Performance Variation in BPT-4000 Hall Thrusters

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Aerojet has delivered 12 BPT-4000 4.5 kW Hall thrusters for the Advanced Extremely High Frequency (AEHF) series of satellites manufactured under a prime contract to Lockheed Martin for the Air Force. Acceptance test performance data has been collected and evaluated for these flight engines. Evaluation of the acceptance test data includes a review of performance trends for compliance with the thruster specification as well as health trends for comparison to the qualification model Hall thruster. Further, the Aerojet test facility is described and measurements taken with an engineering model BPT-4000 are compared across several industry facilities. This data review quantifies the expected variation between flight model BPT-4000s as well as expected variation between industry test facilities.

I. Introduction

Hall thrusters have emerged as an enabling technology for western spacecraft as mass and on-board power continue to grow. Studies also show that Hall thrusters can provide advantages for science missions which would be restricted by mass if traded with an all chemical propulsion system. Hall thruster electric propulsion systems have been demonstrated successfully in both applications. Hall thrusters are in common use on Russian spacecraft for station keeping and the European Space Agency's SMART–1 science mission to the moon successfully demonstrated the use of a Hall thruster as primary propulsion for orbit transfer and capture[1]. In 2004, Loral launched the first Western communications satellite using Hall thrusters for stationkeeping.[2]

In order to serve market demand for high specific impulse and high thrust propulsion for orbit transfer, Aerojet began working on Hall thrusters in the early 1990s. In 2000, Aerojet and Lockheed Martin Space Systems Company (LMSSC) entered into a long term agreement to jointly develop a 4.5 kW flight Hall thruster propulsion system (HTPS) for next generation LMSSC geosynchronous satellites.[3] Figure 1 includes the timeline for the HTPS thruster development activity. Between 2001 and 2003, Aerojet completed a full engineering development model program on the flight-weight BPT-4000.[4] This program included the completion of the flight-weight engineering model design, fabrication of two units, and a comprehensive test program. Aerojet initiated qualification testing in late 2003.

Aerojet qualified the BPT–4000 Hall thruster propulsion system (HTPS) to serve both GEO satellite applications as well as potential NASA Discovery and New Frontiers Class science missions. Subsequent to the Lockheed Martin effort to qualify the thruster for geostationary satellite applications, Aerojet received NASA support to qualify the system to operate at over a 15X range in power from 300 W to 4500 W. In total, the HTPS system has demonstrated

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in qualification >6700 hours of operation and >6800 start cycles at power levels ranging from 300 W – 4500 W and a throughput of over 250 kg of xenon propellant. Testing concluded successfully in October 2005, making the BPT–4000 the highest power Hall thruster certified for commercial space flight. Sine, random vibration, and pyroshock testing, at levels exceeding the environment of a heavy–launch vehicle, have established the ability of the thruster to survive the most demanding launch environments.

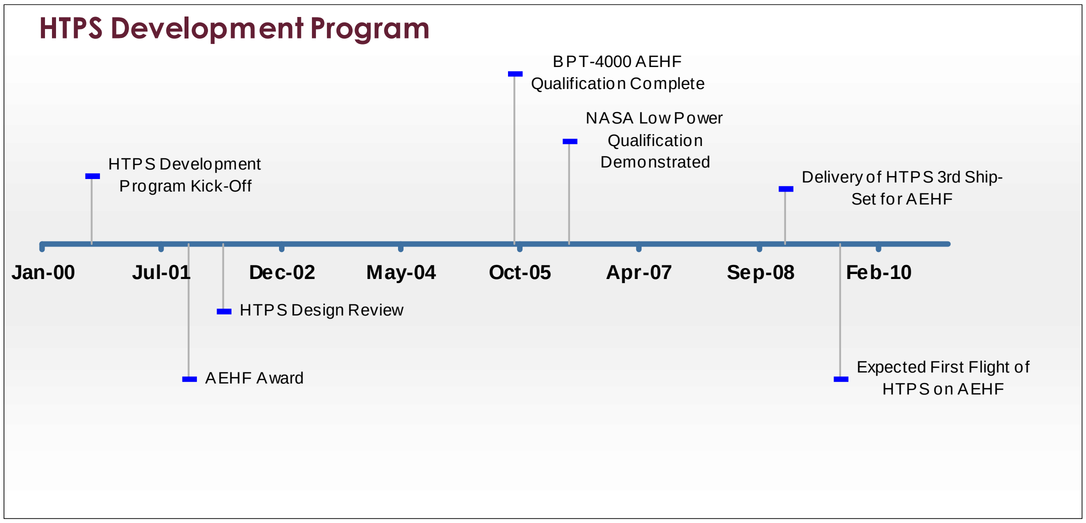

Figure 1. HTPS Development Timeline.

In 2001, Lockheed Martin was awarded a development contract from the Air Force for the Advanced Extremely High Frequency (AEHF) satellites as the successor to the Milstar system.[5] HTPS was selected as part of the propulsion system to serve the new vehicles. Following successful completion of the baseline qualification test, Aerojet initiated the build and test of twelve flight units to support the first three Advanced EHF vehicles. These thrusters were built, tested, and delivered between 2007 and 2009. The hardware delivered by Aerojet includes BPT-4000 thrusters, power processing units (PPU) and associated electrical and propellant feed system components. Pictured in Fig. 2 is a single string of the flight ready HTPS components. Each system has completed testing and has been evaluated to be acceptable for flight.

These twelve thrusters of identical design tested in a single facility provide a basis on which to evaluate the expected unit to unit variability of Hall thrusters. This paper provides a comparison of the thruster acceptance test data for the engines including comparison to the qualification model as well as to bench level verification measurements of key parameters known to affect performance. The second part of the paper provides a comparison of the measured performance of a single Engineering Model (EM) BPT-4000 from various industrial, academic, and government facilities. Together these two assessments provide a basis on which to assess the repeatability of Hall thruster performance that includes unit to unit variability as well as facility induced variability.

Figure 2. Hall thruster propulsion system- thruster, PPU, xenon flow rate controller, filter, and cable.

II. Production Unit to Unit Variability

Between 2007 and 2009, Aerojet has built twelve production BPT-4000 Hall thrusters. All units were identical in design to the qualification model thruster which is described in Reference 4. After assembly, each of the flight units was subjected to a series of function tests and inspection prior to and following acceptance hotfire testing.

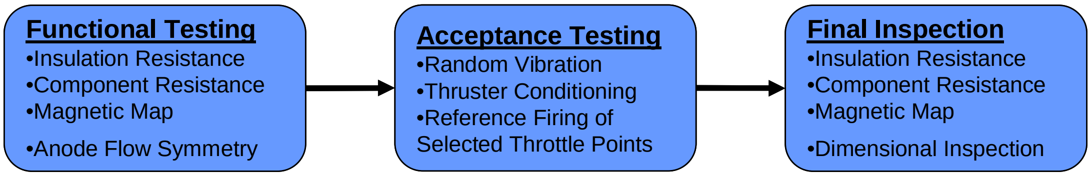

Figure 3. Flight Acceptance Test Series.

Figure 3 describes the general tests performed. Key health checks for the thruster include a gas injection flow symmetry test and a detailed magnetic field map. These checks are intended to verify those parameters that have the strongest influence on thruster performance to ensure success in hot fire testing. The results provide an assessment of the inherent construction variability of the thrusters.

For the gas injection verification, a detailed pressure map of the gas injection manifold is performed while flowing xenon through the manifold and into a vacuum chamber. Pressure in the acceleration region of the thruster is measured at multiple points around the diameter and examined to verify xenon flow is distributed uniformly. Magnetic field mapping is performed at key points during manufacture and test of the thruster as outlined in Fig. 3. The field map includes measurement of over the discharge region both axially and azimuthally. The map is examined to verify that the field is uniform, strength is adequate, and the axial gradient is acceptable. Acceptance test data for gas injection flow symmetry and magnetic field characterization is shown in Figure 4. Production units are compared with the qualification unit, which is labeled number one in each plot. Variation of the health trends in Fig. 4 are within family of historic trends collected during engineering development and qualification of the thruster.

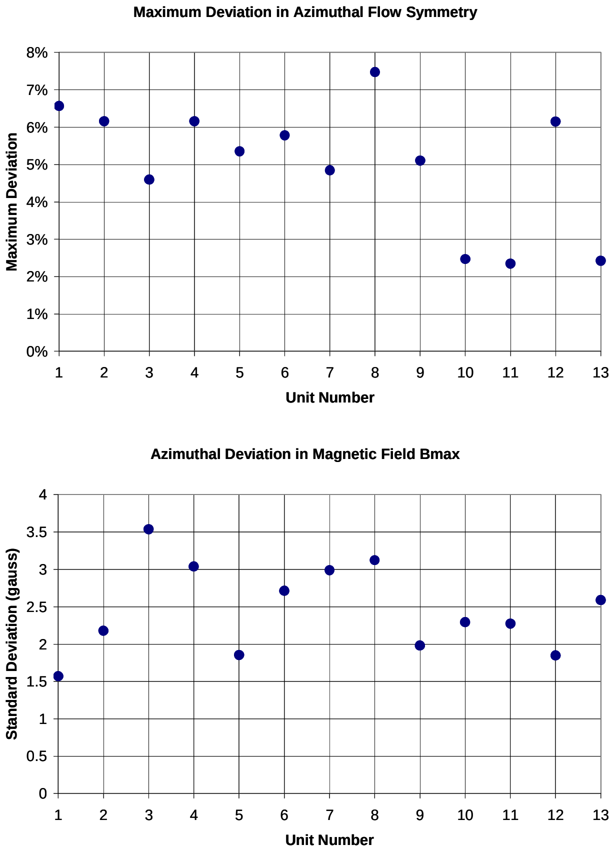

Figure 4. Thruster Health Trends.

A. Acceptance Test Setup

Following functional testing, each engine was subjected to vibration and hot fire testing. All hotfire testing of the qualification and flight model BPT-4000 thrusters was performed at Aerojet's Chamber Two test facility in Redmond, WA. Chamber Two is 2 m in diameter and 7.2 m long. The chamber has two nude cryogenic pumps placed downstream of the BPT–4000 and two cryo–tubs located on either side of the thruster. With a combined xenon pumping capacity of 75,000 L/sec, no–load base pressures were nominally 1×10^{-6} torr. Maximum operating pressures were less than 3.5×10^{-5} torr and, for a given operating condition, were consistent throughout testing. Figure 5 shows a diagram of the facility. The chamber was lined with graphite sheeting and carbon baffles were placed in front of the pumps to prevent facility erosion and minimize back sputter.

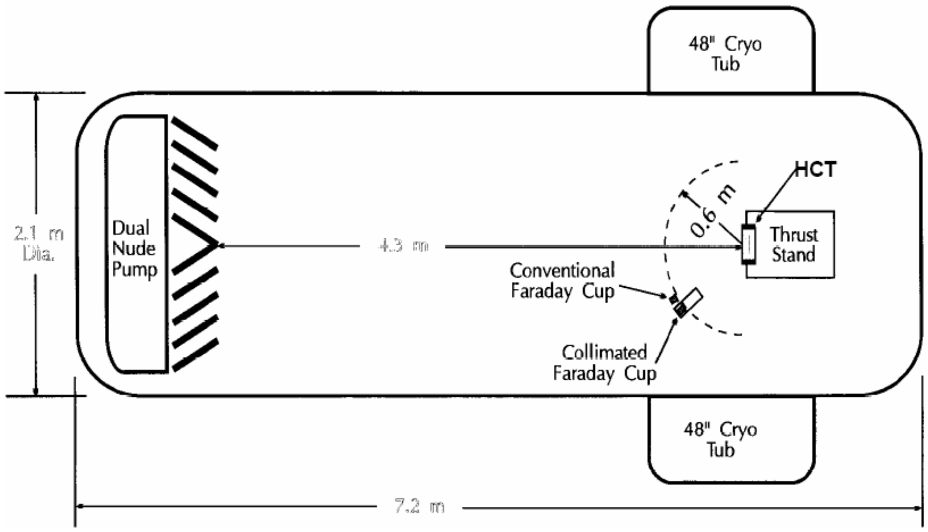

Figure 5. Aerojet Chamber Two Vacuum Test Facility.

During testing, the thruster was mounted on an inverted pendulum thrust stand of similar design to those used at NASA's Glenn Research Center.[6,7] Thrust measurement readings were taken for 30 seconds at the end of each cycle and the zero thrust reading taken for 30 seconds one minute after the cycle concluded was subtracted from the end of cycle measurement to correct for any thrust stand thermal drift. The thrust stand was checked for slope drift at the installation of each thruster with an in-situ hanging weight system. Comparisons show that the null-coil calibration varied less than 1%. Flow rate to the xenon flow controller (XFC) was measured outside of the chamber using a Celerity Model 1661 thermal mass flow meter. Two different meters were used over the course of testing - one with a full scale reading of 500 or 600 sccm. Both have a .35% of full scale reading accuracy for the flow rates associated with the four primary operating conditions. Flow meter calibration was verified throughout testing using either an in-situ constant volume calibration or a DryCal ML-800 primary gas flow calibrator.

During testing, power to each thruster was provided by an EM or qualification model PPU controlled by a PC to simulate the spacecraft computer.[8] A qualification or flight model XFC metered xenon to the thruster via close-loop control by the PPU. Each thruster was tested for multiple cycles at the four primary operating points. The thruster was started from a full off condition for each cycle using a pre-defined start sequence that included a stepped ramp up of power, voltage, and magnet current.

B. Acceptance Test Results

Figure 6 provides the hot fire performance data collected for the flight model thrusters. Cycle averages are plotted for each thruster unit number. The maximum cycle variation was typically less than 1%. Unit number one shown in each plot is the qualification model thruster. Typical thrust variation of a production unit from the average (including the qualification unit) is 3% with no unit exceeding 6%. The variation in specific impulse amongst the production units and the qualification thruster is similar and correlates well with the thrust variation.

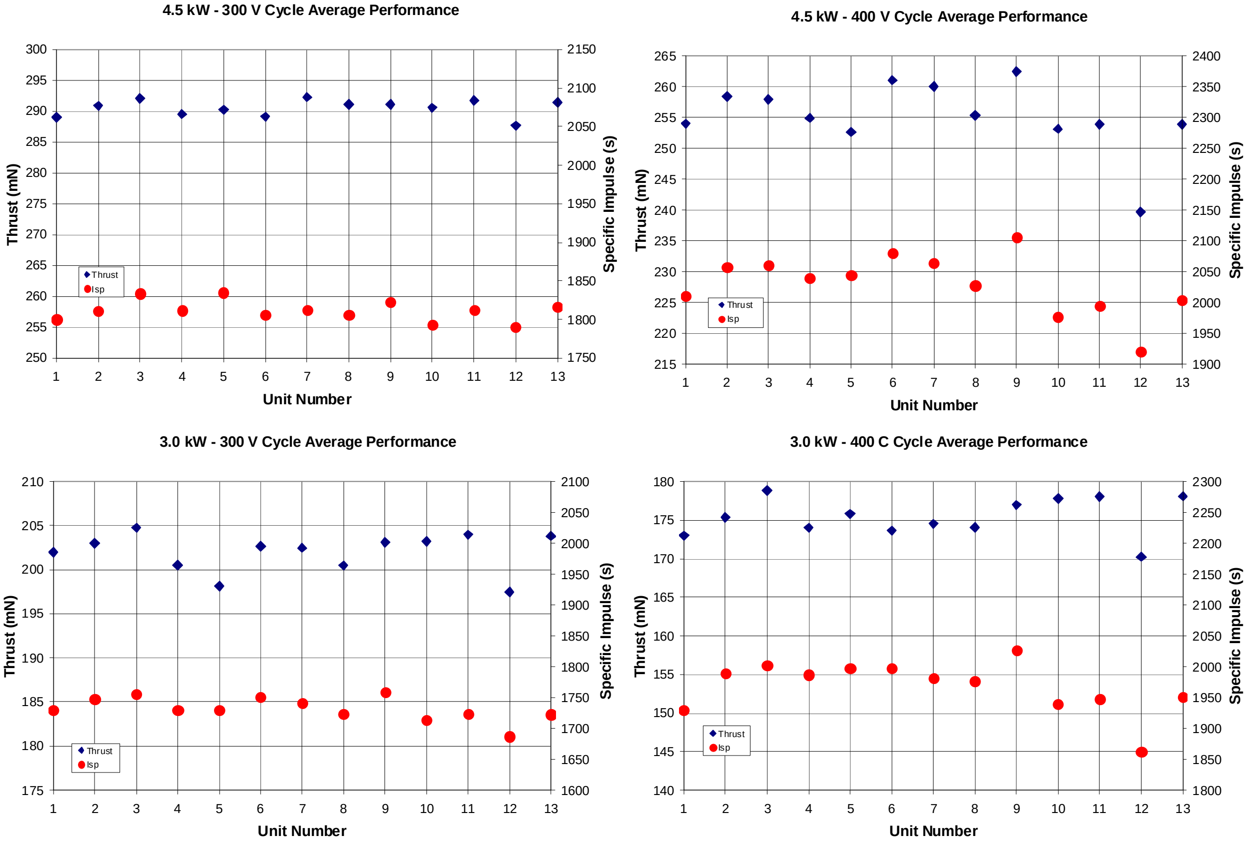

Figure 6. BPT-4000 Flight Model Acceptance Test Performance.

The above data demonstrate that Aerojet has the ability to reliably build multiple BPT-4000 thrusters and achieve repeatable performance. The unit to unit performance variability has been quantified as < +/- 3% which is sufficient to meet spacecraft needs at these performance levels.

III. BPT-4000 Performance Comparison Across Test Facilities

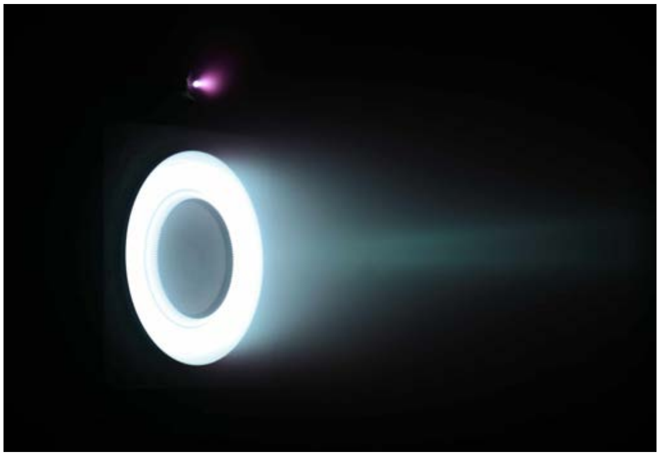

Figure 7. Aerojet BPT-4000 Referee Engine.

Over the course of the past several years, Aerojet has had the opportunity to test a single BPT-4000 engineering model thruster in several key academic and government test facilities. This type of testing can provide a top level assessment of facility variability in Hall thruster performance measurements. The engine used for all of the tests, shown in Fig. 7, is an engineering model thruster equipped with an exit ring geometry equivalent to 1200 hours of erosion at the 4.5 kW -300 V throttle point. This condition was selected to provide a stable baseline for which comparisons can be made since early in thruster life, exit ring geometry and thruster performance can change. Figure 8 is a plot of the BPT-4000 qualification model thruster performance versus time and provides an example of change as erosion takes place. The engineering model thruster is functionally equivalent to a flight model thruster and performance is comparable. Between tests, the configuration of the thruster did not change with one exception. For the testing at PEPL, Aerojet's 19 mm cathode[9] was used instead of the standard 6.35 mm cathode.

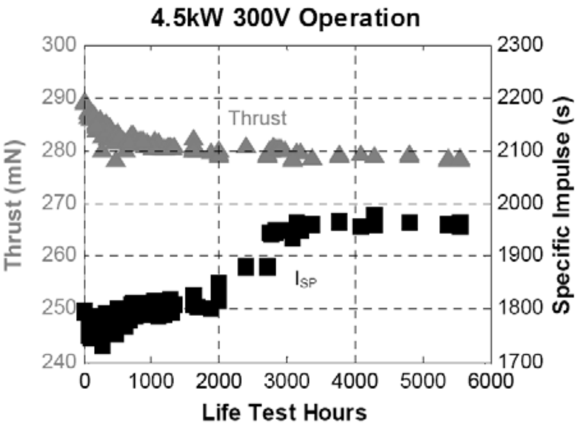

Figure 8. Qual. Thruster Performance Versus Time.

A. Test Setups

Performance data for the thruster have been collected from NASA Glenn Research Center's vacuum facility five (VF5), Air Force Research Lab's (AFRL) Chamber three facility at Edwards Air Force Base, University of Michigan's Large Vacuum Test Facility at the Plasma dynamics and Electric Propulsion Lab (PEPL) and Aerojet's Chamber Two facility. NASA's VF5 is a cylindrical chamber 4.6 meters in diameter and 18.3 meters long, with a no-load base pressure of 1×10^{-7} Torr at a theoretical pumping speed of 3,500,000 l/sec on air.[10] AFRL's Chamber three is a cylinder 3 meters in diameter and 10 meters long. The chamber has a two stage pumping system with cryopanels and turbomolecular pumps. The chamber pumping speed is approximately 140,000 liters per second on xenon and can achieve a base pressure of 10^{-7} Torr. At a xenon flow rates less than 24 mg/s chamber pressure can be below 1.1×10^{-5} Torr.[11] The PEPL Large Vacuum Test Facility is a cylindrical chamber 9 meters long and 6 meters in diameter. This facility, is evacuated by seven LN2-cooled CVI TM1200 reentrant (nude) cryopumps that provide an overall pumping speed of 240,000 l/s on xenon, and a no-load base pressure of less than 2×10^{-7} Torr.[12] The thrust stand at each facility is based on the common NASA inverted pendulum design previously described. The Aerojet Chamber Two facility is described in the preceding section. Figure 9 provides the measured backpressure for each chamber during operation.

In all cases, flow rate to the thruster was measured outside of the chamber using a Celerity Model 1661 thermal mass flow meter. Figure 10 provides a summary of the full scale ranges of the anode and cathode flow meters used as well as their accuracy at the tested flow rates. For all of the setups, the flow meter calibration was verified throughout testing using either an in-situ constant volume calibration or a DryCal ML-800 primary gas flow calibrator. Except in the case of the testing at Aerojet, laboratory power supplies were used to provide power to the thruster, cathode, and magnet coils. At PEPL, Aerojet and Glenn, power was measured via sense lines at the end of the thruster pigtail cable. At AFRL, it was measured at the back of the power supplies outside the chamber.

Facility Pressure (Torr)	Operating Point	
	4.5 kW - 300 V	4.5 kW - 400 V
GRC VF5	-	2.55E-05
AFRL	2.33E-05	1.99E-05
PEPL	6.75E-06	6.60E-06
Aerojet	2.75E-05	2.25E-05

Figure 9. Facility test pressures.

Flow Meter Uncertainty	Meter	
	Anode	Cathode
GRC VF5	+/- .35 mg/s	+/- 0.05 mg/s
AFRL	< +/- .21 mg/s	+/- 0.05 mg/s
PEPL	+/- .21 mg/s	+/- 0.05 mg/s
Aerojet	+/- .21 mg/s	N/A

Figure 10. Mass Flowmeter Uncertainty.

B. Test Results

The BPT-4000 test data collected on referee testing at these facilities is compared in Fig. 11. Test facility uncertainty is shown in the figure for the Aerojet facility data. The source of uncertainty at the Aerojet facility is +/-2% of measurement for thrust and +/-1% for flow rate.

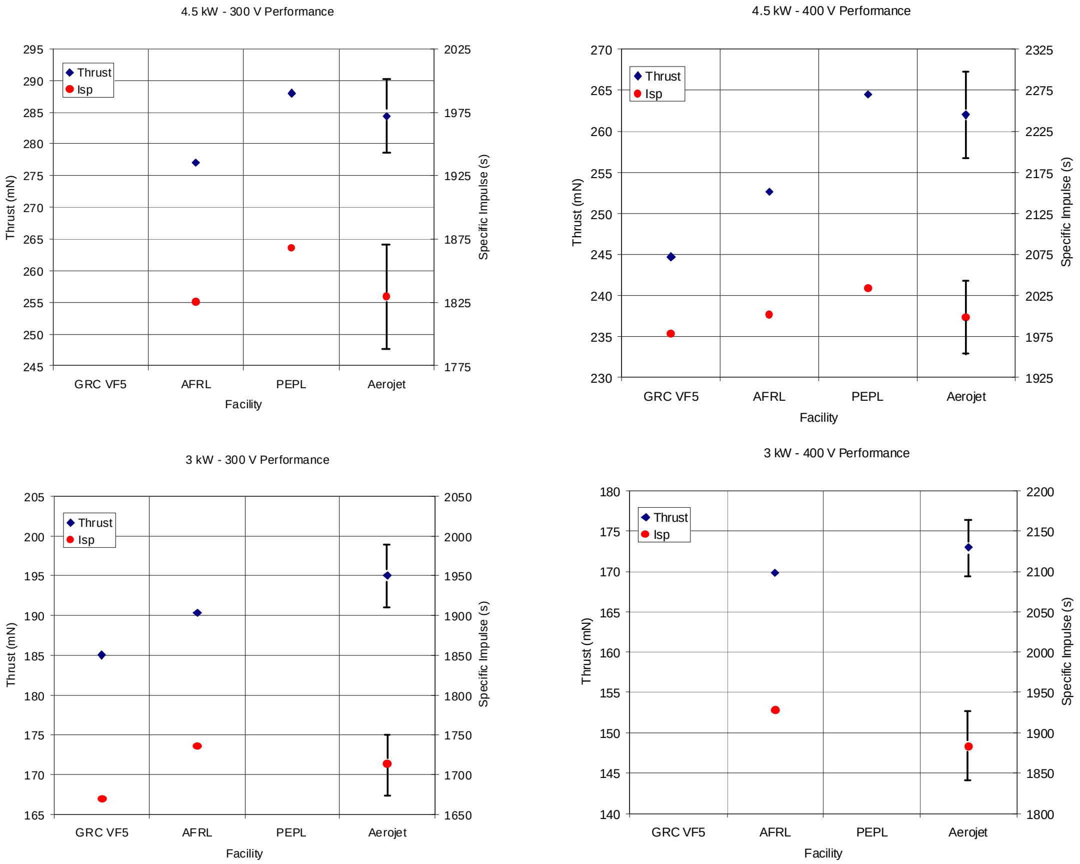

Figure 11. BPT-4000 Referee Thruster Firing Data Comparison.

The data for Aerojet and PEPL show excellent agreement for both thrust and specific impulse with all values within 2%. The AFRL data also shows agreement within the error bars at all operating conditions with a maximum deviation of 3.5%. In all cases, the measured data at AFRL is lower than at Aerojet and PEPL. The most likely source of the higher deviation is the lack of sense lines at AFRL. A 2% power loss or 90 W for the 4.5 kW, 300 V operating condition corresponds to a cable resistance of 0.4 ohms which is well within the expected range. This hypothesis is also consistent with the observation that the lowest deviation is seen at the lowest power and current operating condition (3 kW, 400 V) as well as, the observation that the deviation in I_{SP} is consistently less than the deviation in thrust. The magnitude of the difference between AFRL and PEPL measurements is consistent with the difference measured on the H6 thruster.[13]

The available data from the GRC VF5 testing shows a larger deviation, 4 to 6.5%, than the other facilities. The cause of the difference is unknown. Previous works have speculated that chamber pressure may be a source of variation. However, in this case, low back pressure is not the issue. The GRC VF5 testing was conducted with the thruster located in a bell jar off of the main tank resulting in back pressures comparable to those at both Aerojet and AFRL. Back pressures at PEPL were close to an order of magnitude lower but performance was comparable. The same flow meter calibrated at Aerojet was used for both the PEPL and GRC testing and the deviation in I_{SP} and thrust are nearly the same indicating that the difference is in the thrust.

IV. Conclusions

Aerojet has completed the design, build, and delivery of twelve flight model BPT-4000 Hall thrusters. Functional and hot fire testing has demonstrated the acceptability of these engines for flight. Unit to unit variability of the flight model thrusters has been quantified and shown to be typically +/- 2.5% and +/- 4.5% worst case. Facility to facility test variation for a single referee BPT-4000 has also been assessed and shown to be within similar levels. Together these data provide a strong basis to conclude that the BPT-4000 thrusters can be consistently built to deliver high performance and that this performance can be accurately characterized.

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