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AIAA Joint Propulsion Conference **(Statement A)**
(Huntsville, AL, 17 Jul 00) **(Submission Deadline: 17 Jul 00)**

Preliminary Performance Results of the High Performance Hall System SPT-140

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Abstract

The High Performance Hall System (HPHS) program supports the development and flight qualification of a 4.5 kW electric propulsion system that includes the SPT-140 Hall thruster. The Air Force Research Laboratory (AFRL) and International Space Technology, Inc. (ISTI) are co-funding the HPHS program which is being conducted by a team led by Atlantic Research Corporation (ARC). The team includes ISTI, Experimental Design Bureau Fakel (Fakel), and Space Systems/Loral (S/SL). The Research Institute of Applied Mechanics and Electrodynamics (RIAME) also provided support for this project. The SPT-140 is being designed, developed, manufactured, and tested by Fakel in Kaliningrad, Russia, where extensive performance testing and advanced development have been performed. In addition to the testing in Russia, a suite of experiments on the development model and the qualification model thrusters, sponsored by the US Government, has occurred during 1999 and 2000 and is scheduled to continue through 2000. These experiments include thruster performance, plume characterization, electromagnetic compatibility, and life characterization. This paper presents the status of government testing of the SPT-140 in the United States.

Introduction

Due to their high specific impulse and thrust efficiencies, Hall thrusters are now being considered for use on commercial, research, and military spacecraft. This technology provides economic advantages for a number of missions and its use can be translated into lower launch mass, longer time on station, or larger payloads. The US Air Force, NASA, and industry have shown interest in high power (~5 kW) Hall thruster systems as spacecraft have grown both in size and electrical power capacity. The High Performance Hall System (HPHS) program is developing a 4.5 kW Hall propulsion system that provides significant payoffs for station-keeping, repositioning, and orbit raising applications.

Program Description

The Air Force Research Laboratory (AFRL) and International Space Technology, Inc. (ISTI) are co-funding this cost shared contract (56% government, 44% contractor) under the auspices of the Integrated High Payoff Rocket Propulsion (IHPRPT) initiative. Atlantic Research Corporation (ARC) is the prime contractor. The propulsion system includes the thruster, power processing unit (PPU), propellant management assembly (PMA), and simulated spacecraft hardware. The Experimental Design Bureau/Fakel, a Russian designer and manufacturer of over 110 flight Hall thrusters, is developing the thruster. Space Systems/Loral (S/SL), leveraging their flight qualification experience with the 1.35 kW SPT-100 Hall system, is designing and manufacturing the PPU. An existing, Moog Inc. built, flight qualified PMA will complete the major system components.

The primary objective of the HPHS program is to meet US Air Force IHPRPT goals of improved performance for orbit transfer, apogee insertion, repositioning, and station-keeping. The development effort is focused on the improvement of thruster and PPU performance characteristics. The thruster preliminary design review (PDR) and critical design review (CDR) were successfully completed in December 1997 and March 1999, respectively. A 1200 hour extended duration test of the flight-like demonstration model (DM) thruster is underway at Fakel. The PPU PDR and CDR have also been successfully completed in November of 1998 and October of 1999, respectively. To ensure US government access to SPT-140 thruster technology, ARC will deliver a thruster design package, including engineering drawings, processes, and procedures to a US based escrow agent.

The SPT-140 thruster consists of a coaxial Hall accelerator with an outer diameter of the acceleration channel annulus of 140 mm. All thrusters to be used in the HPHS program will be constructed by Fakel in Kaliningrad, Russia. The SPT-140 has been described in detail elsewhere [1-3]. In order to ensure that the SPT-140 HPHS will meet US Air Force requirements, an extensive series of tests is being conducted by the US Air Force in conjunction with other research and development groups. As part of the HPHS contract, ARC provided the test plans for these tests. The test plans, written by ISTI and SS/L, are based on previous US SPT-100 qualification experience.

The first test series was conducted at NASA Glenn Research Center (GRC) during August 1999. The first test consisted of a performance measurements of the SPT-140 Hall thruster. The second test consisted of electro-magnetic interference (EMI) testing of the SPT-140. The third test consisted of plume contamination testing whose goal was to quantify the impact of the SPT-140 plume on spacecraft solar array and thermal control surfaces. These tests were co-funded by the US Air Force and NASA.

The second series of tests was conducted at the University of Michigan Plasma and Electric Propulsion Laboratory (PEPL). These tests concentrated on measurement of the plume characteristics of the SPT-140. The first test consisted of ion flux measurements with guarded Faraday probes. The second series of tests measured ion energy distributions in the plume. Also during the final portion of this test program, the SS/L constructed brassboard PPU was first integrated with the SPT-140 Hall thruster.

Fabrication of the flight qualification model (QM) thruster is ongoing. The QM thruster and brassboard PPU will undergo an integrated life test scheduled to begin in the autumn of 2000. The test will consist of a simulated life of a 15 year GEO type satellite with orbit topping and station keeping burns. Total thruster operation will be 7,200 hours. This test will be performed at the AFRL Electric Propulsion Laboratory located at Edwards Air Force Base, California.

Performance Testing

A space simulation test of a Russian SPT-140 Hall Effect Thruster was completed in September 1999 at the NASA Glenn Research Center (GRC) Vacuum Facility #6 as part of an Interagency Agreement with AFRL. The thruster was subjected to a three part test which included thrust/performance characterization, electromagnetic interference (EMI), and plume contamination. All test objectives were satisfied, and the thruster performed exceptionally well during the 127 hour test program, which encompassed 33 engine firings. This work will present the results of the performance measurements accomplished during this sereies of tests. The results of the EMI and plume contamination studies are presented in Reference 4.

The test program provided a comprehensive evaluation of thruster operation in preparation for future flight opportunities. The performance test included thrust measurement over a wide variety of operating conditions, and background pressures in order to develop an extensive thruster performance map. Plume ion current density measurements were also taken during the performance testing.

Apparatus

All phases of the test effort were conducted in Vacuum Facility #6 (VF-6). VF-6 is a 21 meter long by 8 meter diameter, horizontal vacuum cham-

Table 1. Test Support Equipment

Item	Model No.	Serial No.
Discharge Power Supply	EMHP-60-42111	1N-0116
Thermothrottle Power Supply	Sorensen SRL40-6	422
Magnet Power Supply	Sorensen SRL20-12	488
Cathode Heater Supply	Sorensen DCR60-30BM5	0410
Ignitor Power Supply	TCR600S1.6-1-D	93E-7826
Valve Power Supply	Kikusui PAD55-3L	13073264
Flow Meter	URS-100-5	01389
Flow Controller	UFC-1660 500 sccm	98350034300

ber located at the Electric Propulsion Laboratory at GRC. The large volume (1 million liters) and high pumping speed (900,000 liters/sec on air) of VF-6 made it well suited for this thruster evaluation. The facility had recently been upgraded with twelve new cryogenic pumps (replacing the original 20 oil diffusion pumps) and Grafoil sputter shielding to support on-going electric propulsion testing at GRC. The GRC research team was responsible for all test support equipment including the thrust stand, power supplies, data acquisition, EMI measurement equipment, and the contamination measurement system.

Separate power supplies were provided for the discharge, magnets, ignitor, cathode heater, thermothrottle and supply valves. A xenon gas supply and flow meter was provided as a main propellant feed to the Fakel Xenon Flow Controllers (XFC), which were located near the thruster. The model and serial numbers for the power supplies and flow control units are provided in Table 1. A Hewlett Packard HP34970A Data Acquisition/Switch Unit, connected to a Dell OptiPlex G1 computer via an RS-232 connection, was used to record all test parameters. Two video cameras installed inside the chamber were used throughout the test program.

The thruster arrived at GRC on August 4, 1999. The package contained one thruster (SPT-140 DM#03), two Xenon Flow Controllers (XFC-140 #02 and XFC-140 #03), and the General Summary ("Formular") instruction enclosed in a metal cylindrical shipping container. The thruster was configured with two cathodes, with only one needed for operation. A photograph of the thruster and XFCs is provided in Figure 1. All instructions for unpackaging, inspection, and measurement as described in the Formular were completed prior to installation in the chamber.

The thruster and XFCs were installed on the thrust stand on August 6 in preparation for the performance test. Figure 2 shows the test configuration. The thrust stand was located in the axial center of the chamber, with the thruster installed approximately 1.2 meters below the tank centerline. The XFCs were mounted on an aluminum plate attached to the rear of the thrust stand, as shown in Figure 3. The XFCs were separated from the thruster to simplify thrust stand harness support and to minimize potential plume damage. The distance from the XFCs to the gas supply ports on the thrust stand was approximately 1 meter. A Faraday cup probe and motor driven sweep arm was installed on the thrust stand to collect ion current at a 1 meter radius from the thruster center on a horizontal plane from –100° to +100° relative to the thruster centerline. The Faraday probe was 1.905 cm (0.75 inches) in diameter.

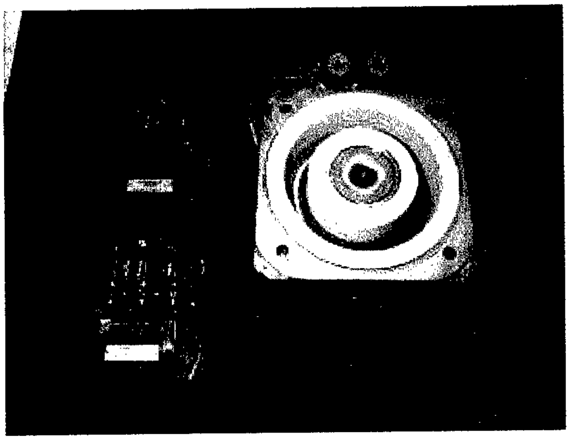

Figure 1. Thruster and XFCs after Unpackaging

Each XFC contained one thermothrottle and three xenon valves: supply, anode, and cathode. The XFCs were configured such that XFC#02 supplied the gas feed for thruster operation with cathode #1 (designated K1 by Fakel) and XFC#03 supplied gas feed for cathode #2 (K2). The layout of the gas supply system, power supply leads, and data signals was devised to allow testing of either XFC/cathode configuration without breaking vacuum. A special control circuit was developed for the valve power supply to provide a 1 second, 25 volt power pulse to actuate the valves, followed by a 10 volt hold to maintain the valves open. A single type K thermocouple was installed on the upper right hand corner of the thruster backplate (as viewed from the rear) to provide a reference of thruster temperature.

A filter circuit consisting of a 20 micro-farad capacitor and 110 micro-henry inductor was installed outside the chamber on the anode discharge power feed. A switchable, 4 ohm ballast resistor was also installed in series with the discharge power supply for protection of the power supply during starting transients. This ballast resistor was only used during initial startups and was not in the anode circuit for any of the performance test points.

Results

The document "High Performance Hall System Test Plan for Performance Testing of the SPT-140 DM Thruster", provided by Atlantic Research Corporation (CDRL A010-4, January 4, 1999) was used as the reference for conducting the performance test. The test plan included thruster performance evaluation under variable chamber background pressure, which was to be accomplished by turning cryogenic pumps off in a stepwise manner. A pumpdown of VF-6 was initiated on August 9 and testing commenced the following morning. A complete graphical summary, showing discharge power level and thrust, over the 4 day performance test can be found in Appendix A. A thruster startup and operations log for the entire test effort at GRC is provided in Appendix B.

The xenon gas supply system was set to provide regulated pressure at 255 +/-10 kPa to the XFCs, which was maintained throughout the testing. The tank base pressure was 1.8×10^{-6} torr prior to starting the thruster. Tank pressure was measured using a Nitrogen calibrated ion gauge located at the tank wall and centered axially in the tank.

The first successful thruster startup, with K2, occurred at 12:28 on August 10. Thruster startup consisted of powering the discharge, magnets, thermothrottle, and cathode heater for 150 seconds before opening the XFC valves. After 10 seconds of xenon flow, a 320 volt ignition pulse was provided to start the thruster. Upon startup, the ignitor and heater were turned-off and the thermothrottle and magnet current settings were adjusted based on the desired operating condition. A 30 minute warm-up period of operation was completed on each cathode before beginning the test sequence. Initial performance mapping was completed on K1 at 300 volts and three different discharge current levels: 15, 10, and 6.67 amps. Magnet optimization was performed at each discharge current setting by maximizing thrust. After a thruster shutdown and restart, Faraday sweeps were completed at each of the three discharge current settings to conclude the initial thruster performance mapping with K1.

Beginning at around 19:28, performance mapping with K2 began after five aborted start attempts. The problem in starting the thruster with K2 resulted from the failure to connect the proper thermothrottle electrical cable at the power supply junction. The initial K2 starts were attempted with power supplied to the thermothrottle on XFC#02 rather than XFC#03. The 300 volt, variable current performance points were completed on K2 while optimizing the magnet current as before. At the conclusion of the first test day, several variable voltage test points (350 and 400 volts) were acquired on K2 at 10 amps discharge current in preparation for the extensive voltage mapping planned for Day 2.

The second day (August 11) of the performance test was devoted to discharge voltage variations, predominantly on K1. An initial warm-up period at 300 volts and 15 A was performed to achieve thermal stability. Tank base pressure was 1.1×10^{-6} Torr. The test plan called for voltage sweeps at discharge currents of 7.5, 10, 12.5, 15, 17.5, and 20 A. The discharge voltage was to be varied from 400 to 200 V in 50 V increments, although voltage was limited to 300 V for both the 17.5 and 20 A sweeps. Magnet current levels were optimized at each condition for maximum thrust. In general, all test points were acquired, although some difficulty was encountered when operating the thruster below 250 V due to significant discharge current oscillations. Day 2 was concluded by operating the thruster with K2 at 300 V and current levels of 7.5, 10, 12.5, and 15 A for comparison to the K1 performance results. After thruster shut-down, three of the twelve cryogenic pumps were turned off in preparation for the first variable background pressure test.

The data points collected at minimum tank pressure are summarized in Table 2. Test point numbers 1 through 18 were collected on August 10 while test points 19 through 47 were collected on August 11. The supply flow in the table represents total xenon flow to the XFCs. Pre-test and post-test calibrations of the flow controller showed excellent agreement, so the pre-test calibration constants were used in the flow calculation. The reported tank pressure was calculated from the following relationship:

$$P_{Tank} = P_{Base} + 0.35(P_{Tank} - P_{Base}) \qquad (1)$$

Where P_{Base} is the base pressure without xenon flow, P_{Tank} is the pressure as indicated by the air calibrated ion gauge during thruster operation, and 0.35 is a correction factor for gauge measurements with a xenon gas background.

The thrust reported in Table 2 is corrected for thrust stand zero-drift. Typical zero-drift thrust corrections were between 0.5% and 2%. Thrust unit conversions were based on the initial calibration constants since periodic calibrations throughout the testing were very repeatable. The specific impulse I_{sp} and total efficiency η were calculated as follows:

$$I_{sp} = \frac{T}{\dot{m}g} \qquad (2)$$

$$\eta = \frac{T^2}{2\dot{m}P} \qquad (3)$$

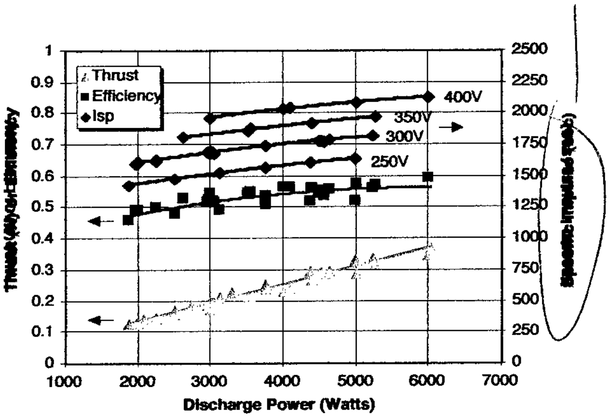

Figure 4. Minimum Tank Pressure Performance Summary

Where T is the measured thrust, ṁ is the total supply flow, g is the Earth's gravitational constant (9.81 m/s^2); and P the thruster power (discharge power plus magnet power).

A graphical summary of the performance data at minimum tank pressure is provided in Figure 4. The graph shows thrust, efficiency, and specific impulse versus discharge power. The thrust and efficiency data are plotted with respect to the left hand vertical axis, and the specific impulse data is plotted with respect to the right hand vertical axis. As shown in the graph, discharge voltage has a strong influence on specific impulse, and thrust can be represented as a near-linear function of discharge power. The faraday probe sweeps for the three, 300 V, variable discharge current conditions with K1 are presented in Figure 5. In all cases, the current density has a double peak on either side of the thrust centerline. The maximum current density for the three cases is about 6, 4, and 2.5 mA/cm^2, respectively for the 15, 10, and 6.67 discharge current levels.

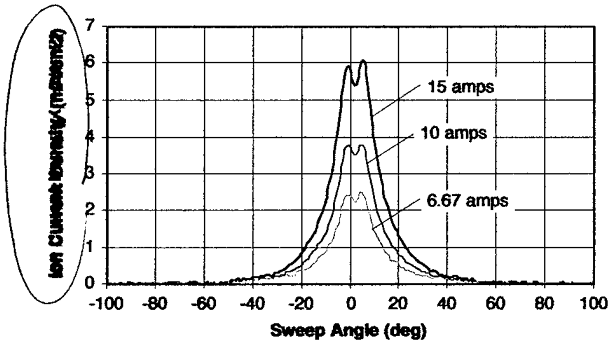

Figure 5. Ion Current Density Measurements at Minimum Tank Pressure

Day 3 (August 12) of the performance test investigated two different background pressure conditions. With 9 cryogenic pumps operating and no xenon flow, the tank base pressure was 1.5x10^{-6} Torr. Tank pressure was about 30% higher as compared to the 12 pump testing with similar xenon flow. All of the variable background pressure testing was performed with K2. Data points were collected at 300 V and current levels of 15 and 10 A. A Faraday probe sweep was performed with the thruster at 300 V and 10 A for comparison to the earlier current density measurements. In addition, variable voltage points were acquired from 250 to 400 V at 10 A discharge current.

After the 9 pump data points were completed and the thruster was shutdown, three additional pumps were turned-off. Approximately 6 hours later on the same day, the tank base pressure re-stabilized at about 5.6x10^{-6} Torr with 6 pumps operating and no xenon flow. Similar test points to those collected with 9 pumps were acquired, including current variations at 300 V discharge and voltage variations at 10 A. In addition, data points were taken at 300 V with matching gas flow rates to those measured at maximum pumping speed (12 pumps) for 10 and 15 A discharge current. A 300 V, 10 A Faraday probe sweep was also completed. At the conclusion of Day 3 following thruster shutdown, four more cryogenic pumps were turned-off.

The final background pressure condition was completed on Day 4 (August 13) of the performance test with 2 cryogenic pumps operating. Base pressure (with no xenon flow) was approximately 4.7x10^{-5} Torr. The same data points collected during the previous background pressure tests were repeated including the 300 V, 10 A Faraday probe sweep. An additional 300 V, 15 A Faraday sweep was also performed. Table 3 provides a complete summary of the variable background pressure test points. In general, the higher background pressure testing resulted in a net decrease in supply flow, relative to the minimum tank pressure points, in order to maintain the same discharge current. This corresponded to apparent increases in both Isp and thruster efficiency, since supply flow is included in the denominator for both equations. This effect is shown graphically in Figure 6 where I_{sp} is plotted against xenon-corrected, tank pressure. A plot of the Faraday probe sweeps for each of the four background pressures with the thruster operating at 300 V and 10 A is provided in Figure 7.

Table 2. Performance Points at Minimum Background Pressure

Test Pt/ Cathode	Time Stamp	Disch volts	Disch amps	Disch watts	Magnet amps	Magnet volts	Supply mg/s	Tank torr	Thrust mN	Isp sec	Total eff
1/K1	14:46	300	15.2	4565	5.3	9.3	16.5	9.9E-06	286	1767	53.8%
2/K1	15:15	300	10.0	2998	5.0	9.2	11.5	7.9E-06	191	1686	51.9%
3/K1	15:31	300	6.6	1992	4.5	8.2	8.1	6.1E-06	127	1608	49.5%
4/K1	16:00	300	15.0	4503	6.5	11.8	16.5	9.9E-06	289	1782	55.1%
5/K1	16:26	300	15.1	4526	6.5	12.9	16.6	9.9E-06	289	1779	54.8%
6/K1	16:34	300	10.2	3050	5.0	9.9	11.7	7.8E-06	194	1683	51.6%
7/K1	17:01	300	9.8	2950	5.0	9.7	11.4	7.5E-06	188	1686	51.9%
8/K1	17:09	300	6.7	1998	4.5	8.6	8.1	6.1E-06	128	1613	49.6%
9/K1	17:35	300	6.6	1968	4.5	8.3	8.0	6.1E-06	125	1603	49.2%
10/K2	20:16	300	15.0	4494	6.5	12.1	16.5	9.6E-06	288	1783	55.1%
11/K2	20:27	300	10.0	3005	5.0	9.3	11.6	7.5E-06	192	1693	52.4%
12/K2	20:42	300	6.6	1986	4.5	8.2	8.1	5.8E-06	127	1604	49.3%
13/K2	21:12	299	15.1	4520	6.5	12.1	16.6	9.9E-06	290	1785	55.3%
14/K2	21:18	300	10.0	2997	5.0	9.3	11.6	7.5E-06	192	1696	52.6%
15/K2	21:26	300	6.6	1994	4.5	8.3	8.1	6.1E-06	128	1609	49.6%
16/K2	21:35	300	10.1	3035	5.0	9.2	11.7	7.5E-06	194	1692	52.4%
17/K2	21:57	351	10.1	3561	5.0	8.7	11.7	7.6E-06	215	1878	55.0%
18/K2	22:11	401	10.2	4100	6.0	10.9	11.8	7.5E-06	236	2041	56.8%
19/K1	11:15	300	15.5	4630	6.5	9.2	16.9	9.1E-06	297	1790	55.7%
20/K1	11:27	299	10.0	2984	5.0	7.4	11.6	6.7E-06	192	1690	52.6%
21/K1	11:34	401	10.0	4007	6.0	9.3	11.6	6.7E-06	230	2031	56.5%
22/K1	11:39	350	10.0	3512	5.4	8.5	11.6	6.7E-06	213	1863	54.6%
23/K1	11:45	300	10.0	2999	5.0	8.0	11.6	6.7E-06	192	1683	52.1%
24/K1	11:50	250	10.0	2515	4.9	7.9	11.6	6.7E-06	169	1480	48.0%
25/K1	11:55	202	10.3	2078	6.6	10.9	11.6	6.7E-06	140	1233	39.4%
26/K1	12:30	300	7.5	2252	4.4	7.1	9.0	5.6E-06	144	1627	50.3%
27/K1	12:37	401	7.5	3001	5.3	8.6	8.9	5.6E-06	173	1967	54.7%
28/K1	12:43	350	7.5	2620	4.8	7.9	9.0	5.6E-06	159	1809	53.1%
29/K1	12:50	250	7.5	1870	4.3	7.1	8.9	5.6E-06	125	1431	46.3%
30/K1	13:07	300	12.5	3749	5.6	9.8	14.1	8.1E-06	240	1738	53.8%
31/K1	13:16	400	12.5	5014	6.7	12.2	14.1	8.1E-06	289	2086	58.1%
32/K1	13:23	350	12.5	4387	6.1	11.4	14.1	8.1E-06	266	1924	56.4%
33/K1	13:34	250	12.5	3128	5.2	9.9	14.0	8.1E-06	210	1526	49.5%
34/K1	13:41	219	12.5	2733	5.9	11.3	13.9	8.1E-06	188	1377	45.3%
35/K1	14:14	300	15.0	4503	6.5	11.7	16.5	9.1E-06	289	1784	55.3%
36/K1	14:21	351	15.0	5260	7.5	14.1	16.5	9.1E-06	320	1971	57.6%
37/K1	14:26	400	15.0	5998	7.4	14.4	16.7	9.1E-06	348	2127	59.4%
38/K1	14:36	250	15.0	3758	5.5	10.8	16.4	9.1E-06	253	1570	51.0%
39/K1	14:42	220	15.0	3294	6.5	12.9	16.2	9.1E-06	225	1420	46.4%
40/K1	15:11	299	17.5	5235	6.4	13.6	18.8	1.0E-05	336	1821	56.3%
41/K1	15:19	250	17.5	4369	5.7	11.9	18.6	1.0E-05	294	1607	52.2%
42/K1	15:30	249	20.0	4986	7.0	15.2	20.6	1.1E-05	331	1638	52.3%
43/K1	15:41	300	20.1	6022	6.7	14.8	21.0	1.1E-05	368	1782	52.5%
44/K2	16:27	299	10.0	2982	5.0	9.2	11.6	6.7E-06	192	1692	52.6%
45/K2	16:33	300	7.5	2246	4.4	8.0	9.0	5.6E-06	144	1623	50.1%
46/K2	16:38	300	12.5	3754	5.6	10.3	14.1	8.1E-06	241	1740	53.9%
47/K2	16:45	300	15.0	4503	6.5	12.3	16.5	9.1E-06	288	1779	54.9%

Note: Test points 48-53 were collected on August 12 with 9 pumps operating. Test points 54-61 were collected on August 12 with 6 pumps. Test points 62-72 were collected on August 13 with 2 pumps.

Table 3. Performance Points at Variable Background Pressure

Test Pt/ Cathode	Time Stamp	Disch volts	Disch amps	Disch watts	Magnet amps	Magnet volts	Supply mg/s	Tank torr	Thrust mN	Isp sec	Total eff
48/K2	10:35	297	15.0	4460	6.5	8.6	16.5	1.1E-05	288	1784	55.9%
49/K2	10:59	300	10.0	2985	5.0	7.5	11.5	8.7E-06	192	1695	52.7%
50/K2	11:25	300	10.0	2994	5.0	8.1	11.6	8.7E-06	192	1696	52.7%
51/K2	11:32	250	10.0	2508	4.9	8.1	11.6	8.7E-06	170	1492	48.7%
52/K2	11:36	350	10.0	3499	5.4	8.9	11.6	8.7E-06	212	1873	55.0%
53/K2	11:43	400	10.0	4008	6.0	10.4	11.5	8.7E-06	231	2037	56.6%
54/K2	17:55	300	14.8	4445	6.5	9.7	16.2	1.9E-05	288	1817	57.0%
55/K2	18:03	300	10.0	3007	5.0	7.8	11.5	1.6E-05	194	1726	53.9%
56/K2	18:29	300	10.0	3002	5.0	8.4	11.5	1.5E-05	194	1721	53.8%
57/K2	18:37	250	10.0	2502	4.9	8.3	11.5	1.5E-05	171	1518	50.0%
58/K2	18:42	350	10.0	3499	5.4	9.2	11.5	1.5E-05	213	1892	55.8%
59/K2	18:47	400	10.0	4001	6.0	10.6	11.5	1.5E-05	231	2048	57.1%
60/K2	18:50	300	10.2	3050	5.0	8.9	11.6	1.5E-05	197	1727	53.8%
61/K2	19:03	300	15.3	4601	6.5	12.3	17.0	1.9E-05	297	1786	55.7%
62/K2	8:14	300	14.4	4322	6.5	8.9	15.6	7.6E-05	285	1865	59.6%
63/K2	8:20	300	10.0	3002	5.0	7.2	11.3	6.9E-05	197	1767	56.1%
64/K2	8:47	300	10.0	2997	5.0	8.1	11.3	6.9E-05	196	1765	55.9%
65/K2	8:50	300	10.0	2996	5.0	8.2	11.3	6.9E-05	196	1765	55.8%
66/K2	9:15	300	10.0	2996	5.0	8.8	11.3	6.9E-05	196	1764	55.7%
67/K2	9:47	250	10.0	2493	4.9	8.5	11.2	6.6E-05	174	1578	53.1%
68/K2	9:53	349	10.1	3519	5.4	9.5	11.4	6.6E-05	217	1942	57.8%
69/K2	10:10	400	10.0	3983	5.0	9.3	10.8	6.6E-05	220	2076	55.6%
70/K2	10:19	301	10.3	3101	5.0	9.4	11.6	6.6E-05	201	1768	55.5%
71/K2	10:30	300	15.0	4495	6.5	13.0	16.1	7.6E-05	294	1858	58.5%
72/K2	10:56	300	15.1	4516	6.5	13.9	16.2	7.6E-05	296	1858	58.5%

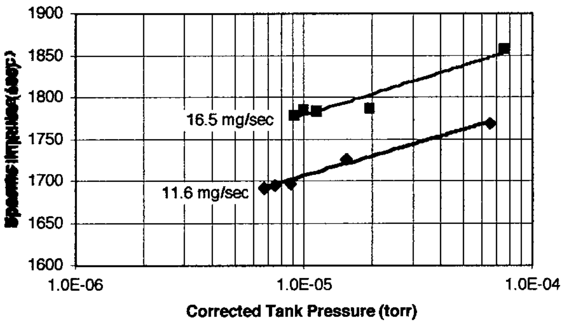

Figure 6. Thruster Specific Impulse versus Tank Pressure with Constant Flow

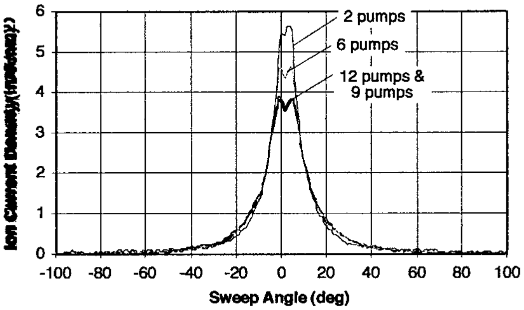

Figure 7. Ion Current Density Measurements at 300 volts and 10 amps Discharge under Variable Background Pressure

At the conclusion of the performance test, the tank was repressurized and the thruster was inspected and removed. The only visible sign of wear was on the ceramic channel which had slightly darkened relative to the pre-test condition. Inspection of the Faraday sweep arm indicated that the arm had traversed beyond the –100° limit switch causing the drive motor to fail. This problem occurred on the final sweep after all required data had been collected. Diagnostic testing was performed to determine post-test condition of the XFCs. Upon leak checking of the individual valves on XFC#02, a significant leak was detected on the cathode supply valve.

Future Work

A 7,200 hour life test of the HPHS, including the SPT-140 and S/SL brassboard PPU, is scheduled to begin in late 2000. The life test will have a duration of approximately 12 months. The firing profile will attempt to simulate the SPT-140 HPHS performing a combination of orbit raising followed by a series of station-keeping and repositioning events.

The life test will be performed in an AFRL high vacuum facility currently being constructed at Edwards Air Force Base, California specifically for this test. The facility consists of a large cylindrical vacuum chamber 3 m in diameter and 10 m in length. The roughing system consists of a dedicated dry Stokes mechanical pump and blower arrangement with a total pumping speed of 450 l/s. Upon initial evacuation of the vacuum facility to approximately 20 mTorr, a turbo molecular pump with a nominal pumping speed of 1,000 l/s is activated to lower the chamber pressure to the cross-over pressure for the cryogenic pumping system. The cryogenic pumping system consists of four 0.6 m by 2.0 m and four 0.6 by 2.5 m helium panels cooled to approximately 20 K. These panels are in turn shrouded by a system of Polycold® baffles to insulate the helium refrigerated panels from heat sources such as the ambient chamber walls and the Hall thruster plume. The total pumping speed of the facility is estimated to be approximately 350,000 l/s on xenon and provide a background pressure better than $2x10^{-5}$ Torr during operation of the SPT-140. Construction is on schedule and the chamber will be completed by January 2000.

The vacuum system will be instrumented to monitor the environment in which the test will be carried out. Two redundant ionization gauges and two cold cathode gauges will be used to monitor the background pressure during the test. All pressure measurements will be traceable to National Institute of Standards and Technology (NIST) standards. Pressure measurements will be supplemented with two residual gas analyzers which will monitor the relative proportions of background gases in the vacuum facility.

The life test of the HPHS will be extensively instrumented. The primary mission of the life test diagnostics package will be to monitor the performance of the SPT-140. This will be accomplished with an inverted pendulum thrust stand previously used in tests at AFRL [9]. The thrust stand has full scale of 360 mN and an accuracy better than ±3 mN.

In addition to the primary mission of performance measurement, the life test diagnostics will also measure a variety of other thruster characteristics. In order to provide an indication of how the plume divergence changes over the lifetime of the thruster, a probe rake with seven guarded Faraday probes similar to those previously used at GRC and PEPL will be placed approximately 1 m from the thruster exit plane. The probes will characterize the ion current density of the plume with sweeps occurring periodically during testing. To measure and record the erosion of the SPT-140 insulator, a comparative photographic system will be utilized. A charge coupled device (CCD) with a resolution better than 200 μm will capture images of the thruster front face through a shuttered view port. The port is approximately 3 m from the thruster exit plane and angled at 45° from the vacuum facility centerline. The images of the thruster will be correlated to produce a time history of the erosion of the SPT-140 insulator throughout the life test. A photograph of the vacuum facility is shown in Figure. 8.

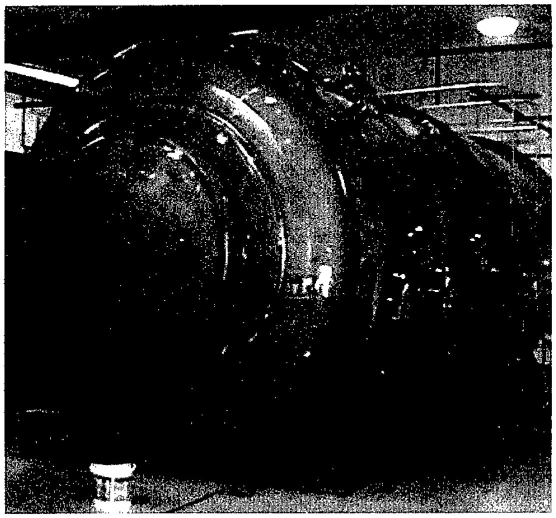

Figure 8. New AFRL vacuum facility for HPHS life extended duration life testing.

Due to the long duration of the testing at AFRL, the vast majority of the diagnostics will be automated. Thruster operations will be monitored and recorded using an Hewlett-Packard HP34970A data logger that will allow the setting of trip points which will be used to ensure the test remains within the specified parameters. The entire thrust measurement procedure will be automated, including the measurements and periodic calibration of the thrust stand. The Faraday probe measurements of the plume will also be automated such that no operator interaction is required to complete the diagnostic program. The erosion measurements will also be automated in a similar manner. The diagnostics system control will consist of a PC running the National Instruments LabView® software package which will provide the logic to operate the diagnostics. The diagnostic computer will ultimately control the test by interacting with the computer controlling the PPU.

Conclusions

A substantial portion of the US tests to qualify the HPHS have been completed. These include performance, EMI, and plume contamination testing performed at GRC as well as plume and ion energy profiling performed at the University of Michigan. The data from these tests have not yet been fully analyzed and this paper contains only initial results and test status. Forthcoming papers will describe the results of these tests in more detail.

Preparations are continuing for the HPHS life test to be performed at AFRL. The new vacuum facility will be completed in January 2000. It is anticipated that check-out of the vacuum facility will proceed as scheduled and the life test will begin by March of 2000. The life test will then be completed by April 2001. At this time, no impediments to this effort are foreseen.

Acknowledgments

The authors would like to thank the many engineers, mechanics, and other support personnel at GRC, the University of Michigan, SS/L, and AFRL who have labored so diligently to ensure the continuing success of the SPT-140 HPHS qualification project.

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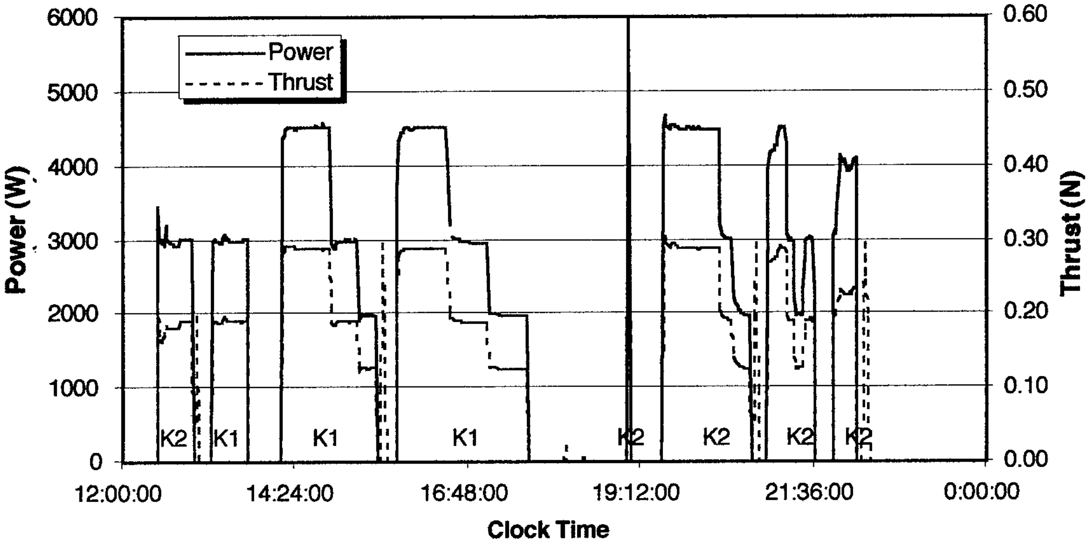
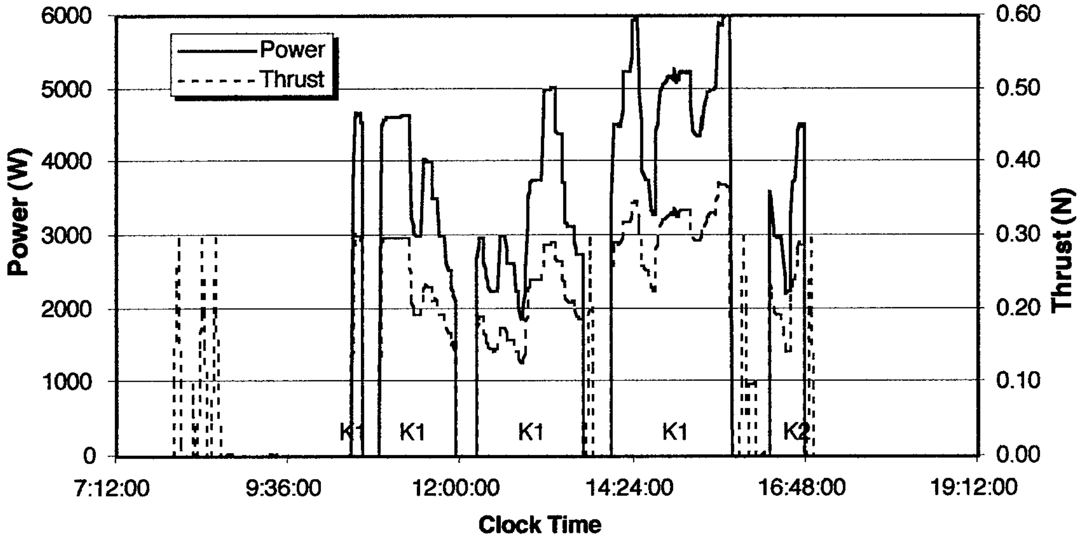
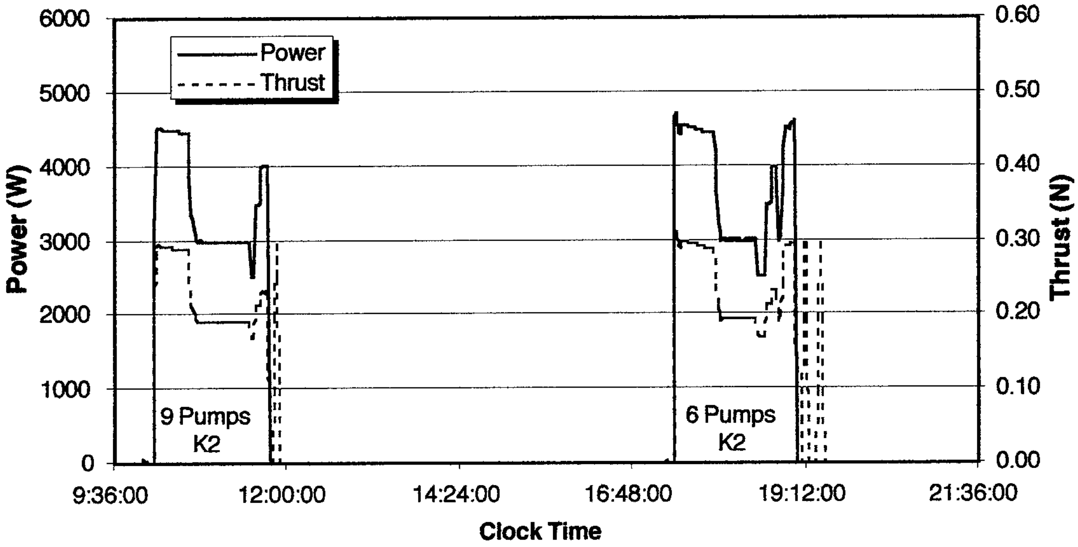
Appendix A: Performance Measurements

8/10/99 SPT-140 Test

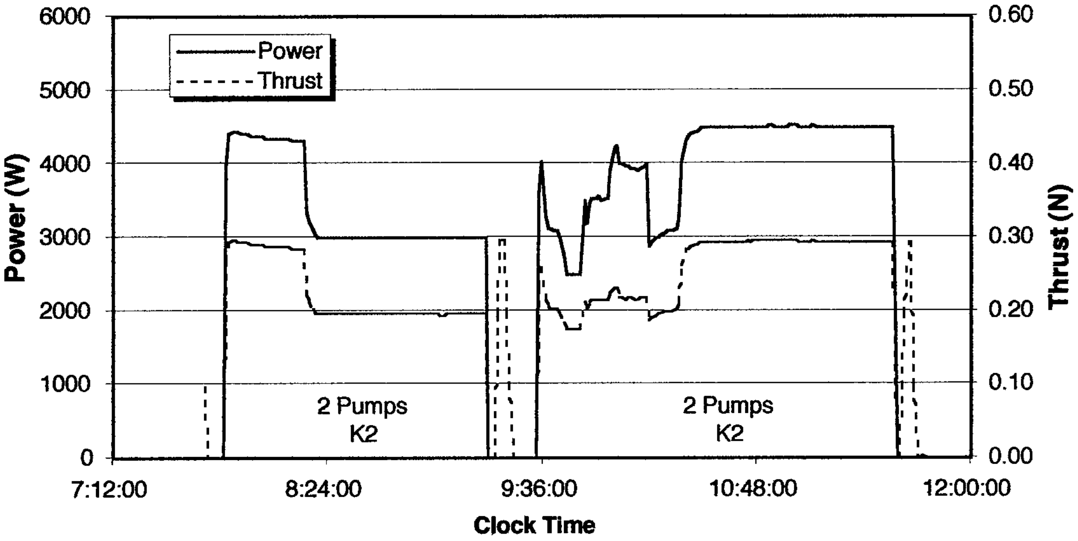


8/11/99 SPT-140 Test





8/12/99 SPT-140 Test



8/13/99 SPT-140 Test

Appendix B: Startup and Operations Log

Start No.	Day	Start	Finish	Duration	Cathode
1	8/10/99	11:38	aborted		2
2	8/10/99	12:04	aborted		2
3	8/10/99	12:28	12:58	0.50	2
4	8/10/99	13:16	13:46	0.50	1
5	8/10/99	14:10	15:30	1.33	1
6	8/10/99	15:47	17:36	1.82	1
7	8/10/99	17:50	aborted		2
8	8/10/99	18:04	aborted		2
9	8/10/99	18:18	aborted		2
10	8/10/99	18:35	aborted		2
11	8/10/99	18:55	aborted		2
12	8/10/99	19:28	20:42	1.23	2
13	8/10/99	20:56	21:34	0.63	2
14	8/10/99	21:50	22:09	0.32	2
15	8/11/99	10:26	10:36	0.17	1
16	8/11/99	10:51	11:54	1.05	1
17	8/11/99	12:09	13:40	1.52	1
18	8/11/99	14:04	15:44	1.67	1
19	8/11/99	16:16	16:44	0.47	2
20	8/12/99	9:43	aborted		2
21	8/12/99	10:08	11:42	1.57	2
22	8/12/99	17:20	19:03	1.72	2
23	8/13/99	7:48	9:16	1.47	2
24	8/13/99	9:33	11:32	1.98	2
25	8/19/99	9:00	aborted		2
26	8/19/99	9:10	9:11	0.02	2
27	8/19/99	9:22	aborted		2
28	8/19/99	9:39	10:17	0.63	2
29	8/19/99	10:35	17:10	6.58	2
30	8/19/99	18:24	19:27	1.05	2
31	8/31/99	11:04	aborted		2
32	8/31/99	11:18	11:50	0.53	2
33	8/31/99	12:22			2
	9/4/99		16:32	100.17	2

Total Operating Time126.92Hours

Total Time (K1) 8.05Hours

Total Time (K2)118.87Hours