraking is over $15M and an order of magnitude more expensive than the usage costs associated with an existing EP orbit insertion. Although the XR-12 would require larger and more expensive solar arrays than used in currently qualified EP systems, the higher thrust delivered would result in a shorter orbit insertion period, less use of the DSN, and likely an overall savings in mission cost.

Recently NASA Human Exploration and Operations Mission Directorate (HEOMD) and Space Technology Mission Directorate (STMD) have identified High Power Electric Propulsion as enabling technologies for potential NASA missions. NASA STMD Game Changing Development (GCD) has been tasked with the developing, maturing, and testing of high-power EP. NASA STMD GCD In-Space Propulsion (ISP) identified several high-power Hall thruster propulsion systems for further evaluation, which included the Aerojet Rocketdyne 12 kW XR-12. During the summer of 2012 Aerojet Rocketdyne and NASA GRC completed performance characterization of the XR-12 in Vacuum Facility 5 (VF-5) to assess the thruster capabilities.

IV. Program Description

The program objective was to develop a flight qualified, 10 kW-class, high-performance Hall thruster propulsion system for near term application. The first phase of the program focused on the design and test of the three primary components of that system, which include the XR-12, a Power Processing Unit (PPU) and a Xenon Flow Controller (XFC).

The laboratory model XR-12 demonstrated performance capabilities consistent with the mission requirements. The thruster successfully completed a 400 hour accelerated wear test to validate the results of Aerojet Rocketdyne zero-erosion design knowledge and erosion model predictions. The cathode successfully completed a 2,600 hour risk mitigation life test.

A breadboard like power processing unit (PPU) was designed and built. The PPU design builds upon Aerojet Rocketdyne's qualified 4.5kW PPU and incorporates several new innovations to improve performance and increase the output power above 12 kW. The PPU design utilizes modular architecture and a configurable parallel/stacked structure to optimize the PPU to support both the 250 V, high power/high thrust mode and 450 V, low power/high I_{sp} operation. High-density modular packaging minimizes PPU mass and significantly helps to increase producibility and decrease cost. Each electrical module of the PPU was fully characterized individually, and the unit demonstrated integrated operation over the full power range.

A Xenon Flow Controller (XFC), leveraging heavily from TRL 9 XR-5 XFC units, was designed and built. Bench level testing and characterization of all key XFC performance parameters were completed successfully. Finally, an integrated system test demonstrated successful operation of PPU, XR-12, and XFC together over the full power range.

Prior to cancellation of the entire TSAT program, an engineering model thruster was designed using lessons learned from laboratory model testing and thermal analysis. The computational designs, analyses and test data were collected and archived in anticipation of future use. Further development towards a flight XR-12 would start with the engineering model design and depending on the mission specific validation requirements for flight could be ready in less than 33 months.

V. Test Facility

Thruster testing presented in this paper was conducted at the Plasmadynamics and Electric Propulsion Laboratory (PEPL) at the University of Michigan.[9] PEPL's 6 meter by 9 meter chamber is the largest university facility in the country (see Figure 3 on the following page for a photograph and cutaway drawing). The chamber incorporates 7 cryopumps, which deliver 240,000 liters per second pumping speed on xenon. Pressure levels measured during full-power operation of the XR-12 were consistently less than 2×10^{-5} torr.

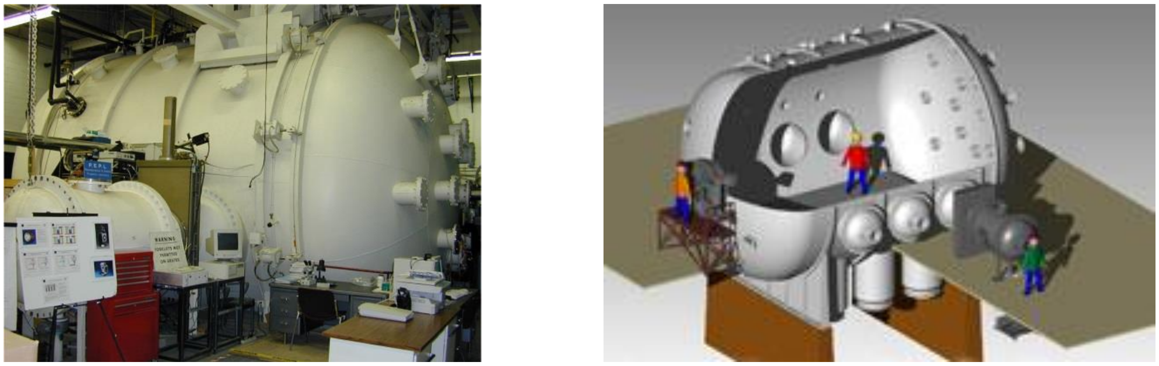

Figure 3. Photograph and artist's depiction of the Large Vacuum Test Facility at PEPL[9,10]

VI. Test Equipment and Software

Thruster operation was controlled and monitored using a custom-built power and telemetry system. Commercial power supplies provided electrical power for the plasma discharge, electromagnets, cathode heater and cathode keeper. The mass flow rates to the anode and cathode were controlled and measured using Celerity 1661 high purity mass flow controllers. Control and data acquisition was accomplished using Opto 22 hardware and a custom control program developed in C#. Data was stored in a custom SQL Database and summarized in "comma separated values" or ".csv" files for quick look data reviews.

Performance measurements were made using an inverted pendulum thrust stand based on the NASA Glenn Research Center design.[11] Typical calibration linearity and repeatability were better than +/-1% during a test series. The thrust calibration slope remained constant (+/-1%) across all operating modes (e.g., all off, cathode operating, magnets energized, thruster operating). The Michigan thrust stand was validated and compared to Aerojet Rocketdyne's thrust stand by operating an engineering model XR-5 at both facilities. Measurements from the two facilities were found to agree to within 2.5% across the operating range of the thruster.

The largest source of thrust stand error was the variation in tare measurements made prior to and subsequent to thruster operation. These offsets affected low power performance measurements most significantly, due to the higher percentage of uncertainty in the measurements. Thrust uncertainty at 4.5 kW was approximately +/-3%. Specific impulse and efficiency calculations include an additional mass flow controller uncertainty of +/-1%.

As part of the XR-12 development activities, a completely new test control software program was created. Lessons learned from the XR-5 development were implemented to make the data acquisition and storage system more flexible and searchable. In addition, the system provided instant performance and telemetry feedback to the thruster operator.

The software program provided for long term data storage and retrieval of all telemetry. The program provided the user with instant feedback, which accelerated the rate at which test series could be competed The program also provided daily summaries of the most important thruster performance parameters using ".csv" files.

IV. Results

Table 1 (see appendix) displays the peak performance values obtained during testing of the XR-12 thruster. Data is shown for the high-power (12 kW) orbit transfer operating point and the low-power (4.5 kW) station keeping point. Corrected thrust adjusts the measured values for thrust stand tare and any interference in the measurement caused by the thruster's magnetic field. Specific impulse measurements include cathode flow rate, but are not corrected for chamber pressure. Chamber pressures were generally less than 2×10^{-5} torr, so background xenon ingestion accounted for less than 0.2% of the ionized propellant.

Several figures of merit may be used for quantifying a given thruster's performance including thrust, discharge power, propellant flow rate and thruster mass. This paper presents the ratio of thrust to power (T/P) and specific impulse (I_{sp}), which is proportional to the quotient of thrust divided by flow rate, because these metrics facilitate comparison to other thrusters of varying size and power level. Figure 4 below is a graph of T/P and I_{sp} for the highest performance measurements recorded during laboratory model thruster testing. The graph includes XR-5 values obtained at the beginning of flight qualification for comparison. Full-power (12 kW) performance measurements were made while operating the XR-12 discharge between 280 and 300 V, whereas low-power (4.5 kW) measurements were made between 400 and 450 V. Power values do not include magnet power. Electromagnetic power consumption varies with coil temperature, and was less than 0.5% of the XR-12 discharge power for the data points shown. Therefore, neglecting this corrections is justified when considering the much larger uncertainties associated with the thrust and flow rate measurements. Curves of constant thruster efficiency are shown on the graph as solid black lines.

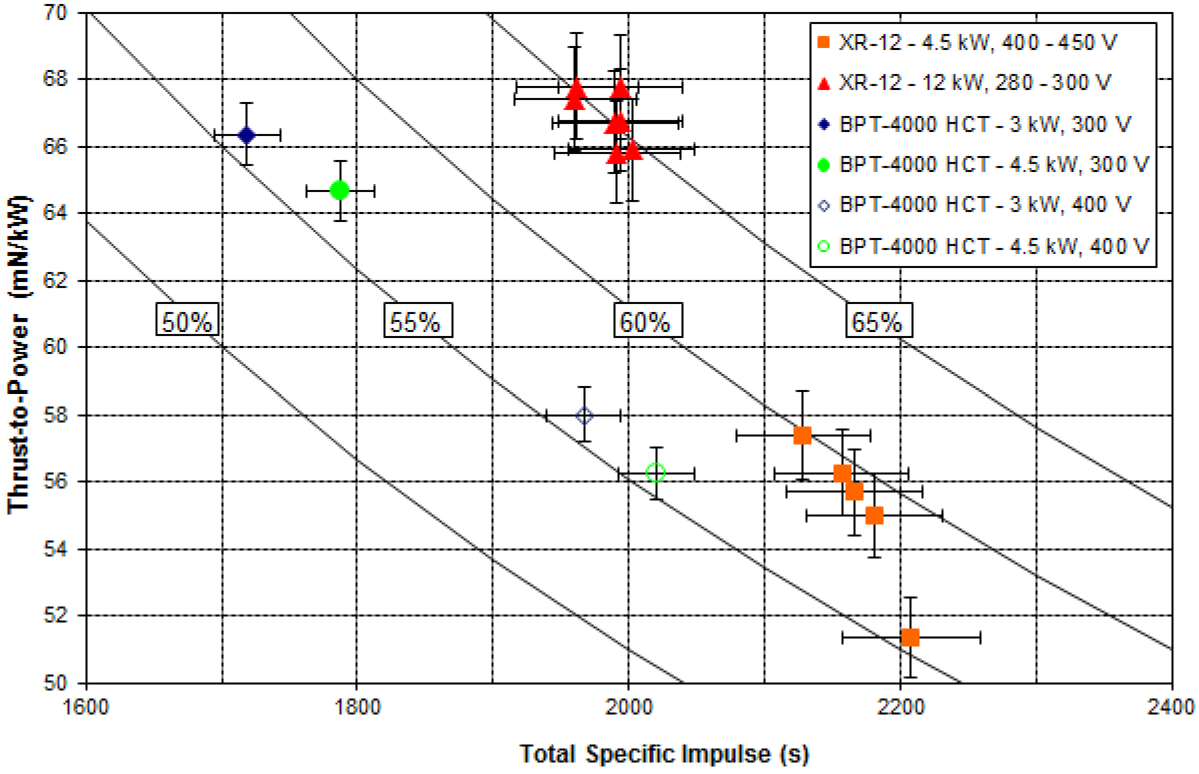

Figure 4. Graph of XR-12 and XR-5 performance measurements

Figure 4 shows that the XR-12 is highly fuel efficient, demonstrating a I_{sp} advantage over the XR-5 of about 200 seconds at both the orbit transfer and station keeping operating points. The XR-12 demonstrated high-efficiency operation across a wide throttling range and improved T/P at full-power. The 12 kW data was collected at a power density 50% higher than the XR-5's 4.5 kW data, which makes the T/P measurements more impressive. Testing showed that the XR-12, like other thrusters,[12-14] achieved higher T/P when the discharge power was reduced.

The I_{sp} values shown in Figure 4 may appear low when compared to other Hall thrusters. However, it is important to note the relative power and discharge voltages used to obtain the performance data. Due to constraints set by the TSAT mission and power processing unit, the high-I_{sp} point was measured using the lowest XR-12 power level (4.5 kW) and no more than 450 V. These constraints are not associated with the thruster, and it is widely known that I_{sp} increases with discharge voltage.[12-19] The power limitation is significant because several thrusters have shown that I_{sp} also increases with power density.[12-18]

In parallel with performance testing, the team conducted thermal analysis. As part of this effort, a 3-D finite element thermal model was created and correlated with test data. The process of correlating the model to the test data helps verify the distribution of plasma heat loads inside the discharge channel used in the model. Results from the thermal analysis of the XR-12 were used to aid in the development of an engineering model thruster design.

X. System Integration Test

An integration or compatibility test was conducted to verify operation of the entire Hall thruster propulsion system at the extremes of the power envelope. During the test, discharge power was delivered to the XR-12 by the brassboard-like PPU. The propellant was metered by the PPU via a XFC, which supplied both the thruster and cathode with xenon. Due to schedule and configuration constraints, the thruster magnets were powered by commercial power supplies.

The integration test was a success in that it showed stable operation of the system over the whole range of operating power. Integrated performance of the thruster was within 3% of values measured using laboratory power supplies. Data analysis verified that the operation of the PPU did not affect the performance of the thruster.

The PPU demonstrated a thruster start-up procedure by controlling the discharge voltage and the flow rate provided by the XFC. The PPU operated the thruster at full power for over four consecutive hours without incident. Temperatures of the individual power supply modules remained cool throughout the test. The PPU was able to halt operation of the thruster without incident. The system integration test made this the highest power Hall thruster system ever tested.

XI. Wear Testing

Hall thruster life is primarily limited by erosion of the insulator rings lining the discharge chamber walls due to high-energy ion sputtering.[20,21] Aerojet Rocketdyne has developed and validated through extensive testing on a variety of Hall thrusters including the 10,000 hour qualification test of the XR-5, a design methodology for arresting Hall thruster erosion thereby enabling projected lifetimes of >40,000 hours. The design approach has been independently confirmed by a physics based Hall thruster model developed by researchers at NASA JPL.[22,23] The XR-12 Hall thruster incorporates these design knowledge and techniques to ensure the long life operation.

To provide further risk reduction, a 400 hour wear test was completed. During this test, the thruster accumulated 300 hours with new, beginning-of-life (BOL) insulator rings to validate erosion model input parameters. This was followed by 100 hours of operation with exit rings machined to simulate an end-of-mission (EOM) geometry. The geometry for the EOM rings was found by correlating Aerojet Rocketdyne's in-house erosion model to the geometry measured after 300 hours of operation.

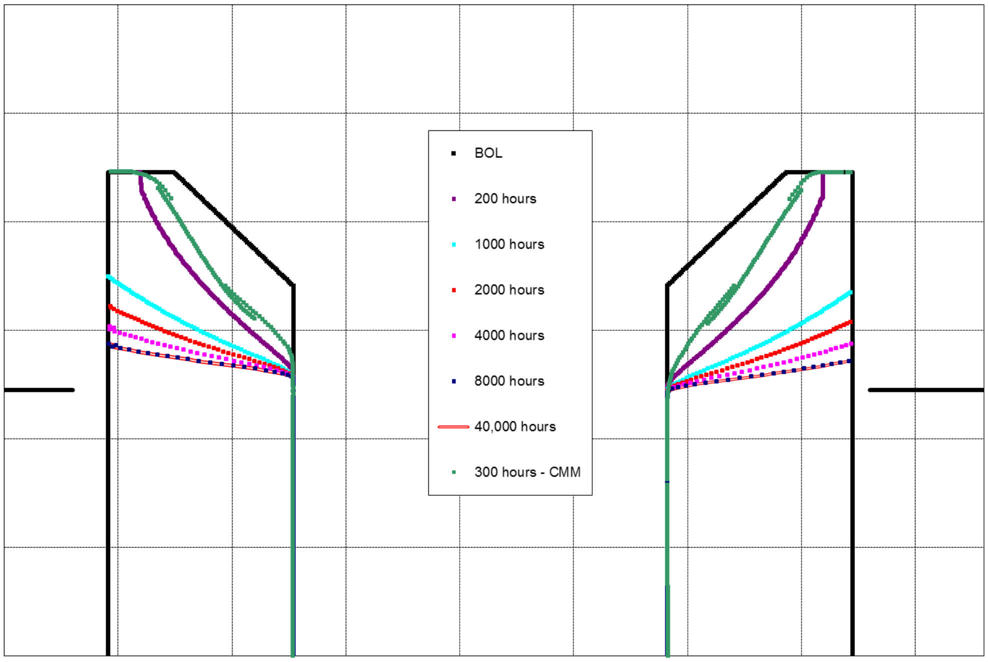

Figure 5. XR-12 predicted and measured erosion of discharge channel ceramic walls.

Figure 5 is a graph of measured (green) and predicted (other colors) erosion of the ceramic insulator rings. The model results assume all operation is at full power. Measurements were made using a coordinate measurement machine or CMM. The model results predicted the upstream erosion corner to within 1 mm of the actual measurements. The results over-predicted downstream erosion, which can be seen when comparing the 200 hour model data (purple) with the 300 hour measured data (green). This result was not unexpected. The erosion model uses input from thruster plume measurements from the XR-5, because these data were not available for the XR-12. It was anticipated that the higher thrust efficiency measured in the XR-12 would be due in part to a more collimated plume.

The reduced erosion rate may be due to the wider channel of the XR-12 or may imply that the XR-12 plume is narrower than that of the XR-5, upon which the model is based. Plume measurements would have helped identify the cause of the variation, but were not collected. However, the fact that the model is slightly conservative in its prediction of erosion at 300 hours adds confidence to the team's assessment of the XR-12 lifetime.

After the analysis of the data was complete, insulator rings were machined to match 8000 hours of operation at 12 kW and an additional 100 hours were accumulated in test. As expected no measurable erosion was observed at the completion of the accelerated wear test. The thruster successfully completed the 400 hour wear test and ran overnight on several occasions with little change in telemetry. Assuming performance does not significantly change over the life the XR-12, the expected total impulse is over 20 meganewton-seconds (MN-s) and throughput is over 1100 kg per engine. For comparison, an ambitious NASA Discovery mission (comet Kopff rendezvous[7]) requires less than 600 kg of propellant and the Alphabus[6] requires less than 1.2 MN-s of impulse.

XIII. Conclusions and Future Work

The XR-12 development program has demonstrated the ability of the laboratory model thruster to meet performance requirements. Erosion model predictions indicate that insulator ring and keeper erosion will be sufficiently low to meet challenging mission life requirements. A correlated thermal model that incorporates detailed understanding of the plasma heat loads has been developed and used to successfully implement thermal improvements into the lab thruster.

Despite cancellation of the TSAT and XR-12 programs, continuing work on HPPS and various electric propulsion mission studies show that there remains strong interest in higher power and higher efficiency Hall thrusters. When a mission and funding for an advanced Hall thruster returns, Aerojet Rocketdyne will draw on the accomplishments and insights garnered on the XR-12 program to retire risk early and quickly move to a more mature and flight-like design. Design features from this program have already been implemented on Aerojet Rocketdyne's HPPS Hall thruster. Even if the TSAT program does not return in its existing mission and architecture, lessons learned from the XR-12 program will continue to positively influence future Aerojet Rocketdyne Hall thruster designs.

As discussed above NASA HEOMD and STMD have identified High Power Electric Propulsion as enabling technologies for potential future NASA missions. Aerojet Rocketdyne believes that the high-power EP work done on the TSAT XR-12 and the HPPS XR-20 Hall thruster programs places Aerojet Rocketdyne in a unique position to rapidly, and cost effectively, deliver a high-power Hall thruster system that could meet or exceed NASA goals.

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Appendix

Table 1. Performance Measurements for XR-12 Hall Thruster

Discharge Power (kW)	Anode Flow Rate (mg/s)	Cathode Flow Rate (mg/s)	Discharge Current (A)	Discharge Voltage (V)	Thrust (mN)	Specific Impulse (s)
4.5	11.5	0.80	11.2	399	257	2129
4.6	11.5	0.80	11.3	410	260	2157
4.5	11.0	0.80	10.8	418	251	2167
4.5	10.7	0.80	10.5	428	246	2181
4.5	10.0	0.70	10.1	445	232	2208
11.9	36.5	3.70	39.6	301	785	1992
11.9	37.0	3.70	39.6	301	796	1994
11.8	36.0	3.60	42.1	280	777	2002
11.6	36.0	3.60	41.3	281	773	1990
11.9	37.5	3.80	42.5	280	807	1994
11.9	38.0	3.80	43.9	270	804	1962
12.1	38.5	3.90	44.8	270	815	1961

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