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High-Specific Impulse Operation of the BPT-4000 Hall Thruster for NASA Science Missions

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To meet the propulsive requirements, cost constraints, and scientific objectives of NASA deep-space missions, high-performance, low-cost electric propulsion (EP) options are needed. Commercial EP technology has matured sufficiently that ion and Hall thrusters are now leading candidates for many of these missions. A commercial Hall thruster system is as much as 50% less expensive than an equivalent ion thruster system, but the maximum specific impulse of commercial, flight-qualified Hall thrusters is presently 2000 s. Extending the specific impulse to 2500-3000 s would increase the Hall thruster mission capture to include nearly all of the missions where EP was applicable. To assess the suitability of extending the specific impulse range of a candidate commercial Hall thruster, a test campaign designed to assess the performance and plasma properties of Aerojet's BPT-4000 during high-specific impulse operation was executed. An inverted-pendulum thrust stand was used for performance measurements. An RPA, ExB probe, and emissive probe were used to measure the ion energy, ion species' current fractions, and plasma potential, respectively, in the far-field plume. For operating conditions spanning 500-800 V discharge voltage and 2.5-5.5 kW discharge power, thrust varied from 134-288 mN, specific impulse from 1980-2720 s, and efficiency from 0.50-0.59. It was concluded that operating the BPT-4000 at specific impulses of 2600 s and 4.5 kW discharge power was within the existing capabilities of the magnetic circuit, thermal margins, and voltage isolation. Based on these results, a delta-qualification for high specific impulse operation and higher propellant throughput via additional testing of the qualification thruster is recommended in order to ready the thruster for near-term infusion into NASA science missions.

I. Introduction

Of the 28 missions currently being considered by the Planetary Decadal Survey, solar electric propulsion (SEP) is potentially applicable to 15 of those missions. To meet the ΔV requirements, cost constraints, and scientific objectives of these missions, high-performance, long-life, <u>low-cost</u> SEP options are needed. Commercial electric propulsion (EP) technology has now matured sufficiently that ion and Hall thrusters are now leading candidates for many of these missions [1,2]. A candidate Hall thruster system that has been shown to meet these needs is Aerojet's BPT-4000, which has been qualified for NASA science missions through a combination of testing, simulations, and mission analysis [1,3-9]. The present study investigates the feasibility of operating the BPT-4000 at high-specific impulse for discharge voltages of 500-800 V and discharge power levels up to 5.5 kW.

The Jet Propulsion Laboratory (JPL) began pursuing commercial EP systems in 2005 [1,10] in response to the cost-growth experienced with the government-developed NSTAR ion thruster on the Dawn mission [11,12]. The cost-growth of NSTAR on Dawn is a manifestation of the once-per-decade flight rate of SEP on NASA missions that makes the cost of the propulsion system very expensive. The cost risk that is endemic to government-developed systems such as NSTAR or the NEXT ion thruster [13] currently under development may be substantially reduced through the use of commercial technologies. Through procurements from commercial product lines with much higher flight rates, substantial cost reductions are possible [1,10].

A commercial Hall thruster system is as much as 50% less expensive than an equivalent ion thruster system [1], but the maximum specific impulse of commercial Hall thrusters is presently 2000 s. Extending the specific impulse to 2500-3000 s would increase the Hall thruster mission capture to include nearly all of the missions where EP was applicable. Such a system would still enjoy a cost advantage over ion thrusters since the simplicity and robustness of the Hall thruster system would be retained. Further, a delta-qualification of an existing thruster for

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high specific impulse operation and higher propellant throughput would be much less expensive than qualifying a new thruster.

The BPT-4000 Hall Thruster Propulsion System (HTPS) was developed through a joint effort between Lockheed Martin Space Systems and Aerojet as a 4.5 kW electric propulsion system for geosynchronous Earth orbit (GEO) satellite applications [3,7,14]. The first flight of the BPT-4000 is scheduled for the summer of 2010 on the first Advanced EHF spacecraft [7]. The qualification life test (QLT) for GEO applications with the Qualification Model (QM) BPT-4000 was completed in 2005 [14,15], and was subsequently extended through two life test extensions that brought the total operating time to over 10,400 h for discharge power of 1-4.5 kW. Aerojet has also measured sub-kW performance and plume properties down to 0.3 kW discharge power [3]. Measurements at JPL on an Engineering Model (EM) thruster that is the subject of this paper have demonstrated multi-hour operation as low as 0.25 kW. Table 1 summarizes the total impulse, operating time, thruster starts, and propellant throughput that were demonstrated through the end of the second life test extension. The total impulse of 8.7 MN-s now exceeds the 7.2 MN-s demonstrated during qualification testing of NASA's NSTAR ion thruster that is now flying on NASA's Dawn mission [11,12]. Erosion measurements from the QLT indicated that very little discharge channel wear occurred between 5,600 h of operation and 10,400 h [7]. Based on the erosion rates observed during the QLT, the throughput capability could far exceed 1000 kg if additional life testing were to be performed with the QM thruster that has been preserved for further testing [7]. Physics-based models developed at JPL to study the plasma and erosion processes in Hall thrusters have been used to interpret the results from the QLT and are discussed in Ref. [8]. The qualified life and throttling capabilities of the BPT-4000 and its low-cost relative to government systems make it an attractive candidate for near-term infusion in cost-capped science missions such as the NASA Discovery and New Frontiers programs [1,16].

Table 1. Demonstrated capability of the BPT-4000 Hall thruster [7]. Based on the erosion rates observed during qualification life testing, the throughput capability could exceed 1000 kg if additional life testing were to be performed.

Parameter	BPT-4000 Demonstrated
Total Impulse	8.7 MN-s
Total Firing Time	10,400 h
Total Thruster Starts	7,316
Total Xenon Throughput	452 kg

Previous efforts to qualify the BPT-4000 for NASA missions have only considered operating conditions that were within the existing capabilities of the power processing unit (PPU). This approach was taken in order to minimize the first flight costs of implementing a BPT-4000 on a NASA science mission. With the thruster qualification completed, consideration is now being given to how the performance may be extended in order to increase mission capture. A PPU compatible with the unregulated input bus voltage of NASA spacecraft is being jointly developed by Aerojet and JPL. This PPU is also being designed to provide up to 800 V output, which is necessary to increase the specific impulse. In its present form, the BPT-4000 PPU is capable of operating the thruster at a maximum specific impulse of approximately 2000 s and discharge power of 4.5 kW.

To assess the suitability of extending the operating range further, a test campaign was executed with the objective to evaluate the performance and operating characteristics of an Engineering Model (EM) Aerojet BPT-4000 Hall thruster operating at greater than 2000 s specific impulse. The test campaign was constructed in order to determine the feasibility of operating at up to 2700 s specific impulse and to identify what would be needed to qualify the thruster for high-specific impulse operation. Experiments were performed in a large vacuum chamber at JPL. An inverted-pendulum thrust stand was used for performance measurements. An RPA, ExB probe, and emissive probe were used to measure the ion energy, ion species' current fractions, and plasma potential, respectively, in the far-field plume. Testing showed that the thruster was stable and capable of sustained operation at operating conditions spanning 500-800 V discharge voltage and 2.5-5.5 kW discharge power. Thrust varied from 134-288 mN, specific impulse from 1980-2720 s, and efficiency from 0.50-0.59. It was concluded that operation at discharge voltages up to 800 V and discharge power up to 4.5 kW are within the existing capabilities of the magnetic circuit, thermal margins, and voltage isolation. Based on these results, a delta-qualification for high specific impulse operation is recommended in order to ready the thruster for near-term infusion into NASA science missions.

II. Experimental Apparatus

A. BPT-4000 Hall Thruster

Experiments were performed with the same Engineering Model (EM) BPT-4000 thruster and experimental apparatus reported in Ref. [5] and summarized here. A photograph of the thruster installed on the thrust stand in the vacuum chamber is shown in Figure 1. Figure 2 is a photograph of the thruster operating at 800 V, 4.5 kW.

Two sets of pre-machined boron nitride insulator rings were used during the course of the experiments. The first corresponded to the shape that the insulator rings eroded to after 1,200 h of thruster operation and the second set of rings corresponded to 6,800 h of operation [7]. Because it was observed during life testing that erosion practically stopped after 5,600 h of operation, we also refer to this geometry as the “steady-state” geometry. For the experiments reported here, all measurements were taken with the 6,800 h rings unless otherwise noted. The insulators were conditioned by operating the thruster for several hours before acquiring performance and plume data. We discuss further our reasoning for using these insulator ring geometries in section III.A.

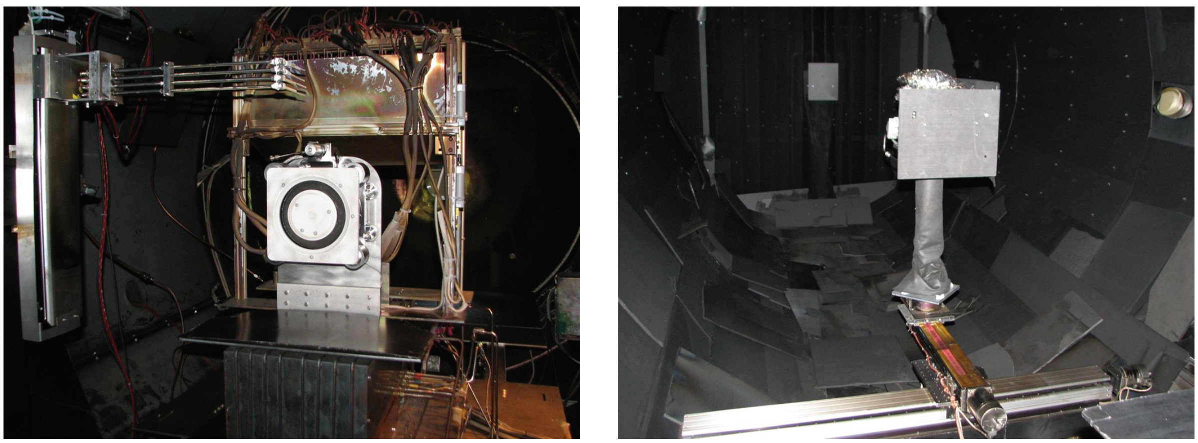

Figure 1. Photographs of the experimental configuration showing the thruster installed on the thrust stand (left) and the far-field plume probe array (right).

Figure 2. Operation of the BPT-4000 at 800 V, 4.5 kW.

B. Vacuum Facility

Experiments were performed in the Endurance Test Facility (ETF) at JPL. The 3 m diameter by 10 m long vacuum chamber has been used previously to test ion [12,17] and Hall thrusters [5,18-20] at power levels exceeding 20 kW. The cryogenically pumped facility routinely achieves base pressures between 10^{-8} and 10^{-7} torr. At the maximum xenon flow rate of 15.43 mg/s, the operating pressure in the ETF was $1.3\text{x}10^{-5}$ torr, equivalent to a pumping speed of 170 kl/s.

C. Power Electronics and Propellant Delivery System

Power and propellant were delivered to the BPT-4000 with commercially available power supplies and flow controllers [5]. The discharge filter consisted of a 80 μF capacitor in parallel with the discharge power supply outputs. As is common practice with Hall thrusters, the cathode heater and keeper were used only during the thruster ignition sequence. Research-grade xenon propellant was supplied through stainless steel feed lines with 50 and 500 sccm mass flow controllers. The controllers were calibrated before the experiment and were digitally controlled with an accuracy of ±1% of the set point.

D. Thrust Stand

Thrust measurements were acquired using the same water-cooled, inverted-pendulum thrust stand with inclination control and active damping used during the NSTAR ion thruster Extended Life Test [12] and other Hall thrusters [5,18,20]. Upon initial exposure to vacuum, the thruster was operated for at least two hours to allow for outgassing of thruster components. Thrust measurements were typically conducted at constant power, in intervals of 30 to 60 minutes, following the outgassing procedure. Thermal drift and inclination of the thrust stand were accounted for during post-processing.

It is generally accepted in the Hall thruster community that pressures of less than $2\text{x}10^{-5}$ Torr are sufficient to reliably obtain performance measurements without needing to correct for neutral gas ingestion [21,22]. This criterion was met in these experiments and no attempts to correct for neutral ingestion were made.

Calibrations were performed daily by deploying a series of known weights ten times each [5]. As shown in Figure 3, these weights spanned the range of 39 to 302 mN. When inclination and thermal drift were accounted for, the response of the thrust stand was repeatable and linear to the applied force. Thermal drifts of the thrust stand zero are typically the single largest uncertainty in the measurement. These drifts are partially offset at low-power due to the reduced thermal loads on the thrust stand. Analysis of thrust stand uncertainty indicated a range of ±1-2%, with the largest uncertainty occurring at the lowest power. Given the uncertainty of the thrust, mass flow rate, current, and voltage, the propagated uncertainty for specific impulse was estimated as ±1.4-2.8% and ±2.3-4.6% for efficiency, again with the largest uncertainty occurring at the lowest power.

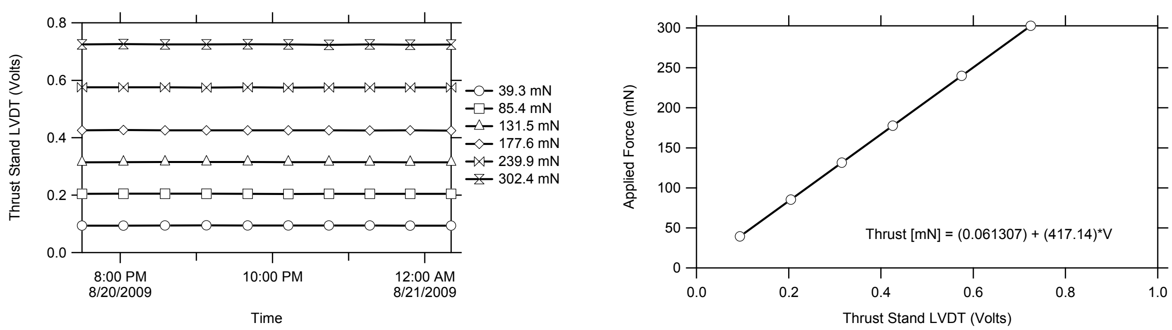

Figure 3. Thrust stand calibration results. Left: LVDT response to calibration weights. Right: Thrust stand calibration curve.

E. Discharge Current Probe

A pair of 20 MHz current probes and an 8-bit, 500 MHz oscilloscope were used to measure discharge current oscillations during steady-state thruster operation with an accuracy of ±3% [5]. The current probes were located on the anode and cathode sides of the power input between the thruster and discharge filter described in section II.C. Oscillations were quantified by calculating the oscillation amplitude of the discharge current defined by

$$\Delta \equiv \frac{1}{\langle I_d \rangle} \sqrt{\frac{\int_0^{\tau} \left[I_d(t) - \langle I_d \rangle \right]^2 dt}{\tau}}, \tag{1}$$

where $I_d(t)$ is the time-dependent discharge current, $\langle I_d \rangle$ is the time-averaged discharge current, and τ is the sampling period.

F. Far-field Plasma Probes

Shown in the right photograph of Figure 1, an array of plasma probes were deployed in the far-field plume region [5]. The probe array consisted of an ExB probe, a Retarding Potential Analyzer (RPA), and an emissive probe, that were used to measure ion species' current fractions, ion energy, and plasma potential, respectively. The probes were positioned in the plume using a pair of linear translation stages and a rotary stage. The axial position of the probes was 1.5 m downstream of the thruster. The radial position of the probes was aligned with the mid-channel radius of the thruster, with the probes rotated to align with the local current density vector, which roughly resulted in the probes being pointed at the center of the thruster. The direction of the current density vector was determined by measuring the probe current as a function of angle. For the ExB probe, the probe was biased to the voltage corresponding to the Xe^{+} ion species and for the RPA the probe was biased to the voltage corresponding to the maximum in the ion voltage distribution.

1. ExB Probe

An ExB probe, or Wien filter, is a band-pass ion filter that selects ions according to their velocities through the application of crossed electric and magnetic fields [5,23,24]. Because the velocity of multiply-charged ions in Hall thrusters is proportional to the square root of their charge-state, an ExB probe can be used to discriminate between ion species. Analysis of the ion current from the probe characteristic can then be used to compute the ion species' current fractions.

The ExB probe used in these experiments was used previously with other high-power Hall thrusters [5,18,24]. Following Shastry's method to maintain plume attenuation due to charge-exchange collision less than 30% [24], the probe was positioned downstream of the thruster such that the maximum product of the pressure and distance was $p*z = 2x10^{-5}$ Torr-m. Analysis of the probe spectra and a correction accounting for the loss of main beam ions due to charge-exchange collisions also followed Shastry's method [24].

Measurements of the ion species' current fractions were accomplished using the single sampling location described above. Although a more accurate measurement would account for the azimuthal distribution of multiply-charged ions in the plume through multiple measurements weighted by the local current density, Reid found that results accurate to within 1.5% of the plume-weighted average could be obtained through a single measurement when the probe was radially located on the mid-channel radius and pointed at the thruster center [25]. Based on Reid's results, a single sampling location was used as this choice balances well the accuracy of the measurement and the time required to obtain it.

The combined standard uncertainty of the ion species' current fractions computed from the ExB probe spectra has been estimated as 3% in Xe^{+}, and 20% in Xe^{2+} and Xe^{3+}.

2. Retarding Potential Analyzer (RPA)

A retarding potential analyzer (RPA) selectively filters ions by applying a retarding potential across an inlet grid [26]. The probe acts as a high-pass filter by allowing only ions with voltages (i.e., energy-to-charge ratios) greater than the grid voltage to pass and reach a collection electrode. The derivative of the resulting current-voltage characteristic is then proportional to the ion voltage distribution function.

The same RPA used in Ref. [5] was used for the experiments. Measurements of the ion voltage distribution were taken with respect to facility ground. Plasma potential (V_p) measurements taken with the emissive probe, which was the same probe used in Ref. [5], were used to correct the RPA data so that the true ion voltage distribution could be computed, i.e., $V_{true} = V_{rpa} - V_p$. The most-probable ion voltage (V_{mp}) and the ion loss voltage (V_l) were then found from the true ion voltage distribution. The most-probable ion voltage was defined as the voltage where the ion current was greatest. The ion loss voltage was then computed as the difference between the discharge voltage and the most-probable ion voltage, i.e., $V_l = V_d - V_{mp}$. The uncertainty of the most-probable voltage was estimated as ±1%. Finally, the full-width at half-maximum (FWHM) of the ion voltage distribution was also calculated in order to characterize the spread of ion voltages present in the beam. The FWHM was defined as the difference in volts above and below the most-probable voltage where the ion current fell to one half its maximum value.

III. Results

Figure 4 shows the operating conditions investigated over the course of all experiments conducted at JPL with the BPT-4000. Current, voltage, and power throttling ranged from 1-15 A, 125-800 V, and 0.15-5.5 kW, respectively. Ref. [5] first reported on a subset of these results and was focused on low power operation (<1 kW). Although we will briefly discuss some other operating conditions, the primary focus of the experiments presented here are for operation over 2.5-5.5 kW, 500-800 V. These data are collectively referred to here as the high-specific impulse test campaign.

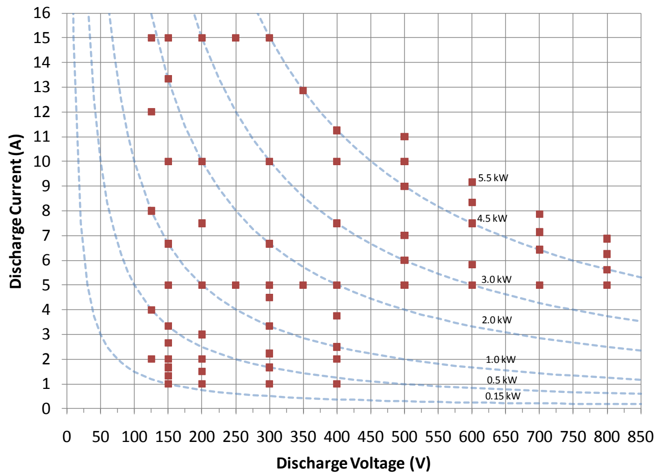

Figure 4. Operating conditions investigated over the course of all experiments conducted at JPL. Lines of constant discharge power are drawn for reference. Current, voltage, and power throttling ranged from 1-15 A, 125-800 V, and 0.15-5.5 kW, respectively. In this paper, the focus is on operation from 500-800 V, 2.5-5.5 kW.

The primary objectives of the high-specific impulse test campaign were as follows:

1. Demonstrate that the BPT-4000 is capable of sustained operation (several hours) at voltages up to 800 V and discharge power of 4.5 kW.
2. Map the performance of the BPT-4000 under high-voltage operation (>400 V) in order to generate throttle curves that may be used in mission studies.
3. Investigate the feasibility of operating the thruster in excess of 4.5 kW discharge power at voltages of 500-800 V.
4. Collect plasma property data in the plume of the thruster necessary for validating outputs of computational performance and lifetime models.

A. Insulator ring performance comparison (1,200 h vs. 6,800 h)

For commercial applications, the BPT-4000 is operated at four conditions corresponding to 3.0 or 4.5 kW discharge power and 300 or 400 V discharge voltage. These are the most well characterized operating conditions for the thruster and serve as a reference point for verifying nominal operation of the thruster and the test facility during the JPL experiments. The measurements reported in Ref. [5] all used insulator rings pre-machined to the 1,200 h geometry. This geometry was chosen because at this point performance is very close to the time-averaged value for the entire life test [7]. It was shown in Ref. [5] that the JPL measurements deviated from the time-averaged thrust by only 0.4-1.8%. This was taken as an indication that the measurements were representative of the time-averaged performance of the BPT-4000.

After the 1,200 h insulator ring experiments, a new set of rings pre-machined to the erosion corresponding to 6,800 h of operation was installed (see section II.A). Because it was observed during life testing that erosion practically stopped after 5,600 h of operation [7], we also refer to this geometry as the “steady-state” geometry. Table 2 compares the performance measured with the two sets of insulator rings for a range of operating conditions spanning 150-400 V, 0.23-4.5 kW. Excellent agreement is found for virtually every operating condition, with the average difference being less than 2% in thrust, specific impulse, and efficiency. These results are consistent with the QLT that showed the performance of the thruster reaching nearly constant values after the first few hundred hours of operation. As a representative example, data from the QLT is compared with the JPL measurements in Figure 5 for the 4.5 kW, 300 V operation condition. We conclude based on all of these results that within the uncertainty of the measurement techniques, the use of pre-machined insulator rings is an effective means to reproduce the time-dependent performance of the BPT-4000 measured during the QLT.

Table 2. Comparison of performance measured with insulator rings pre-machined to the 1,200 h and 6,800 h (steady-state) erosion geometry.

Condition	Rings	Thrust	%Diff	Total Isp	%Diff	Total Eff	%Diff
300 V, 3 kW	1200 h	192.7		1740		0.542	
	6800 h	193.1	0.2%	1728	-0.7%	0.541	-0.2%
400 V, 3 kW	1200 h	171.5		1917		0.531	
	6800 h	175.1	2.1%	1918	0.1%	0.544	2.4%
300 V, 4.5 kW	1200 h	278.6		1843		0.553	
	6800 h	280.4	0.6%	1843	0.0%	0.557	0.7%
400 V, 4.5 kW	1200 h	251.2		2016		0.545	
	6800 h	256.9	2.3%	2035	0.9%	0.563	3.3%
Averages (3-4.5 kW)			1.3%		0.1%		1.6%
150 V, 0.225 kW	1200 h	N/A		N/A		N/A	
	6800 h	15.6		606		0.203	
150 V, 0.30 kW	1200 h	21.4		705		0.244	
	6800 h	23.2	8.2%	687	-2.6%	0.257	5.3%
200 V, 0.30 kW	1200 h	19.8		824		0.262	
	6800 h	20.2	2.0%	786	-4.6%	0.256	-2.3%
200 V, 0.40 kW	1200 h	27.8		920		0.311	
	6800 h	27.5	-0.9%	894	-2.8%	0.299	-3.9%
200 V, 1.0 kW	1200 h	78.5		1126		0.430	
	6800 h	79.4	1.1%	1143	1.5%	0.442	2.8%
300 V, 1.0 kW	1200 h	66.7		1391		0.450	
	6800 h	67.6	1.4%	1372	-1.4%	0.451	0.2%
200 V, 2.0 kW	1200 h	141.8		1307		0.450	
	6800 h	139.9	-1.3%	1267	-3.1%	0.431	-4.2%
400 V, 2.0 kW	1200 h	115.9		1764		0.496	
	6800 h	119.8	3.4%	1781	1.0%	0.520	4.8%
Average (all data)			1.7%		-1.1%		0.8%

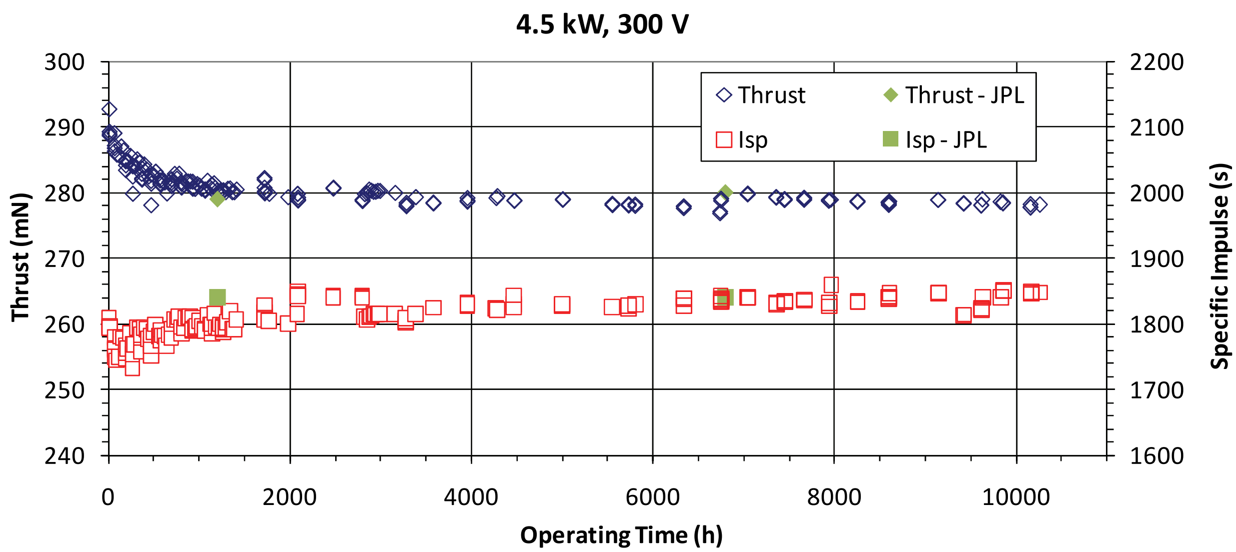

Figure 5. Comparison of the measured thrust and specific impulse from the life test QM thruster and values measured at JPL on an EM thruster with insulator rings pre-machined to the erosion geometry after 1,200 or 6,800 h (steady-state) of operation.

B. High-specific impulse operation (500-800 V, 2.5-5.5 kW)

High-specific impulse operation was evaluated by increasing the discharge voltage of the thruster to greater than the maximum voltage of 400 V that the existing PPU can provide and by varying the discharge power over 2.5-5.5 kW (the maximum discharge power of the existing PPU is 4.5 kW). At each operating condition, the cathode flow fraction was maintained at 7% of the anode flow rate for all conditions and was operated without using its heater or keeper [5]. Performance was mapped for a given operating condition by varying the magnetic field strength while maintaining a constant discharge power. Power was held constant by fixing the discharge voltage and then adjusting the anode mass flow rate to achieve the desired discharge current (for each magnetic field setting).

Figure 6 shows thrust, total specific impulse, and total efficiency as a function of discharge power and voltage. All data in the figure are equal to or less than magnetic coil currents already demonstrated in the QLT. (The reasoning for using these coil currents is discussed further below.) Thus, these data represent the performance of the existing system without requiring any changes to the thruster or PPU. Over discharge power of 2.5-5.5 kW and discharge voltage of 500-800 V, thrust varied from 134-288 mN, specific impulse from 1980-2720 s, and efficiency from 0.50-0.59. The maximum specific impulse of 2720 s was measured at 800 V, 5.5 kW. At 800 V and the current maximum power of 4.5 kW, thrust, specific impulse, and efficiency were 184 mN, 2620 s, and 52%, respectively. At 4.5 kW, the maximum efficiency of 58% corresponded to operation at 500 V. The decrease in efficiency as the voltage was increased from 500-800 V at constant power was not unexpected due to the known decrease in the mass utilization efficiency with decreasing current density. This was the primary motivation for operating the thruster up to 5.5 kW. For instance, increasing the power from 4.5 to 5.5 kW at 800 V increased the specific impulse by 100 s and the efficiency by 3%.

Achieving efficient, long-life Hall thruster operation at high specific impulse is challenged by voltage isolation, thermal margins, and magnetic field considerations [21,27,28]. The BPT-4000 propellant isolator has the necessary voltage margin for this range of voltages. No arcing or voltage isolation issues occurred during any of the testing. Thermal and magnetic field margins are discussed further in the following.

As noted in section II.D, performance measurements were acquired over windows of thruster operation of 30 to 60 minutes each. However, continuous thruster operation exceeded these windows by several hours during magnet optimization studies or plume measurements. The entire high-voltage test campaign included over 25 h of thruster operation at voltages of 500 V or greater, including one day with more than 10 h of operation. The longest single operating time was a 4 h run conducted at 4.5 kW and voltages of 500-800 V. During this testing window, the voltage on the magnet coils reached a steady-state value, which in Hall thrusters is usually taken as an indication that the thruster body has reached thermal equilibrium [29]. Lastly, temporal drifts of discharge current or thrust never exceeded values typically seen at lower voltages [5]. Based on the totality of these observations and those from other high-power, high-specific impulse thrusters [21,27-30], it was concluded that operating the BPT-4000 at voltages of 500-800 V and 4.5 kW of power had little or no impact on the thermal characteristics of the thruster. While formal analyses and testing of the thermal margins are still required to qualify the thruster for high-voltage operation, it is not anticipated that this work will reveal any significant issues.

The same cannot yet be said for operation at 5-5.5 kW due to the limited amount of time spent at these power levels. Operation at these powers was limited to runs of less than 30 minutes each (between thrust stand zeroes), but were conducted on days when the thruster had already been operated for several hours. Temporal drifts of discharge current or thrust never exceeded values typically seen at lower voltages [5]. The total run time at 5 kW or greater was about 2 h. Similar to high-voltage operation at 4.5 kW or less, no evidence of thermal issues were apparent and we have high confidence in the measured performance. However, given the relatively short amount of time spent at >5 kW power, additional analyses and testing are still needed before it can be determined if high-power operation is a viable development path for this thruster.

Performance was mapped as a function of magnetic field intensity for each operating condition investigated (not shown). For discharge voltages of 500 V or greater, it was found that the magnetic coil current corresponding to maximum performance was usually higher than the maximum current demonstrated during the QLT [7] (the optimum depended on voltage and power). However, for these conditions the efficiency only differed from the true optimum by 1-3%. Modifications to the magnetic circuit could alleviate this limitation and allow the thruster to operate under optimum magnetic field strengths [21,27] and improve performance, but this might require more extensive efforts to delta-qualify the thruster. An alternative path that would represent a much lower qualification cost is to operate the BPT-4000 within the capabilities demonstrated during the QLT, and it was found during this testing that the thruster performance was still acceptable while doing so (Figure 6).

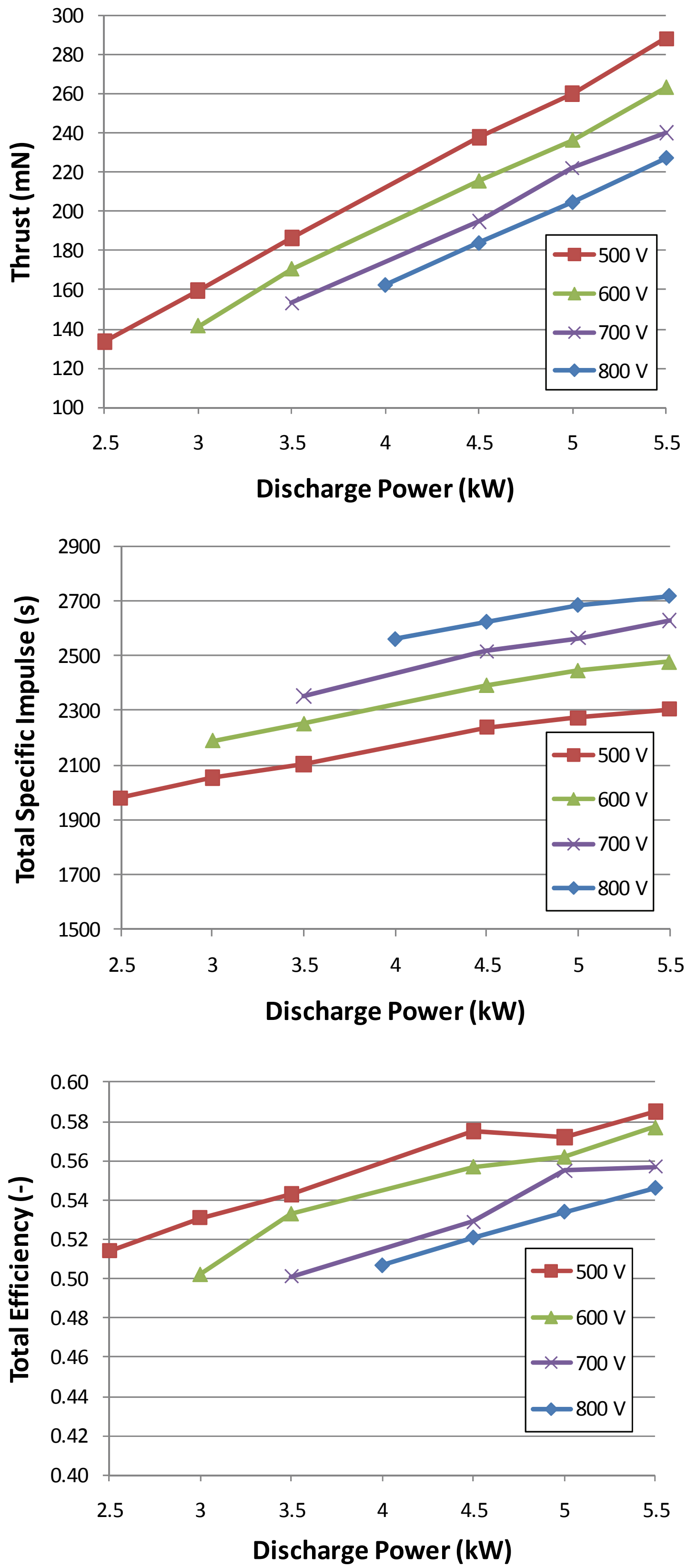

Figure 6. Thrust, specific impulse, and efficiency of the BPT-4000 operating over 500-800 V, 2.5-5.5 kW.

C. Far-field probe data (500-800 V, 2.5-5.5 kW)

Figure 7 plots the amplitude of discharge current oscillations and the breathing-mode frequency from the discharge current probe on the anode side of the discharge at a constant power of 4.5 kW over 300-800 V. The oscillation amplitude was computed from Eqn. (1) and the breathing-mode frequency was computed from the Fourier transform of the discharge current. The data show that the oscillations in the BPT-4000 increase between 300 and 400 V and then decrease over 400-800 V. A similar trend was found in the results of Ref. [21]. The breathing-mode frequency followed a dependence with voltage similar to the oscillation amplitudes, which was unexpected since to first order we expect the breathing-mode frequency to scale with the ion and neutral velocities (i.e., with discharge voltage) [31]. Previous studies found a continuous increase in frequency with voltage in an optimized thruster operating at constant mass flow rate [21]. In the BPT-4000 data, power was held constant as voltage was increased, which may have contributed to the observed dependence of the breathing-mode frequency with voltage.

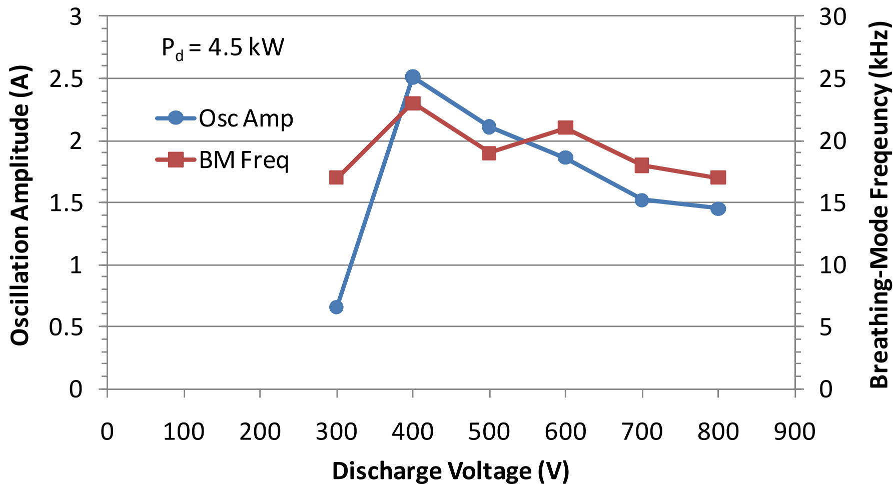

Figure 7. Oscillation amplitude and breathing-mode frequency from the discharge current probe on the anode side of the discharge.

Figure 8 plots the ion loss voltage and FWHM (defined in section II.2) as measured with the RPA for operation over 300-800 V, 4.5 kW. These two quantities are plotted in absolute terms (left) and as a fraction of the discharge voltage (right). In absolute magnitude, the loss voltage and FWHM both increase with voltage, but as a fraction of the discharge voltage, a monotonic decrease for the FWHM was measured while the loss voltage approaches a constant value at voltages of 600 V or greater.

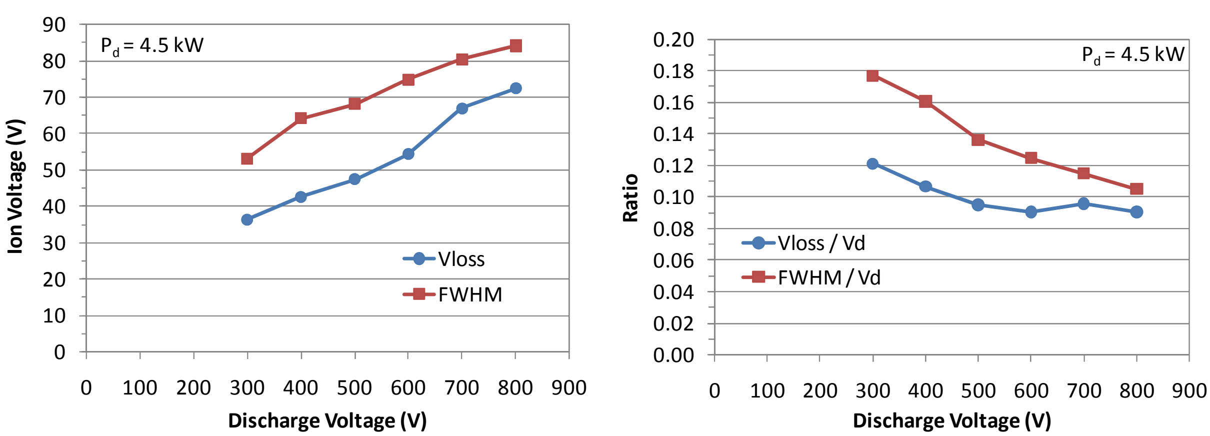

Figure 8. Ion loss voltage and full-width at high-maximum (FWHM) as measured with the RPA for operation over 300-800 V, 4.5 kW. Left: Loss voltage and FWHM in absolute terms. Right: Loss voltage and FWHM as a fraction of the discharge voltage.

Figure 9 plots the ion species' current fractions measured with the ExB probe for operation over 300-800 V, 4.5 kW. As the voltage increased, a monotonic increase in the Xe^{+} current fraction from 0.696 to 0.802 was measured. This trend seems counterintuitive at first, since we expect the Xe^{+} fraction to decrease with discharge voltage as the electrons are heated to higher temperatures thereby producing more multiply-charged ions. This is the trend observed in previous studies of high-voltage Hall thrusters conducted at constant flow rate [27]. In the BPT-4000 data, we again note that the current decreased as the voltage was increased which influences the production rate of multiply-charged ions. This is because the largest ionization rate for the creation of multiply-charged species are not from neutrals but from other ions [25,32]. Thus, if the current is decreased at constant voltage, less multiply-charged ions will be created because there are less ions around to create them. This dependence has been verified through experiments and simulations in Ref. [25]. In the BPT-4000 data, there are two competing effects determining the fraction of multiply-charged ions present: 1) the rise of the discharge voltage that heats electrons and increases multiply-charged ion production, and 2) the decrease of the discharge current that lowers the multiply-charged ion production. Due to the monotonic increase in the Xe+ population, these data imply that the production rate from other ions outweighs the increase from higher electron temperatures.

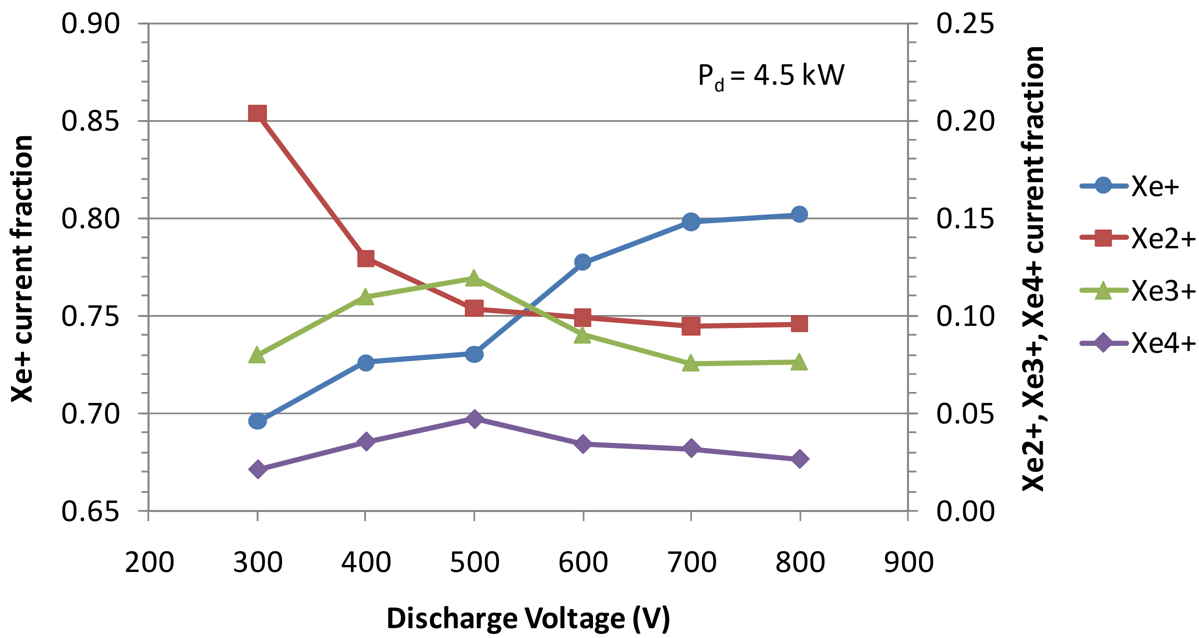

Figure 9. Ion species' current fractions measured with the ExB probe for operation over 300-800 V, 4.5 kW.

IV. Discussion

Performance measurements of the BPT-4000 show that increasing the specific impulse from 2000 to 2600 s at a constant discharge power of 4.5 kW requires an increase of the discharge voltage from 400 to 800 V. High specific impulse can result in several detrimental effects to thruster operation and life that are well known, including: the voltage rating of isolated surfaces may be exceeded, thermal stresses may rise due to higher power deposition at the discharge chamber walls, and erosion rates may be increased due to the proportional increase in ion energy with the discharge voltage [21,27]. Voltage isolation and thermal stress concerns have largely been eliminated due to the results presented here. What remains is to systematically address the potential impacts on thruster life through experiments and simulations. While such an assessment is beyond the scope of the present work, we review some basic considerations below.

The propellant throughput capability of a Hall thruster is typically limited by discharge chamber erosion due to high-energy ion impact of the walls [4]. Following the arguments of Kim [33], the discharge chamber wear rate of a Hall thruster depends primarily on the power density. Consider the discharge chamber wall undergoing sputtering through ion impacts. The radial recession rate of the wall is given by the product of the perpendicular ion current density and the energy and angle dependent sputtering yield for the wall material given by

$$\frac{dr}{dt} = \dot{\xi} = j_{i,\perp} Y\left(E,\theta\right). \tag{2}$$

Neglecting the angular dependence, the sputtering yield over a wide range of ion energies is roughly proportional to the discharge voltage (ion energy)

$$Y\left(E,\theta\right) \approx Y(E) \sim V_d . \tag{3}$$

The ion current density to the wall is proportional to the propellant flow rate

$$j_{i,\perp} \sim \dot{m}_a \sim I_d . \tag{4}$$

Thus, the wall recession rate is proportional to the power (really, the power density)

$$\dot{\xi} \sim V_d I_d \sim P_d . \tag{5}$$

A more appropriate metric than propellant throughput for stating thruster life is the total impulse, which is the product of the thrust F and the total operating time T

$$I_t = F \times T . \tag{6}$$

If we define the operating life as the amount of time it takes for the wall to erode through its radial thickness h, and noting that thrust is proportional to power ($F \sim P_d$), we have

$$T = \frac{h}{\dot{\xi}} \sim \frac{h}{P_d} \tag{7}$$

Combining these relations yields

$$I_t = F \times T \sim P_d \frac{h}{P_d} \approx \text{constant} \tag{8}$$

Thus, for a given thruster, the total impulse is independent of the operating condition. This relation will hold over some throttling range near the nominal thruster power. The BPT-4000 QLT results have demonstrated very good agreement with the relation over at least 1-4.5 kW and 200-400 V. The extent to which this scaling holds at discharge voltages greater than 400 V will need to be determined through experiment and simulations, but we do not anticipate large scale deviations. This is justified for two reasons. First, in these experiments, the BPT-4000 was operated at its maximum power of 4.5 kW while increasing discharge voltage. Second, the results of the QLT that showed that erosion essentially stopped during testing. Assuming then that Eqn. (8) remains valid, this implies that the total impulse already demonstrated in the QLT still holds for high-specific impulse operation of the BPT-4000.

Finally, we note that parallel efforts to develop a PPU compatible with unregulated input bus voltage and capable of providing the increased output voltages necessary for high specific impulse operation are currently in progress. Through a joint Aerojet and JPL effort, a breadboard discharge converter is presently being developed. Partnerships with other government agencies are expected to continue this work to a breadboard PPU by mid-FY11. Additional funding will likely still be needed to complete the PPU qualification. If properly funded, a BPT-4000 thruster and PPU capable of high-specific impulse operation could be qualified in less than three years.

V. Conclusion

A test campaign designed to assess the performance and plasma properties of the BPT-4000 operating at high specific impulse has demonstrated that the thruster may be operated at specific impulses of 2600 s at 4.5 kW power and that the specific impulse can exceed 2700 s with only a modest increase in power to 5.5 kW. Magnet coil currents used for all operating conditions over 500-800 V were within the range of values used in the existing PPU and have already been demonstrated during life testing. Although operation was not truly optimized, operating the magnetic circuit within the limits of the current system has the advantage of not requiring any changes to the thruster or PPU, which would minimize the costs to delta-qualify the technology. Additional analyses of thruster lifetime and component thermal stresses are still needed, but are not expected to reveal significant issues.

Based on the success of this testing, a delta-qualification of the existing thruster is recommended for operation up to 800 V, 4.5 kW. Life testing of the QM thruster, which has already demonstrated 452 kg propellant throughput, should be restarted in tandem with efforts to establish a physics-based understanding of the erosion processes through detailed plasma simulations. Such a testing and modeling effort should have as its goal to establish the ultimate life of the thruster, which has been estimated to far exceed a metric ton [7]. Lastly, a PPU compatible with unregulated bus voltages and capable of 800 V outputs must also be qualified. An effort to develop this PPU is already underway by Aerojet and JPL, but will likely need additional resources to complete qualification.

A more ambitious, long-term program with the resources to include a full re-qualification of the thruster could also consider modifications to the magnetic circuit to allow for optimum magnetic field strengths and improvements to the thermal margins to allow for operation at power as high as 9.0 kW. Operation at such a high power density would likely reduce the life of the thruster, but given the very large throughputs that the existing BPT-4000 is expected to be capable of, such reductions may prove to be of little consequence compared to the impact this thruster would still have on future deep-space missions.

Acknowledgments

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These experiments would not have been possible without the generous loan of the BPT-4000 that was provided by Aerojet and Lockheed Martin. Thanks to Kristi DeGrys at Aerojet and Vadim Khayms at Lockheed Martin for supporting the hardware loan and Alex Mathers at Aerojet for preparing the thruster and providing excellent support for the experiments throughout.

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Appendix I – Throttle Curves

Throttle curves suitable for use in trajectory solvers have been generated for the BPT-4000 based on data obtained through qualification life testing and the data set collected during testing at JPL reported in this paper and in Ref. [5]. The curves include the power-dependent PPU efficiency and are constructed to reproduce the time-averaged performance from the qualification testing. Multiple curves are in use at JPL, but the ones most commonly being studied are:

1. **High-I_{sp}** – For a given PPU input power, operates at the discharge current and discharge voltage combination that yields the greatest specific impulse for discharge voltages less than or equal to 400 V. Applicable to the existing flight system.
2. **High-Thrust** – For a given PPU input power, operates at the discharge current and discharge voltage combination that yields the greatest thrust for discharge voltages less than or equal to 400 V. Applicable to the existing flight system.
3. **Ext-High-I_{sp}** – Extends the High-I_{sp} curve above to higher specific impulse for system input power greater than 2.7 kW and discharge voltages up to 800 V. The existing flight system is not yet capable of operating at these specific impulses. This curve should only be used for studies seeking to quantify the benefits of a future high-specific impulse BPT-4000 system.

The performance parameters for each of these curves are depicted in Figure 10 and Figure 11. Figure 12 presents polynomial curve fits that are compatible with many of the trajectory solvers used in mission studies.

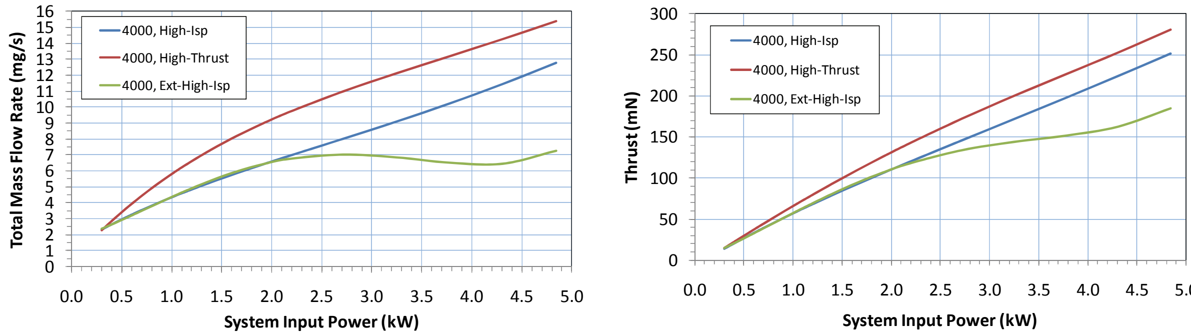

Figure 10. Mass flow rate and thrust for various BPT-4000 throttle curves.

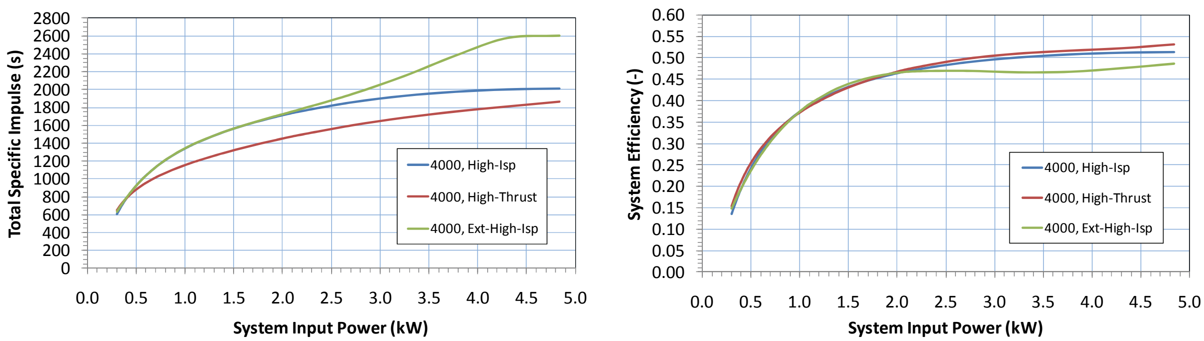

Figure 11. Specific impulse and efficiency for various BPT-4000 throttle curves.

BPT-4000 High-Isp Throttle Curves

Valid over input power range of 0.302 – 4.839 kW

Mass Flow [mg/s] = -0.008432*P[kW]^4 + 0.148511*P^3 - 0.802790*P^2 + 3.743362*P + 1.244345

Thrust [mN] = -0.095437*P[kW]^4 + 1.637023*P^3 - 9.517167*P^2 + 72.030104*P - 7.181341

BPT-4000 High-Thrust Throttle Curves

Valid over input power range of 0.302 – 4.839 kW

Mass Flow [mg/s] = -0.011949*P[kW]^4 + 0.235144*P^3 - 1.632373*P^2 + 6.847936*P + 0.352444

Thrust [mN] = 0.173870*P[kW]^4 - 1.150940*P^3 - 2.118891*P^2 + 77.342132*P - 8.597025

BPT-4000 Ext-High-Isp Throttle Curves

Valid over input power range of 0.302 – 4.839 kW

Mass Flow [mg/s] = 0.086106*P[kW]^4 - 0.727280*P[kW]^3 + 1.328508*P[kW]^2 + 1.998082*P[kW] + 1.653105

Thrust [mN] = 1.174296*P[kW]^4 - 10.102479*P[kW]^3 + 19.422224*P[kW]^2 + 47.927765*P[kW] - 1.454064

Figure 12. Polynomial curve fits for various operating schemes of the BPT-4000. It is important to use the coefficients as shown in order to maintain the accuracy of the fit.

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