Preliminary Study of Arcjet Neutralization of Hall Thruster Clusters*

Quentin E. Walker and Mark A. Cappelli
Thermosciences Division, Mechanical Engineering Department
Stanford University
Building 520
Stanford, CA 94309-3032
650-725-2024 / 650-723-2020
qwalker@stanford.edu / cap@stanford.edu

William A. Hargus, Jr.
ARFL, Edwards Air Force Base
Building 8895
Edwards, CA 93524
661-275-6799
william.hargus@edwards.af.mil

John Schilling
W.E. Research LLC
Rosemond, CA 93560
661-275-6795
schillin@spock.usc.edu

IEPC-01-63

Clustered Hall thrusters have emerged as a favored choice for extending Hall thruster options to very high powers (50 kW – 150 kW). This paper examines the possible use of an arcjet to neutralize clustered Hall thrusters, as the hybrid arcjet-Hall thruster concept can fill a performance niche amongst available propulsion options. We examine missions on which this hybrid concept would be a competitive or favored thruster option, report on fundamental experiments to understand how much electron current can be drawn to a surrogate anode from the plume of low power arcjets operating on hydrogen and helium, and then demonstrate the first successful operation of a low power Hall thruster-arcjet neutralizer package. In the surrogate anode studies, we find that the drawing of current from the arcjet plume has only a weak effect on overall arcjet performance (thrust), with a slight decrease in arc voltage with increased extracted current. A single Hall thruster – arcjet neutralizer package was constructed for the hybrid concept demonstration. The arcjet operated at very low powers (~ 70-120W) on helium, at a mass flow rate of 4.5 mg/s, and was able to effectively neutralize the ~ 200 – 900W xenon Hall thruster causing little measurable departure from the hollow-cathode neutralized Hall thruster VI characteristics up to 250V. At higher helium mass flow rates, the Hall discharge current is slightly perturbed from its expected values, due most likely to the ingestion of helium. Further developments of the hybrid concept to clustered configurations and higher powers will require a vacuum facility that can pump tens of milligrams of helium while maintaining the low pressures needed for normal xenon Hall thruster operation.

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 [1].

Historically, electric propulsion research has been directed primarily at medium power technologies (500W – 5 kW) for stationkeeping, rephasing, and orbit topping applications. Electric propulsion in this class is largely commercialized and now seeing widespread use on commercial satellites. With the commercialization of these devices, research emphasis on mid-power electric propulsion is expected to decline. The technology should be of sufficient maturity, and the commercial payoffs sufficiently large, that further performance advances would be accomplished by the private sector [2].

The U.S. Air Force Research Laboratory (AFRL) has initiated a program to develop Hall thruster systems that operate at power levels well in excess of current state-of-the-art. Program goals are for operation in the 100 kW to 150 kW range which address the Air Force priorities for orbit transfer vehicles (OTV) and rescue vehicles capable of repositioning and rescuing of marooned space assets. The power range is based on that expected from proposed Air Force programs using deployed sails of thin-film solar arrays, and will adapt as predicted power availability changes. Possible solutions to achieving this higher power range involve clustering Hall thrusters with trade-off comparisons discussed below.

Researchers at Stanford University have proposed alternative Hall thruster configurations and concepts that can fill propulsion performance gaps to provide moderate specific impulse (~900 – 1600s) at high thrust, while maintaining a high overall propulsion efficiency (>55%). They have shown that a xenon Hall cluster neutralized by a moderate power helium arcjet can meet such performance criterion if the two sources can simultaneously operate without interactions that compromise the operation of any one individually [3]. In previous experiments, attention was focused on how much electron current can be drawn from the plume of a helium arcjet without adversely affecting its operation [3]. The results met success criterion that justified further experiments, described below, that demonstrate, for the first time, that an arcjet can be used to neutralize a Hall thruster, without adversely affecting the hall thruster operation.

This paper provides the first discussion, mission/propulsion package analysis, and demonstration experiment that warrants a larger scale laboratory study, in particular, to fully characterize the operation of a *single arcjet –clustered Hall thruster* package, as it is demonstrated that a hybrid rocket of this sort has advantages over a pure Hall thruster cluster when short missions (less than 60 days) are desired. However, such an experimental study pushes the present capabilities of ground test facilities, requiring the ability to maintain sufficiently low pressures (below 10^{-4} torr) for accurate performance characterization while pumping 10-50 mg/s each of helium and xenon.

Clustered Hall Thruster Mission Definition

During the past year, AFRL has sought to define the optimal method of approaching the mission need through discussion with industry, other government agencies and universities. The study resulted in the following design criteria [2]:

- The high-power system should use Hall thrusters, as opposed to ion thrusters, due to their superior specific mass (2 kg/kW for Hall versus 8 kg/kW for ion thrusters)
- The high power system should be assembled from a cluster of lower power devices to reduce qualification and testing costs. A clustered system also offers the flexibility needed to meet varied power budgets on future missions. Changing the number of units in the cluster varies system power.
- The unit thruster should be a commercial flight-qualified thruster. To minimize dry mass, it should also be the highest power Hall thruster that is expected to be used for GEO stationkeeping.
- An even number of thrusters should be clustered, in opposite magnetic polarity, to cancel out the Hall thruster torques.
- The unit thruster power should be sufficiently low so as to allow testing in current ground test facilities. Test facility costs for a

monolithic 100 kW Hall thruster could dominate the program costs.

- Based on these considerations, the unit thruster power level is expected to be in the 8 kW to 10 kW range. Hall thrusters in this range are currently in development under both NASA and AFRL programs.
- The individual Hall thrusters must be independent (i.e. no sharing of magnetic circuits or structure) so that the base units can be individually flight-qualified prior to integration into the cluster.
- Both the thruster and the PPU should be modular to minimize qualification costs. Optimal design for the propellant management system remains an open issue.

In general the primary advantage of a clustered approach to 100 kW-class power levels concedes performance in favor of cost. The relative advantages of each approach are summarized in Table 1.

An important consideration is the cost of qualifying a cluster versus the cost of qualifying a monolithic thruster. For each thruster to be qualified, ground testing lasting as long as two years is necessary in order to qualify the thruster for on-orbit use. As thrusters grow in size, scaling laws required that the background pressure of the test facilities fall as the scale length of the thruster increases [4]. This will eventually necessitate that new, larger facilities than are currently available be constructed for ground qualification. The aim of this effort is to use the highest available powered Hall thruster for use in clustering. This will provide the most flexibility for future Air Force and commercial missions at the lowest cost. As new thrusters of increasing power are qualified, clusters of these thrusters will be flown.

AFRL has initiated a program to understand the physics and practical implications of interactions within clusters of four Hall thrusters. The clustering project will initially experimentally characterize the interactions of the plumes with thrusters that are relatively inexpensive to operate and small enough not to require extensive vacuum facilities. In addition, by initially examining low power (200 W) thrusters, the plumes will be denser and it is anticipated that interactions will be more severe than plumes of higher power Hall thrusters. The preliminary test bed consists of four Busek Co. BHT-200-X3 Hall thrusters in a cluster of four. The thrusters have been delivered and mounted into the test fixture at AFRL. Plume measurements have begun and thruster cross-talk studies are ongoing. Figure 1 shows the cluster firing in Chamber 6 at AFRL.

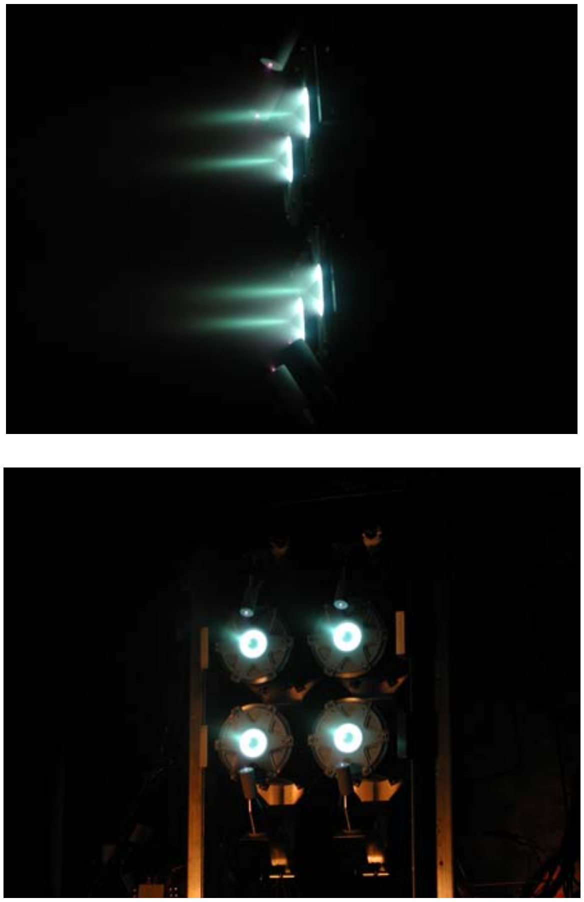

Figure 1. Cluster of 4 independently powered Hall thrusters (BHT-200-X3) operating within AFRL Chamber 6.

Neutralization Issues

With the Air Force interest in clustering of Hall thrusters, concepts involving the neutralization of more than one thruster using a single cathode-neutralizer have emerged. Cluster testing at AFRL has yet to address this possibility and is presently limited to four independent thruster units, each with a unique cathode floating potential. Once the cathodes are electrically connected, issues such as cathode current stealing with several cathodes and incomplete neutralization with a single cathode are likely to appear.

Table 1. Trade-offs between a clustered and monolithic approach to high-power electric propulsion.

Criteria	***100 kW class Monolithic***	***Clustered 10 kW***
Performance		
Efficiency	Higher	Lower
Specific Impulse (300V)	Same	Same
System Dry Mass	Lower	Higher
Reliability		
Thruster	About the Same	About the Same
PPU/PMA	Higher	Lower (more parts)
System Overall	Lower	Higher (redundancy)
Operational Flexibility		
Throttling	Lower	Higher
Orbit raise (Full power)	Same	Same
Station-keeping Suitability (Low power)	Lower	Higher
Suitability for Maneuvering/Vectoring	Lower	Higher
Scalability (up and down in power)	Lower	Higher
Developmental Cost	Very High	Low
Test Facility	Not Available/Very High	Availability/Very Low

We believe that clustering for higher power and higher thrust applications also opens the door to new opportunities. Typically, Hall thrusters expend 10% of their propellant through their hollow cathode neutralizers. Since this propellant does not pass through the cross-field ionization/acceleration region within the thruster, this propellant is not accelerated and produces no thrust. Hollow cathode neutralization produces an immediate 10% decrease in specific impulse (I_{sp}), generally before any thruster inefficiency is considered. This issue has spawned an entire field of Hall thruster research the goal of which is to reduce and if possibly eliminate the propellant requirement for neutralization. Researchers are currently examining low flow hollow cathodes where lower work function materials are used as emitters to reduce required the cooling and hence the propellant required. Other researchers are looking into the possibilities of altogether removing the need for cathode propellant through the use of Field Emission Array Cathodes (FEACs). These devices currently hold some promise for smaller thrusters, but require large surface areas to neutralize those thrusters. For arrays of thrusters with powers of 100 kW or greater, there is insufficient area available on a FEAC neutralizer for adequate electron emission. In addition, FEACs are sensitive to oxidation and to ion backflow, both of which rapidly degrade performance.

Arcjet Neutralization and the Hybrid Arcjet-Hall Thruster Concept

Researchers at Stanford University have embarked on a course of study that explores a new avenue for Hall thruster neutralization. Rather than attempt to minimize the propellant used in neutralization of the Hall thruster anode discharge, the concept is to use a cathode-neutralizer that also produces useful thrust. We have chosen to examine the arcjet as an electron source to neutralize the main Hall thruster discharge and to produce thrust [3].

Since an arcjet is a high plasma density device ($n_e \sim 10^{12}$–10^{13} cm^{-3}) that is capable of supporting and amplifying electron current through volume ionization, it is capable of neutralizing a cluster of Hall thrusters. For optimum cluster performance, a high efficiency arcjet is required. Helium arcjets are capable of efficiencies greater than 60% due to the absence of frozen flow losses [3]. Because of the arcjet's lower I_{sp}, the hybrid arcjet-Hall cluster will have an overall lower I_{sp} than that of a pure cluster of Hall thrusters, but will produce a system with higher thrust efficiency and total lower wet mass for select missions

The performance estimates discussed below of the hybrid thruster concept assumes that the arcjet and Hall thrusters operate without performance penalties when working together. It is known that each thruster exhibits instabilities that may impede performance when they are operated simultaneously. The arcjet used in the experimental studies discussed later in the paper was originally designed to operate with hydrazine, and its operation on helium has proved to be challenging. The arc voltage fluctuates in the hundreds of kilohertz range, and the average arc voltage drifts on the time scales of seconds, most likely due to thermal instabilities. The Hall thruster also exhibits fluctuations in the 10 –200 kHz region, such as loop, azimuthal, ionization, and drift type instabilities among others [5-7]. A coupling between these instabilities is expected. Furthermore, it is not yet known if drawing large levels of electron current from the arcjet plume will compromise the performance of the arcjet itself. Compromised arcjet efficiency results in lower cluster performance, making the concept less competitive with alternative propulsion packages. Similarly, Hall thrusters will generate the necessary plume potential (due to space charge) to draw the required neutralizing current and unusually high potentials will reduce the Hall thruster performance.

As mentioned above, the development of the hybrid thruster concept will require a vacuum facility that can achieve the low pressures needed for typical xenon Hall thruster operation while pumping helium to sustain the arcjet discharge. In order to develop this thruster concept, we report in this paper the results of a number of smaller scale studies that have been completed before investing the efforts into developing or redesigning ground test facilities for scaled-up testing. Instead of investing efforts to attain a vacuum system which can meet the pump requirements for the hybrid cluster, proof-of-concept studies were performed, first with surrogate anodes (which take the place of a Hall thruster anode, but do not require propellant flow and very low densities), and then with a single low power (< 1 kW) Hall thruster, operating in tandem with a specially-developed ultra-low power (< 100W) helium arcjet. This combination of a low-power arcjet and a low-power Hall thruster can be operated in the vacuum chamber at Stanford, while maintaining modest pressures, but not sufficiently low to obtain reliable thrust data. In addition to describing the surrogate anode tests, this paper reports on the operation of this first hybrid thruster package, and compares the Hall thruster operating characteristics to that of the Hall thruster neutralized with a hollow cathode.

Experimental Setup

The nominally 1 – kW arcjet[‡] thruster used to study the basic problem of current draw from arcjet plumes is a radiatively cooled laboratory type thruster designed and built at the NASA Glenn Research Center [8]. This is the same thruster that has been extensively studied and characterized with various diagnostics while operating on helium and other propellants [9-11]. The tungsten nozzle has a 0.635 mm diameter throat and a conical diverging section with an area ratio of 225 (9.53 mm exit diameter).

The low-power (~100W) arcjet used in the hybrid thruster studies was designed and built at Stanford University. A schematic of the thruster is shown in Figure 2. The nozzle is composed of tungsten with a 0.30 mm diameter throat, a conical diverging section with an area ratio of 286 (5 mm exit diameter) and diverging angle of 15°. The rear housing is composed of stainless steel 316, and the cathode connection to the body is made through a Conax electrode gland. Seals in the arcjet are made with graphite gasket material, and grooves in the front boron nitride insulator induce swirling motion of the propellant as it enters the converging side of the nozzle. The Hall thruster used in the demonstration experiments is of a conventional co-axial design, that we have not yet described in prior publications, and the characterization of this thruster will be presented in forthcoming papers. Briefly, the thruster consists of a boron nitride channel with an outer diameter of 73 mm, a channel depth of 21 mm and a channel width is 15.5 mm. It was initially developed to study the effects of varying channel geometry (width) on Hall thruster performance. A commercial hollow cathode (Ion Tech HCN-252) is used to neutralize the resulting ion beam and provide the necessary electron current to sustain the discharge. The cathode body was kept at the vacuum chamber ground potential.

The first experiments reported on below involve a series of studies designed to determine the adverse effects that drawing substantial electron currents (from an arcjet plume) may have on arcjet operation and/or

---

[‡] Throughout this paper, we will refer to this arcjet as a "1 kW" arcjet, as that was the nominal design power when used on hydrazine propellant. In fact, when operating with helium, the power dissipated is sometimes well below 1 kW, typically 300 – 700 W.

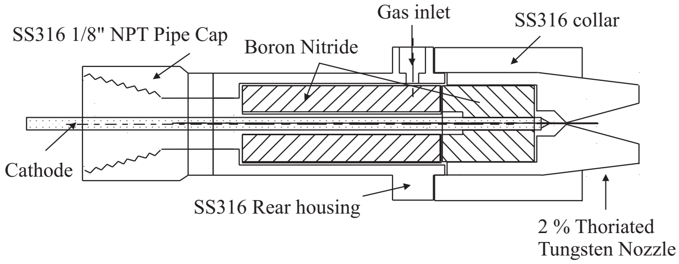

Figure 2. Schematic of the low-power arcjet.

performance. This involved designing a "surrogate" anode to take the place of what would be the Hall thruster, to serve as an electron collector. During the collection of electron current to the anode, the thrust of the arcjet was monitored by way of a scanned impact pressure probe.

The surrogate anode and impact pressure measurements were conducted in a 0.56 m diameter cylindrical stainless steel chamber 1.09 m in length. Two mechanical pump-blower combinations operating in parallel provide a total pumping speed of 2000 l/s to evacuate the chamber.

Surrogate Anode

The surrogate anode used in this study is a copper circular plate 15 cm in diameter that is placed 15 cm from the center of the arcjet. The anode consists of a circular copper conductor that sits in a boron nitride insulator. An alumina ring straddles the insulator and conductor in order to hold the conductor in place. The insulator sits on top of a type 304 stainless steel plate that acts as a thermal resistance and in turn sits on a copper base. The anode is connected to a DC power supply that can provide 300 Volts and 20 amps. The current drawn by the power supply is measured across a shunt resistor with a DC multimeter. Figure 3 shows the relative positions of the arcjet and copper anode. The anode is electrically isolated from the arcjet and its supporting structure.

Figure 3. Photograph of the experimental setup for the arcjet neutralization studies. The arcjet shown in this photo is the higher power, nominally 1-kW laboratory thruster developed by NASA.

Impact Pressure Probe

The thrust of the 1-kW arcjet is measured with an impact pressure probe. Previous studies show that the thrust measured by integrating the impact pressure profile agrees well with that measured with a thrust stand [11]. A detailed description of the probe is given in Ref 9, and Figure 4 shows the experimental setup for these experiments. The copper probe is 28.6 mm in length and 15.9 mm in diameter with an opening at the tip of 0.51 mm in diameter. The probe tip is attached to a copper collar-body assembly with the required coolant connections and placed on a translation stage that moves horizontally with respect to the arcjet. The pressure profiles are taken within 0.5 mm of the exit plane of the arcjet, and the probe is water cooled to withstand the arcjet plume impingement. The pressure within the pitot probe test volume is measured by use of a 0-13.3 kPa MKS capacitance manometer. The probe is

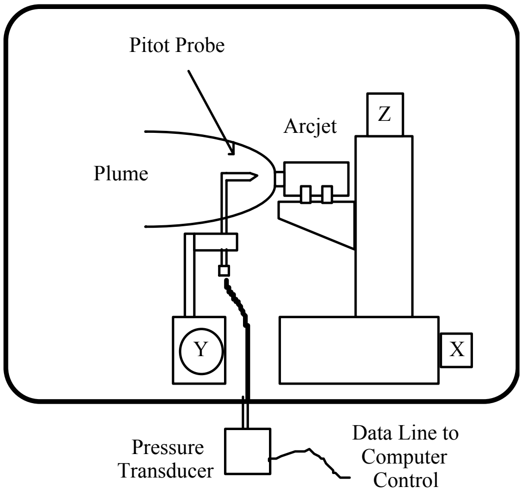

Figure 4. Experimental setup for the impact pressure probe measurement.

moved in increments of 0.25 mm, and it pauses between 5 to 10 seconds at each position. It takes approximately 20 minutes to scan across the exit plane of the arcjet. The manometer reading is acquired digitally at a rate of 1 kHz.

Hybrid Arcjet-Hall Thruster Demonstration

Figure 5 and Figure 6 show the schematic and photograph of the setup of the hybrid arcjet-Hall thruster. The anode of the arcjet is held at ground potential while the cathode is biased negatively relative to ground. Measurements of the arc discharge voltage are read from the power supply and the arc discharge current is measured across a shunt resistor. Within the vacuum chamber, the center-to-center distance between the arcjet and Hall thruster is 12 cm. The arcjet exit plane is parallel to the front plate of the Hall thruster. A separate 300V, 10 A power supply is used to bias the Hall thruster anode. The voltage is read from a digital multimeter, and the Hall discharge current is read across a shunt resistor. The hybrid demonstration was conducted in a 1 m diameter cylindrical non-magnetic stainless steel chamber 1.5 m in length. Two 50 cm diameter elbow sections are attached on either end of the main section to support 50 cm diffusion pumps. The pumping speed on xenon is 9000 l/s. An ionization gauge measures the pressure within the vacuum chamber, and a thermocouple gauge monitors the line pressure for the diffusion pumps. A view of the thruster in operation is shown in Figure 7.

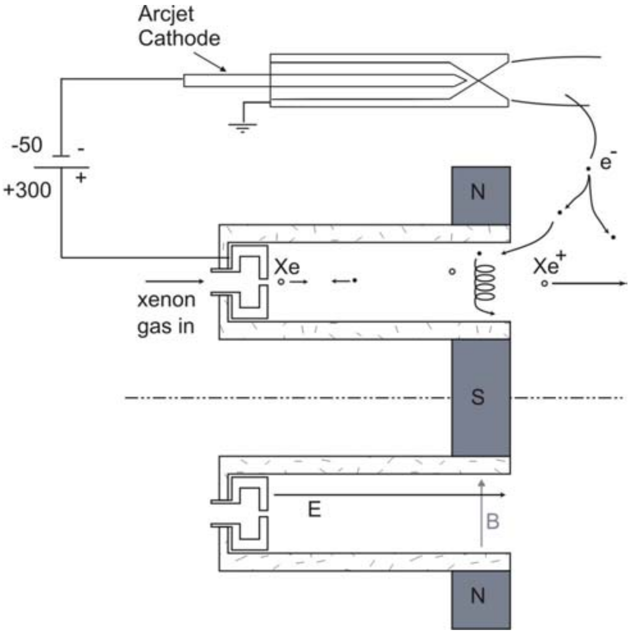

Figure 5. Schematic of the hybrid arcjet-Hall thruster.

Figure 6. View of the hybrid thrust within the vacuum tank.

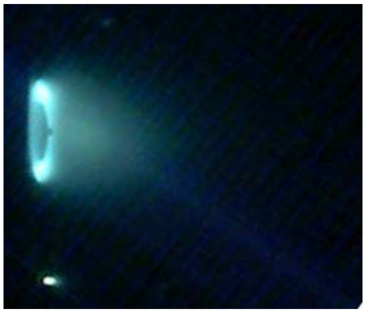

Figure 7. Side view of the hybrid arcjet-Hall thruster in operation.

Results and Analysis

1-kW arcjet and surrogate anode

The nominally 1-kW arcjet voltage and the surrogate anode current are monitored as the voltage applied to the anode is varied. Figure 8 shows the amount of current extracted from the helium arcjet plume while biasing the surrogate anode. In these experiments, the mass flow rate is a fixed parameter (36.2 mg/s) while the arcjet is operated at various arc discharge current levels. It is apparent that in almost all cases studied, currents greater than the arc current itself can be extracted from the arcjet plume. Specifically, the extracted electron current can be up to 134% of the arc current for the helium arcjet plume. However, it is noteworthy that appreciable currents are not extracted until the anode voltage is above 30V. As the surrogate anode voltage is increased, the amount of extracted current is found to increase nearly exponentially, and then reaches a point where further increases in voltage do not result in increases in the drawn electron current (saturation).

As shown in Figure 9, the arc discharge voltage is found to generally decrease as the surrogate anode voltage increases. When measured in terms of the discharge power, the power of the arcjet is reduced

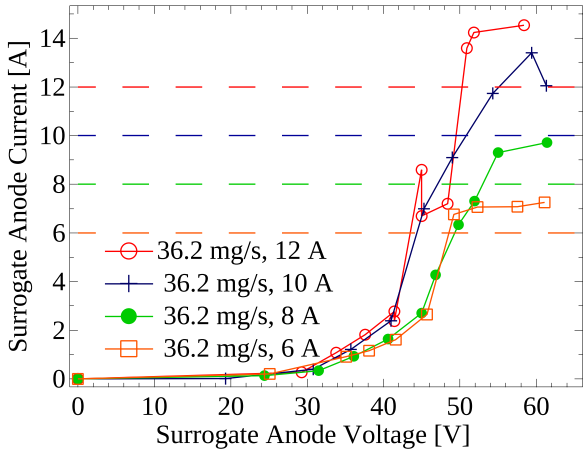

Figure 8. The helium arcjet neutralization current provided as the surrogate anode voltage increases.

from 740 to 320 W. The largest voltage decrease occurred at the highest sustainable anode (bias) voltages. However, the arcjet first responds (in the highest discharge current cases) with an increase in discharge voltage following an increase in anode bias voltage.

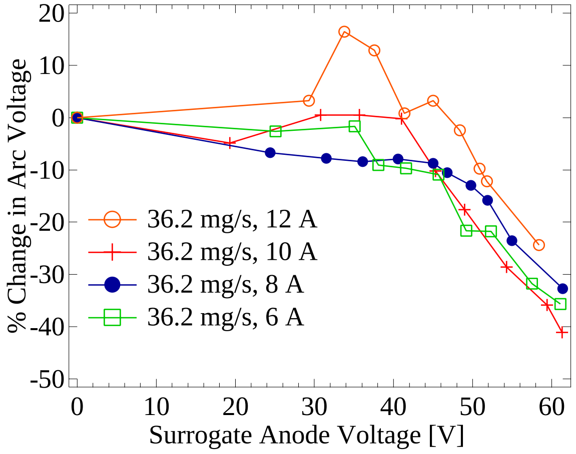

Figure 9. The helium arcjet voltage change as the surrogate anode voltage increases.

The source of the extracted current has not yet been quantified, although we believe that its origin is the arcjet cathode, the arcjet anode (note that it is grounded, and so it can provide current to a positively biased anode), or the plasma itself. The decreasing arc voltage at a constant arc current suggests that the plasma conductivity is increasing with increased levels of anode bias, possibly due to increased temperature and hence ionization. This increase in volume ionization acts as a current multiplier, to increase the drawn current.

The above results show the dependence of the extracted current on the arc current. With the helium arcjet, the extracted current is consistently 121% of the arc current except at the arc current of 10 A at which the extracted current increases to 134%. Another control parameter for the arcjet is the mass flow rate, and in another set of tests the arcjet current was the fixed parameter (6 A) as the mass flow rate was varied. Table 2 shows the mass flow rate, the greatest percent change in the arc voltage, and the maximum amount of current drawn to the anode. The maximum extracted current decreases with increasing mass flow rate. For the applications as a cathode, this trend is encouraging since the efficiency of the hybrid arcjet-Hall thruster increases with decreasing arcjet mass flow rates.

Table 1. Maximum neutralization current at various mass flow rates with 6 A arc current.

Mass Flow Rate [mg/s]	Maximum % ΔV_{arc} [-]	Maximum Anode Current [A]
18.2	-33.37	8.27
27	-32.10	7.6
36.2	-35.67	7.26
45.4	-29.34	7.25

These results demonstrate that the high power (~500W) helium arcjet used here can provide the currents needed to neutralize a high power (5 kW) Hall thruster, and quite possibly, a cluster of four or five low power clusters. However, as previously mentioned, the arc voltage instabilities occur near the same frequencies as the Hall thruster, and the performance of the arcjet maybe impaired when current is extracted from it. In the next set of measurements, we characterized the arc voltage fluctuations with and without the surrogate anode biased.

1-kW arcjet voltage fluctuations

Previous studies of arcjets operating on helium mentioned that the arc voltage fluctuates during

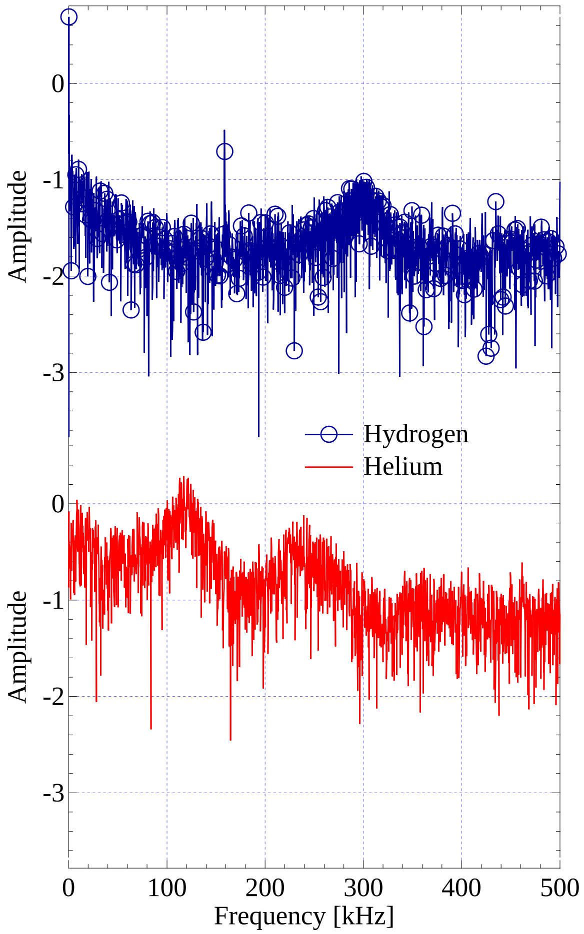

Figure 10. A comparison of the arc voltage power spectra for the hydrogen (13.7 mg/s, 10 A) and helium (36.2 mg/s, 10 A) 1-kW arcjets

operation [9, 12]. These voltage fluctuations cause fluctuations in thrust and other flowfield properties. In this study, the arc voltage was monitored with a Tektronix P5200 High Voltage Differential Probe and acquired into a DAQ5120 card in a PC. In these analyses we examined fluctuations up to 10 MHz and compared them to the fluctuations of the quasi-steady arcjet operating on hydrogen. Figure 10 shows part of the spectral amplitude (logarithmic scale) of the low-frequency fluctuations with an arc current of 10 A and a mass flow rate of 27 mg/s for helium and 13.7 mg/s for hydrogen. The hydrogen arc voltage is 150V and the helium arc voltage is near 65V. At these low frequencies the differences between the two are evident. The helium arcjet shows a broadband feature near 120 kHz and its harmonic near 240 kHz. The hydrogen arcjet only has a broadband feature near 300 kHz. Also, a comparison of the amplitudes shows that the low-frequency fluctuations are stronger in the helium arcjet. At the higher frequencies, the helium arcjet has a broadband feature centered near 2 MHz that is not present in the hydrogen arcjet. Also, it should be noted that the helium arcjet also experiences drift that occurs on time scales measured in minutes. When the arcjet transitions to a different voltage mode, different frequency components dominate. The low frequency fluctuations continue to be present, but the broadband features are not always at the same location, though they are always present and in the same hundreds of kHz region.

The arc voltage fluctuations changed somewhat when the arcjet provided electron current to the surrogate anode. In the case of hydrogen propellant, the low frequency fluctuations below 300 kHz increased in strength. There were no substantial differences for high frequency fluctuations. The changes in the fluctuation spectra for the case of a helium flow were somewhat more dramatic in comparison. These are

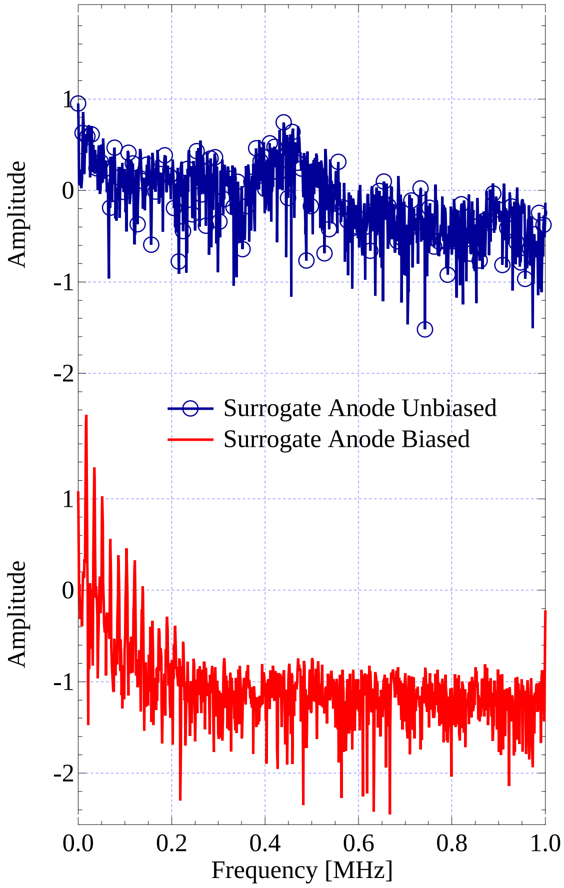

Figure 11. Helium arc voltage fluctuations with and with the surrogate anode biased.

shown in Figure 11. For the case shown, the arc current is 10 A and the surrogate anode current is 13 A. In general, the intensity of the fluctuations decreased across the entire spectrum from 5 MHz to almost near DC, although there is the emergence of a peak at about 450 kHz.

Impact Pressure Measurements

In addition to monitoring changes in the fluctuating nature of this arcjet, we also monitored performance changes while the plume provided current to the anode. That the helium arcjet is able to attain higher thrust efficiencies in comparison to arcjets operating on other propellants [9, 12] is demonstrated in the thrust measurements conducted with the impact pressure probe. Figure 12 and Figure 13 depict the variation in the thrust, specific impulse, and thrust efficiency at 10 A discharge current with mass flow rate. As expected, the thrust increased with the increase in mass flow rate, with the specific impulse and thrust efficiency exhibiting a distinct maximum at a specific energy of 20 MJ/kg. The same measurement was conducted with the surrogate anode biased. Table 3 shows the results with the arcjet current at 10 amps and flow rates of 27 and 36.2 mg/s. The thrust does not substantially change when current is extracted from the arcjet. The differences between the measurements are within the error of the measurement, i.e. +/- 6 mN.

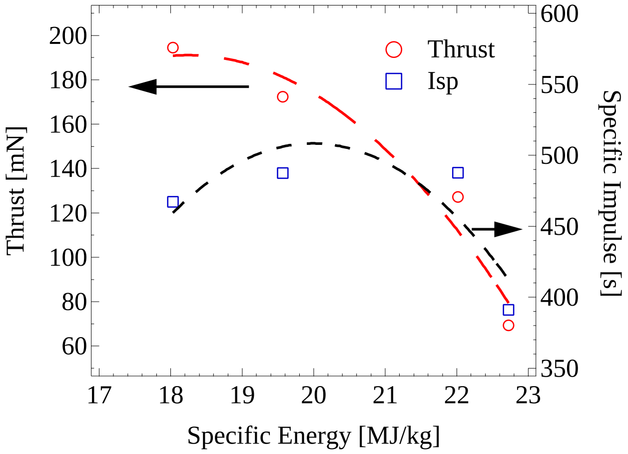

Figure 12. Thrust and specific impulse for the 1-kW helium arcjet with a current of 10 A and various mass flow rates.

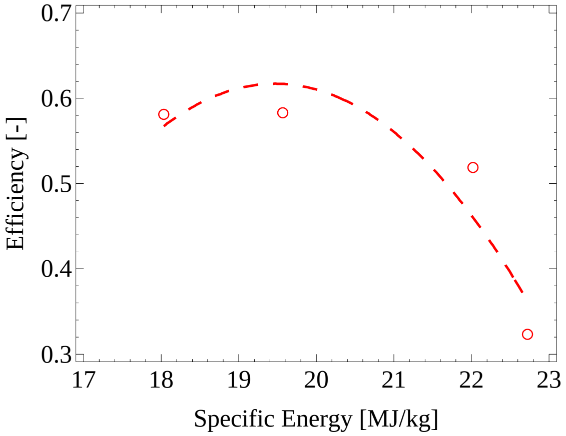

Figure 13. Thrust efficiency of the helium arcjet with a current of 10 A and various mass flow rates.

The impact probe used in this measurement is copper and was grounded during the scans. Nevertheless, the probe disrupted the current extraction from the arcjet when the probe came close to the center of the arcjet plume. The anode current fell from near 13 A to 3 A and then recovered as the probe traversed the arcjet exit plane. As shown earlier, when less current is removed from the arcjet, the arc voltage increases. In this case, the arc voltage remained near its value when the probe was not in the center of the flow, so the plasma sampled by the probe went through the same conditions as the

Table 3. Comparison of arcjet performance when drawing current from cathode plume.

Mass Flow Rate [mg/s]	Arc Voltage [V]	Arc Current [A]	Anode Voltage [V]	Anode Current [A]	Arc Thrust [mN]	Specific Impulse [s]
36.2	67	10	0	0	163	461
36.2	55	10	50	13	157	444
27	55	10	0	0	122	459
27	49	10	50	13	124	471

plasma sampled by the probe with a higher anode current. Since the pressure is integrated across the exit plane to derive the overall thrust, the pressure near the periphery of the arcjet nozzle radius is more heavily weighted than the pressure near the center. In order to gain more information about the flowfield near the center of the arcjet and how drawn current from the plume may affect it, a non-intrusive laser-induced fluorescence method is presently being developed and will be presented in future papers.

Low-power arcjet surrogate anode

The results obtained with the higher power (1-kW) thruster demonstrate the arcjet can be used to neutralize an anode without significant changes in its performance. The next step would be a lab demonstration of the hybrid thruster concept. As previously mentioned, the biggest obstacle in operating a hybrid thruster is finding a vacuum facility to handle the simultaneous operation of both thrusters. To partially circumvent this difficulty we built a low-power arcjet that operates at lower mass flow rates (< 10 mg/s) compared to the 1-kW arcjet and therefore can operate with a Hall thruster within one of our vacuum chambers. Once the low-power arcjet was constructed we determined how much current its plume can neutralize by repeating experiments with the surrogate anode.

Figure 14 and Figure 15 show the amount of current extracted from the low-power arcjet plume and the change in arc discharge voltage while biasing the surrogate anode. In these experiments, the arc discharge current was either 3A or 2A with a mass flow rate of either 12.9 mg/s or 8.6 mg/s. In contrast to the 1-kW arcjet, only currents less than the arc current were extracted from the plume. Specifically, with an arc discharge current of 3A, the maximum extracted current was 83% of the arc current while with an arc discharge current of 2A it was 75% of the arc current. However, it is noteworthy that just as with the 1-kW arcjet, appreciable currents are not extracted until the anode voltage is above 30V. As the surrogate anode voltage is increased, the trend is similar to the description for the 1-kW arcjet. In addition to differences in the extracted current, there are also differences in the changes in the arc discharge voltage as the surrogate anode is biased. Whereas the 1-kW arcjet arc discharge voltage decreased up to 40%, the low-power arcjet arc discharge voltage only decreased 7%. Only at the fixed arc discharge current of 2 A and 8.6 mg/s mass flow rate did the trend mimic the trends observed with the 1-kW arcjet. With the higher arc discharge currents of 3 A, the discharge voltage increased before it decreased towards to the value where the anode has a 0 V bias.

Hybrid arcjet-Hall thruster demonstration

The demonstration of the hybrid thruster requires the Hall thruster to operate at a higher than normal vacuum chamber pressure. Without the helium flow, the pressure measured with the ion gauge is 10^{-4} torr (uncorrected reading). With a helium mass flow rate of 4.5 mg/s the ion gauge remained at 10^{-4} torr while with a flow rate of 8.6 mg/s the reading increased to 2.8×10^{-4} torr. Since the correction factor for helium is near 6, the vacuum chamber pressure increased to nearly 2×10^{-3} torr during the hybrid operation.

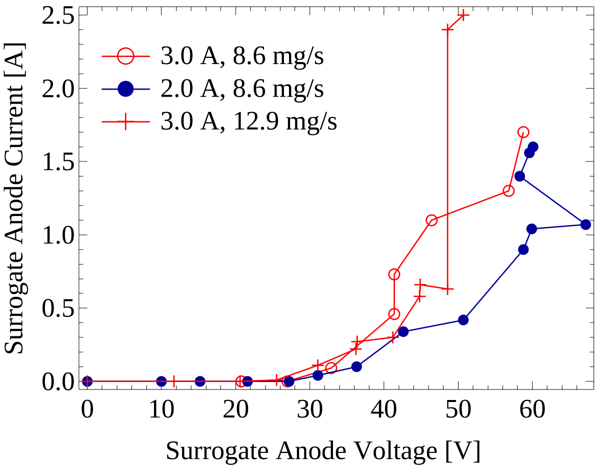

Figure 14. The neutralization current provided by the low-power helium arcjet.

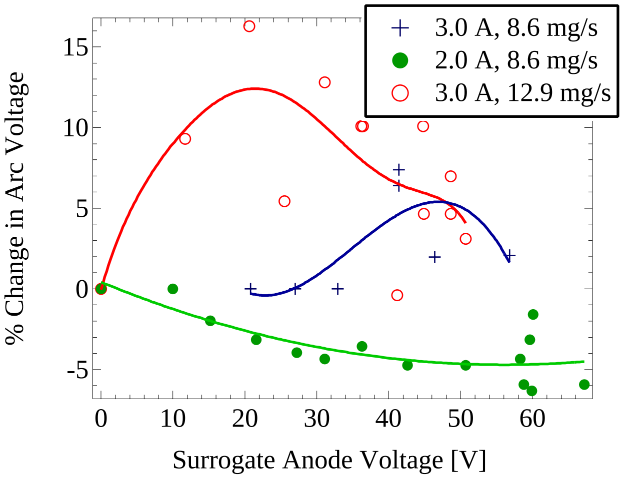

Figure 15. The low-power arcjet voltage change as the surrogate anode voltage increases.

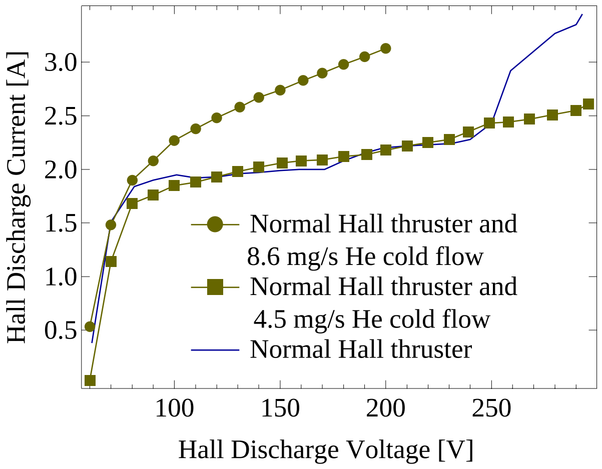

Figure 16. Comparison of the Hall thruster VI curves for different helium flow rates into the vacuum chamber. The normal Hall thruster refers to the Hall thruster neutralized with the hollow cathode.

Effects of the higher pressure were measured by examining changes in the Hall thruster operation. VI curves were created for these conditions as well as the hybrid thruster. In all of these studies, the Hall thruster was operated with a mass flow rate of 20 mg/s through the anode and 3 mg/s through the hollow cathode when needed. The magnetic field peaked near 150 G on the channel centerline. The VI curves taken when helium is flowed into the vacuum chamber are shown in Figure 16. The higher pressure did not change the Hall discharge near the first knee in the VI curve. With the lower helium mass flow rate of 4.5 mg/s, the VI curve matches the VI curve of the normal Hall thruster (the Hall thruster operating with the hollow cathode) up through 250V. Above 250V the upward kink is not present, but the VI curve continues its linearly upward trend. At the higher mass flow rate of 8.6 mg/s, the Hall discharge current continues to increase after the first knee instead of leveling near 2.2A. Above 210V a discharge would appear behind the Hall thruster and it would immediately shut-off.

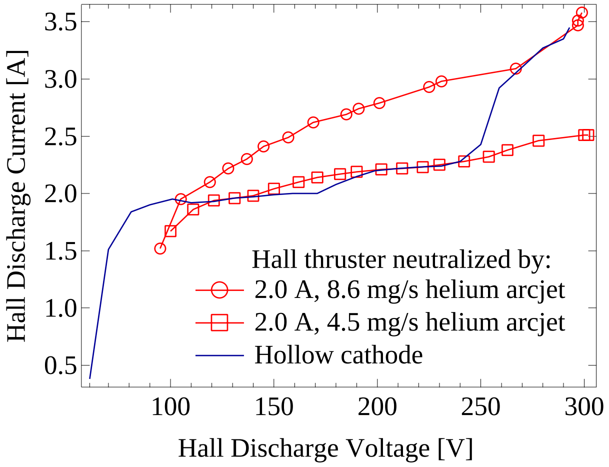

Figure 17. A comparison of the VI curves for the hybrid and hollow cathode neutralized Hall thrusters.

Figure 17 compares the VI curves of the hybrid to the Hall thruster neutralized with a hollow cathode. In the hybrid thruster the hollow cathode is not used at all, and there is neither power nor mass flow through it. To start the hybrid thruster, the arcjet is started with an arc discharge current of 2A. The Hall thruster anode voltage is increased which begins the glow discharge, and the magnetic field strength is increased to initiate the Hall discharge mode. VI curves for the hybrid thruster show a number of interesting features. At both helium mass flow rates the first knee of the VI curve occurs at a higher voltage compared to the hollow cathode neutralized Hall thruster. Between 120 and 240V, the hybrid using 4.5 mg/s of helium propellant has the same VI curve as the Hall thruster with hollow cathode. Above 250V, this hybrid discharge current does not increase to 2.8A but continues along a linear trend up to 300V. This curve is exactly the same as the curve for the hollow cathode neutralized Hall thruster with 4.5 mg/s of cold helium flowing into the vacuum chamber. The hybrid using 8.6 mg/s of helium propellant perturbs the VI curve below the kink at 250V, but matches the VI curve at the higher voltages afterward. Compared to the Hall thruster operating with 8.6 mg/s of cold helium, the VI curve is shifted to the right, i.e. a lower discharge current at a given voltage. Also, violent arc discharges did not appear at the higher mass flow rates. Instead, for each case, near the upper Hall discharge voltages, brief discharges would appear on various electrically grounded surfaces in the vacuum chamber.

The surrogate anode tests attempted to determine how much current could be extracted from the arcjet plume. According to the results shown previously, only 1.5A of current could be drawn from the arcjet plume with an arc discharge current of 2.0A and mass flow rate of 8.6mg/s. In the hybrid configuration with the same arc discharge current and mass flow rate, the arcjet plume could provide the electron currents to neutralize a Hall discharge requiring 3.5A. This indicates that the surrogate anode tests may indicate a lower bound on the amount of current that can be extracted from the arcjet plume. In order to determine limits to how much current can be extracted, the arc discharge current is decreased at a fixed arcjet mass flow rate until it can no longer neutralizer the Hall thruster. Without adequate neutralization the Hall thruster ceases operate. The arc discharge voltage is also recorded as the arc discharge current is varied. Figure 18, Figure 19, and Figure 20 show these results for the arcjet with different mass flow rates. In all cases, the arc discharge voltage immediately decreased when the Hall thruster initiated operation. The Hall discharge current and voltage remained fixed as the arc discharge current varied. In Figure the voltage of the Hall thruster is set to 115V and with a 2 A, 8.6 mg/s arcjet the Hall discharge current is 2A. At an arc current of 1.5A, 133% of the arc discharge current could be extracted from the arcjet plume before the Hall thruster shut-off. In Figure 19 the Hall discharge voltage is set to 300 V and with a 2 A, 8.6 mg/s arcjet the Hall discharge current is 3.1A. Up to 181% of the arc current was extracted at an arc discharge current of 1.1A. Figure 20 is at the same condition as Figure 19 except at a lower flow rate of 4.5 mg/s. The Hall discharge current decreased to 2.5A and the maximum extracted current was 133% of the arc discharge current. When the arcjet plume could not provide the neutralizing currents needed, the Hall thruster would shut-off, the arcjet would remain operational, and the arc discharge voltage increased. Also, in all cases the low-power arcjet could neutralize much more current than anticipated by the surrogate anode studies.

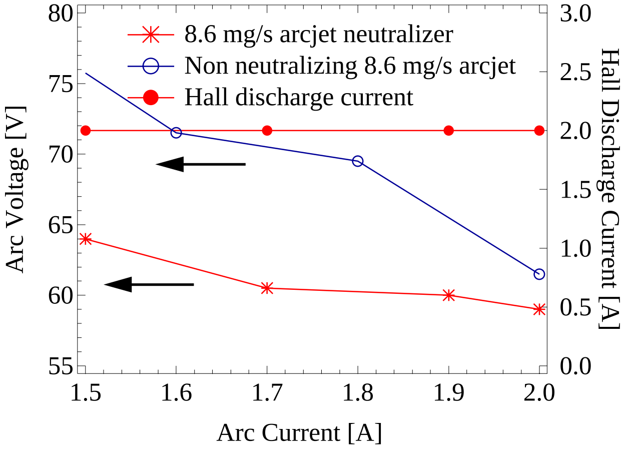

Figure 18. Low-power arcjet (8.6 mg/s mass flow rate) VI curve while neutralizing the Hall thruster (2A, 115V).

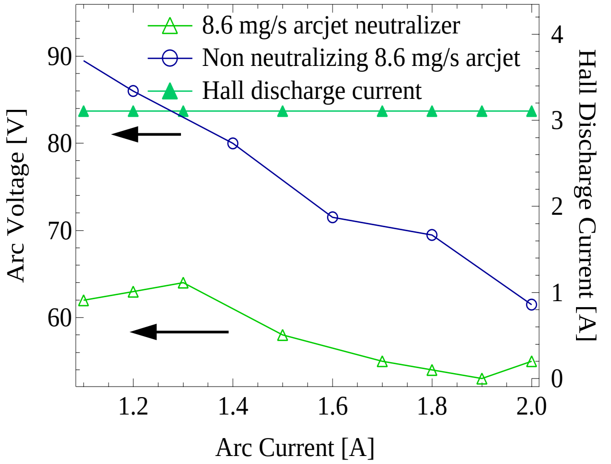

Figure 19. Low-power arcjet (8.6 mg/s mass flow rate) VI curve while neutralizing the Hall thruster (3.1A, 300V)

The current fluctuations of the Hall thruster were measured to determine what effects, if any, the arcjet voltage fluctuations have on the hybrid thruster operation. Figure 21 and Figure 22 show the Hall discharge current oscillations up to 200 kHz with a Hall discharge voltage of 110V and 210V respectively. At the lower voltage, the Hall thruster neutralized with the hollow cathode shows a characteristic mode near 11.6 kHz and its harmonics with another (weak) feature near 160 kHz. With the higher voltage there is a breathing mode near 7.3 kHz and another strong feature near 34 kHz, the latter mode is the subject of much research. The addition of cold helium to the vacuum chamber causes the fluctuation intensity to increase and the dominant frequency components to shift.

Relative changes in the fluctuations intensity are shown in Table 4 and Table 5. At the lower mass flow

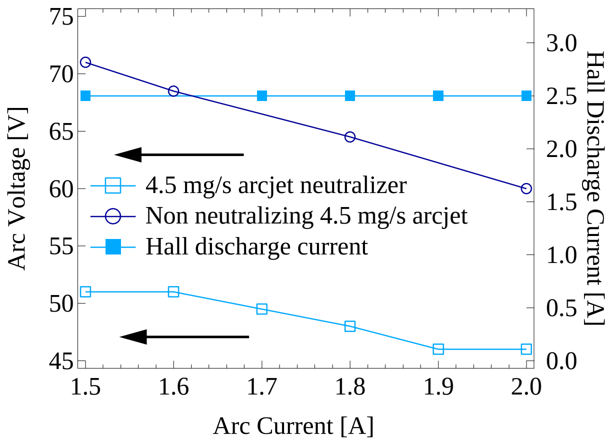

Figure 20. Low-power arcjet (4.5 mg/s mass flow rate) VI curve while neutralizing the Hall thruster (2.52 A, 301V).

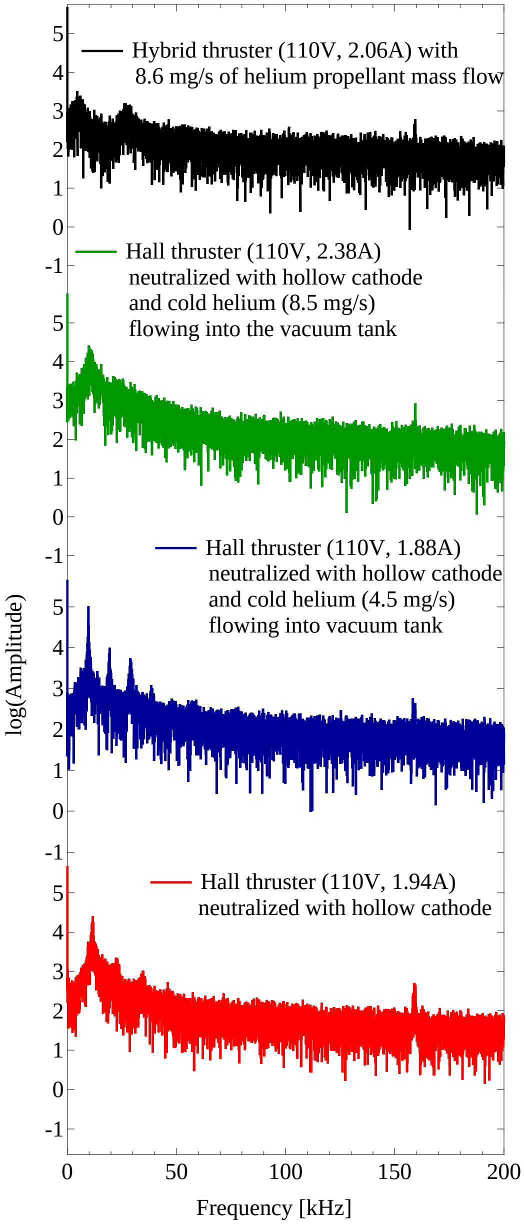

Figure 21. Comparison of Hall discharge current fluctuations with a Hall discharge voltage of 110V.

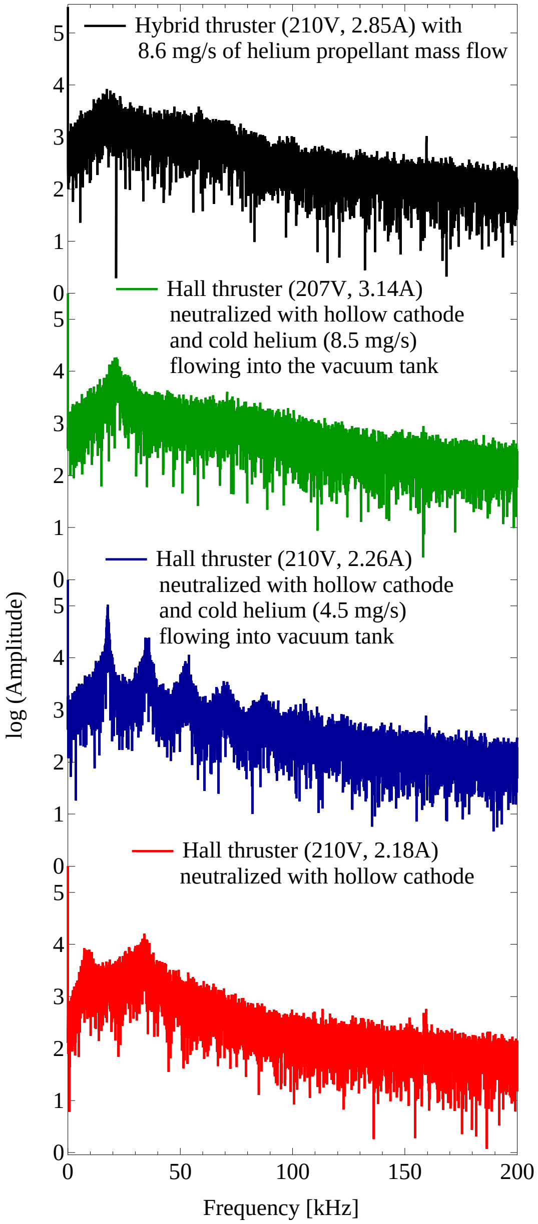

Figure 22. Comparison of Hall discharge current fluctuations with a Hall discharge voltage of 210V.

rate, the thruster also enters into a different operating mode. The current oscillations are sinusoidal at 110V, and the thruster is almost in a pulsed mode at 210V. At 8.5 mg/s, the oscillation intensity further increases, but it is no longer in a pulsed mode. The breathing modes are near 9 and 21 kHz for the 110 and 210V cases respectively with no harmonics present. With the hybrid thruster, the current oscillations are damped up to 50%. The breathing mode is near 5 kHz at the low voltage with another feature near 26 kHz. At the higher voltage, there appears to be a broad feature near 20 kHz.

The evaluation of the hybrid thruster not only includes a demonstration of its operation but also an analysis of its potential use. As previously mentioned, the hybrid arcjet-Hall cluster will be able to fill a niche in performance between arcjets and Hall thrusters. Within this niche the hybrid thruster can offer better

Table 4. Change in current fluctuations at a Hall discharge voltage of 110V.

Configuration	Helium mass flow rate [mg/s]	% Change in current oscillations
Cold flow	4.5	72
Cold flow	8.5	109
Hybrid	8.5	-50

performance than other propulsion systems. In the following mission analysis, the hybrid thruster, using various propellant combinations, is compared to clustered Hall thrusters and chemical propulsion systems to determine which missions would benefit from the continued development of the hybrid thruster concept.

Mission Analysis

In order to compare the hybrid arcjet-Hall thruster to conventional propulsion options, we examined a reference mission where a 2,000 kg satellite traverses from low-earth orbit (LEO, 400 km) to geosynchronous orbit (GEO, 35,786 km). Such spacecraft represent the typical payload for Delta-IV class launch vehicles, using direct insertion to GTO and a solid apogee kick motor to circularize in GEO. Advanced electric propulsion allows the use of a smaller and less expensive launch vehicle, such as the Atlas IIAS and Delta II (7,700 and 3450 kg payload to LEO, respectively [13]), which delivers the spacecraft and a high I_{sp} electric orbit transfer vehicle (EOTV) to LEO, and the EOTV lifts the spacecraft to GEO over the course of several months. Individual Hall thrusters have been proposed for orbit raising, to reduce propellant mass and thus allow the use of these less expensive launch vehicles, but are typically associated with unattractive trip times of greater than 90 days due to their low thrust.

Model

Table 6 lists the assumptions made in this analysis. Such missions inherently require trading launch weight (and thus cost) savings against the time required to reach the operational orbit. We have therefore, determined the launch weight versus travel time curves for several of the hybrid cases described above, along with reference cases for pure Hall thruster clusters individually using hollow cathode neutralizers and chemical rockets with both storable and cryogenic propellants.

Table 5. Change in current fluctuations at a Hall discharge voltage of 210V

Configuration	Helium mass flow rate [mg/s]	% Change in current oscillations
Cold flow	4.5	29
Cold flow	8.5	3
Hybrid	8.5	-43

Launch weight to LEO (400 km, 28.5°) is determined by separately considering the masses of payload, propulsion, propellant, tankage, and miscellaneous structure and mechanisms. Payload is fixed at 2000 kg. Propulsion systems are linearly scaled from the cases described below to provide the thrust necessary to carry out the orbit transfer in the specified time. For this purpose, a low thrust LEO to GEO transfer is assumed to require 5.2 km/s ΔV at an 87.5% duty cycle, determined by the method of Pollard [14]. Propulsion system mass includes a dedicated solar array sized to the power requirements of the thruster. An array specific power of 40 W/kg, typical for radiation-hardened solar concentrator systems, is assumed. Propellant requirements are determined by the rocket equation using the measured, or predicted specific impulsion and the aforementioned 5.2 km/s ΔV. For chemical systems, two impulsive burns totaling 4.25 km/s are substituted. Tankage fractions are assumed to be 10% for supercritical xenon, liquid

Table 6. Model assumptions.

Solar array specific mass	40 W/kg (radiation hardened)
Structural fraction	5%
Duty cycle	87.5% (mission averaged)
Tankage Fraction	
Xenon	10%
Helium	15% (cryogenic)
Hydrogen	20% (cryogenic)
Delta-V	
Low thrust	5.2 km/s
Impulsive	4.3 km/s

oxygen, and storable chemical propellants, 15% for liquid helium, and 20% for liquid hydrogen. All but the liquid helium cases are supported by current upper stage design practice [13]. The 15% tankage fraction for helium is an interpolation based on the density of liquid helium and comparable to the estimate of Welle et al [15]. Finally, a extra 5% is assumed for structure, mechanisms, and controls, again supported by current upper-stage designs.

Systems

The mission analysis is completed for the following cases.

Case 1:

Table 7 shows the standard Hall thruster cluster considered in this study. It consists of four SPT-140 Hall thrusters along with cathodes and power processing units [16]. Also shown in Table 7 is a 2.5 kW helium arc jet system with performance based on the measurements presented by Welle [15]. The arcjet was scaled linearly from experimental arcjet performance data at 700 W and from commercial arcjet system mass to a proposed value of 2.5 kW in order to neutralize the cluster of four SPT-140 Hall thrusters. A 2.5 kW helium arcjet is expected to have a discharge current of 50A. As shown earlier, the 1-kW helium arcjet consistently neutralize Hall thruster current of 120% of the arcjet discharge current, in this case 60 A of four SPT-140 Hall thrusters, the highest performing available commercial Hall thruster. The final column in Table 7 presents the combined performance of the cluster of four SPT-140s using the helium arcjet as a neutralizer. As would be expected, the Isp drops by 29%, but significantly the thrust to weight and thrust to power ratios rise by 22% and 16% respectively. The overall Isp is still above 1200 seconds and with significantly increased thrust. It is important to note that the arcjet-neutralizer presented in Table 7 does not represent the ideal case for a helium arcjet, but rather a linear scaling of published results to higher power levels. Case 1 therefore serves a lower bound.

Cases 2 and 3:

Case 1 is based on performance data measured using helium propellant in an arcjet designed for hydrogen propellant, and is thus far from optimal. Table 8 shows what we believe to be a reasonable extrapolation of the capabilities of an optimized helium arcjet. This thruster operates at 5.75 kW with a specific impulse of 900 s and an efficiency of 60%. The Case 2 hybrid propulsion system is also shown. This system results in a combined I_{sp} and efficiency of 1325 s and 53%. This is a slight improvement from Case 1. We feel that Case 2 is representative of the system that could be constructed if an effort was undertaken to design a helium arcjet for this purpose.

Case 3, also shown in Table 8, presents the idealized helium arcjet for use as a neutralizer of the clustered SPT-140 system. This is based on the extrapolation of Welle as the best performance that could be extracted from a helium arcjet [15]. To construct an arcjet with these performance characteristics would represent a considerable research and development effort. Therefore, Case 3 three should be viewed as the upper bound, or idealized scenario

Table 7. Case 1: SPT-140 cluster with and without nominal helium arcjet neutralizer. The 2.5 kW He arcjet is scaled from ref. [15].

	SPT Cluster w/ Cathodes	SPT Cluster w/o Cathodes	Arcjet-Neutralizer	Hybrid System
Power (kW)	18		2.5	20.5
Thrust (N)	1.160		0.375	1.535
Isp (s)	1770	1947	598	1256 (-29%)
Efficiency	56%	62%	44%	46%
Flow (mg/s)	66.8	60.7	63.9	124.6
Discharge (V)	300		50	
Discharge (I)	50		50	
Dry Mass (kg)	96.4	95.4	9.1	104.5
Thrust/Mass (N/kg)	0.0120		0.0412	0.0147 (+22%)
Thrust/Power (N/kW)	0.0644		0.150	0.0748 (+16%)

Table 8. Case 2 and 3, the improved and ideal helium arcjet neutralizers

	Case 2 Improved helium arcjet neutralizer		Case 3 Ideal helium arcjet neutralizer	
	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System
Power (kW)	5.75	23.75	10	28
Thrust (N)	0.780	1.940	1.190	2.350
Isp (s)	900	1325 (-25%)	1200	1481 (-16%)
Efficiency	60%	53%	70%	61%
Flow (mg/s)	88.5	149.2	101.0	161.7
Discharge (V)	115		200	
Discharge (I)	50		50	
Dry Mass (kg)	21.0	116.4	36.4	131.8
Thrust/Mass (N/kg)	0.0371	0.0167 (+39%)	0.0327	0.0178 (+48%)
Thrust/Power (N/kW)	0.136	0.0817 (+27%)	0.119	0.0839 (+30%)

Cases 4 and 5:
The systems examined in the previous cases require dual propellant storage and feed systems, an undesirable complexity. We therefore consider the use of common propellants for both the cluster of Hall thrusters and the arcjet neutralizer. Table 9 presents Case 4 where we have examined the use of a xenon arcjet. As there is no experimental data available with xenon propellant, the arcjet is an estimate of performance using the relative atomic weights of xenon and helium based on the helium arcjet presented in Case 2. It assumes that the efficiency will be comparable to a helium arcjet since there will be minimal frozen flow losses and that the discharge characteristics and specific power are invariant. As expected due to the higher atomic mass of xenon (131.4 amu), the I_{sp} of a xenon arcjet is 157 s, much lower than the helium arcjet in Case 2.

Table 9. Case 4: Xenon arcjet neutralizer

	Arcjet-Neutralizer	Hybrid System
Power (kW)	5.75	23.75
Thrust (N)	4.460	5.620
Isp (s)	157	193 (-89%)
Efficiency	60%	22%
Flow (mg/s)	2896	2963
Discharge (V)	115	
Discharge (I)	50	
Dry Mass (kg)	21.0	116.4
Thrust/Mass (N/kg)	0.0327	0.0483 (+300%)
Thrust/Power (N/kW)	0.119	0.237 (+267%)

Table 10 presents a compromise Case 5, where both the Hall thruster cluster and arcjet use argon as the propellant. In this case, the power level and I_{sp} of the SPT-140 Hall thrusters are kept constant. Since there is no data on the performance of the SPT-140 Hall thruster on argon propellant, the estimations of performance shown in Table 10 should only be taken as an optimistic case for this scenario.

In Cases 4 and 5, the hybrid system performance is dismal. These two cases are included for completeness to show that if an arcjet neutralizer is to be used; separate propellant flow systems are required in order to produce reasonable hybrid system performance.

Cases 6, 7, and 8:
These cases present the hydrogen equivalents to Cases

Table 10. Case 5: Argon arcjet neutralizer /Hall cluster

	SPT Cluster w/o Cathodes	Arcjet-Neutralizer	Hybrid System
Power (kW)	18	8.625	26.625
Thrust (N)	0.93	3.7	4.630
Isp (s)	1947	285	344
Efficiency	62%	60%	29%
Flow (mg/s)	48.6	1323	1372
Discharge (V)	165	115	
Discharge (I)	90	75	
Dry Mass (kg)	95.4	31.4	126.8

1, 2, and 3. Case 6, presented in Table 11, shows the standard SPT-140 cluster with a 6.75 kW hydrogen arcjet neutralizer. This arcjet is a scaled version of the NASA Lewis 1 kW arcjet system [15]. Case 1 and Case 6 have similar performance. Case 7, also shown in Table 11, presents a hybrid system with an improved performance 12 kW hydrogen arcjet. This arcjet represents the performance that could be expected from an arcjet designed explicitly for hybridization based on current technology. Table 11 also shows Case 8, which represents the upper bound of hydrogen arcjet performance.

Model Results

The results of cases 1-3 (helium) and 6-8 (hydrogen) are shown in Figure 23 and Figure 24. Results from Cases 4 and 5 were not deemed to be of interest due to their poor performance characteristics. In addition to the various cases previously discussed, three additional cases are presented for comparison. The pure Hall cluster is provided for comparison so that the benefits, if any, of arcjet neutralization are evident. As a check of the general principle of using electric propulsion for orbit raising, the total LEO mass required for both storable chemical motors (Isp = 340 s) and cryogenic chemical engines (Isp = 446 s) are also provided. This study limited total LEO mass to less than 14,000 kg in order to make the comparisons in this study reasonably congruent with actual launch capabilities. Several general trends are immediately evident. In all cases, if the allowed trip time is sufficiently long, the Hall thruster, due to its higher I_{sp}, will always be the lowest mass system. This is only amplified by the fact that the tankage fraction for xenon storage is less than that for cryogenic helium or hydrogen. Therefore, the maximum trip time examined is 120 days.

The nominal hydrogen Case 6 does not significantly improve over the pure Hall thruster case over any portion of the range of trip times. In fact, the nominal hydrogen case has a slightly higher total LEO mass over most of the range. The optimal, very optimistic, Case 8 does show reduced total LEO mass for trip times of less than 103 days. At 60 day trip times, this case reduces total LEO mass by 995 kg over the pure Hall thruster case; although, it should be remembered that at the mass for both these cases is at least 1,150 kg greater than the cryogenic chemical case. In order to match the cryogenic chemical case, the pure Hall case requires 68 days, Case 8 requires 65. Of course for this trip time, the nominal Case 6 is 225 kg more massive than the pure Hall case.

Although the hydrogen Cases 6-8 have higher specific impulses than the corresponding helium Cases 1-3, the higher thrust and lower tankage fraction of the helium arcjet neutralizer combine to produce a significant improvement over the pure Hall thruster case. The pure Hall case does not reduce the total mass to LEO

Table 11. Cases 6,7, and 8. The hydrogen arcjet neutralizer

	Case 6 Nominal hydrogen arcjet		Case 7 Improved hydrogen arcjet		Case 8 Ideal hydrogen arcjet	
	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System	Arcjet-Neutralizer	Hybrid System
Power (kW)	6.75	24.75	12	30	18.75	36.75
Thrust (N)	0.850	1.740	0.920	2.080	1.400	2.560
Isp (s)	900	1402 (-21%)	1200	1526 (-14%)	1500	1674 (-5%)
Efficiency	38%	48%	45%	52%	55%	57%
Flow (mg/s)	66	126.5	78	138.9	95.2	155.9
Discharge (V)	135		240		375	
Discharge (I)	50		50		50	
Dry Mass (kg)	24.6	120	43.7	139.1	68.3	163.7
Thrust/Mass (N/kg)	0.0346	0.0145 (+21%)	0.0211	0.0150 (+25%)	0.0205	0.0156 (+30%)
Thrust/Power (N/kW)	0.126	0.0703 (+9%)	0.0767	0.0693 (+8%)	0.0747	0.0697 (+8%)

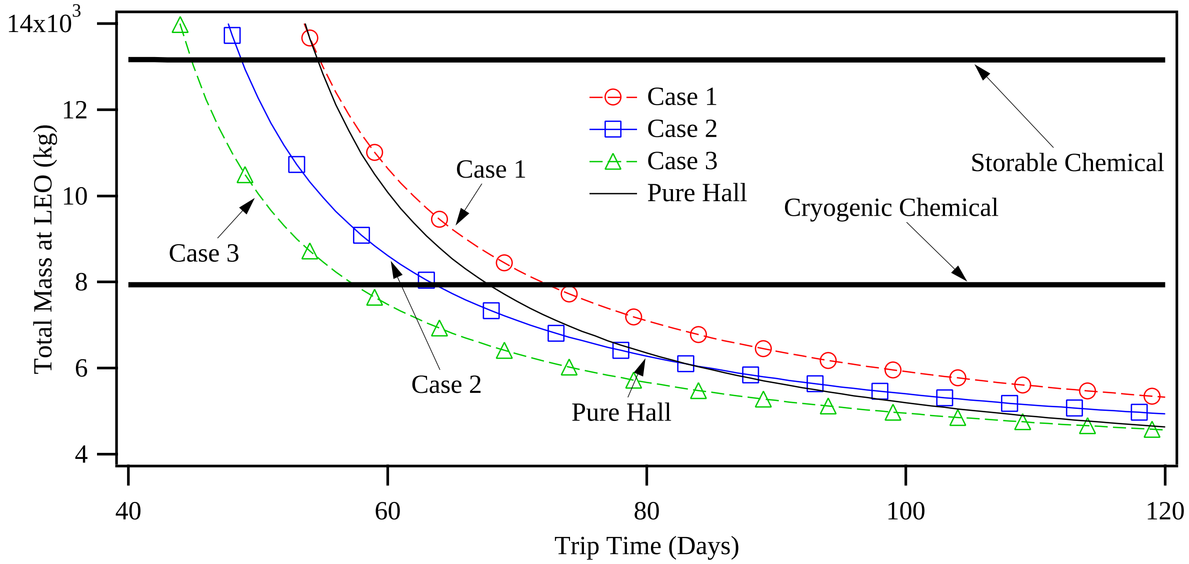

Figure 23. Mass at LEO for helium arcjet neutralizer cases (1-3) for various trip times.

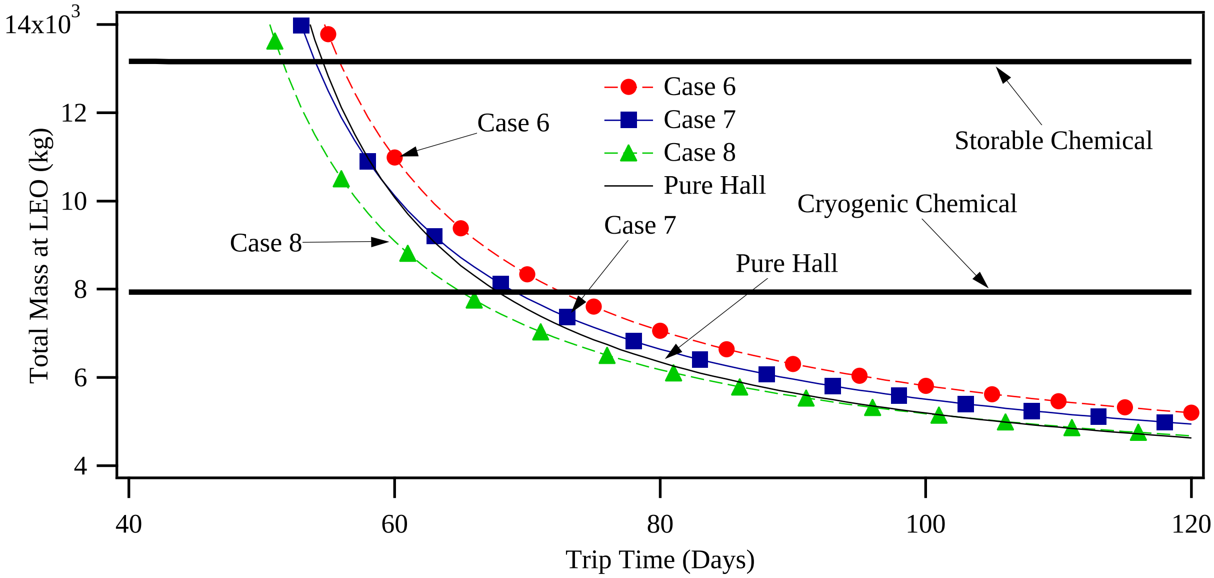

Figure 24. Mass at LEO for hydrogen arcjet neutralizer cases (6-8) for various trip times.

over the nominal helium Case 2 until trip times of 83 days and with total masses 1800 kg less than the cryogenic chemical case. Meanwhile, the optimistic Case 3 has a lower mass than the pure Hall case for trip times of up to 134 days. At 60 day trip times, the total mass to LEO is 2,600 kg less with Case 3 than it is with the pure Hall system. In fact at a 60 day trip time, the mass for the Case 3 mission is 460 kg less than that for the best chemical system. Even the more conservative Case 2 mission is less massive than the pure Hall thruster mission by 1,470 kg at 60 day trip times. Although Case 2 is 680 kg more massive than the optimal cryogenic chemical case, it is 4,540 kg less massive than the storable chemical case.

The pure Hall case requires a 68 day trip time to lower the necessary mass launched to LEO to the level of the cryogenic chemical case (7,950 kg). The conservative Case 1 requires a 73 day trip time to equal the LEO launch mass of the cryogenic chemical case. The more optimistic Cases 2 and 3 require 64 and 58 days which are less than the pure Hall thruster trip time. It is also interesting to note that the Atlas IIAS is capable of launching a 7,700 kg payload into LEO. This is 250 kg less than the mass at LEO required by the cryogenic chemical case. Therefore, the model mission cannot be currently launched by an Atlas IIAS vehicle with even the most capable LEO to GEO chemical transfer stage. Using the maximum rated launch capability of the Atlas IIAS , the pure Hall cluster would deliver the model spacecraft to GEO in 70 days. Our conservative Case 1 would deliver the same payload to GEO in 75 days. Cases 2 and 3 would deliver the payload in 66 and 59 days, respectively. Downselecting to an Atlas IIAS from a larger vehicle would result in significant launch cost savings.

From the analysis above, it is evident that the ideal hybrid system will require the use of a helium arcjet. This restricts the system to short term missions (less than 120 days) due to the issues associated with the on-orbit storage of liquid helium. For this reason, hybrid Hall-arcjet systems will be of limited use for general orbit maneuvering due to the storage requirements of liquid helium. However, a niche for initial high ΔV missions exists for this technology as is shown in the above mission analysis.

Conclusions

The results presented here provide support for the continued development of helium arcjet sources as neutralizing cathodes for high power clustered Hall thrusters. The neutralization of a Hall thruster with an arcjet plume creates a moderate thrust, moderate specific impulse thruster package that can fill a performance niche that is currently unattainable. This study demonstrated that substantial current can be drawn from an arcjet thruster plume, estimated the impact that drawing current may have on the operation and performance of the arcjet thruster, demonstrated the feasibility of using an arcjet thruster plume to neutralize a Hall thruster, and presented missions in which the hybrid thruster would offer better performance than competing propulsion systems.

Studies with the 1-kW arcjet proved that arcjets could neutralize an anode without a significant change in performance, but with changes in operation. At the current saturation limit (typically 120% of arc discharge current) there is a 40 to 30 percent decrease of the arc voltage with little, if any, impact on the thrust as determined by an impact pressure probe. The arc discharge voltage instabilities, which are present with the arcjet operating on helium propellant, are dampened when current is drawn from the arcjet plume.

The low-power arcjet plume provided more current than expected to neutralize the Hall thruster. From the surrogate anode studies, it appeared that the maximum extracted current would be less than the arc discharge current. As with the 1-kW arcjet, the arc discharge voltage was perturbed when current was drawn to the surrogate anode. However, it was noticed that the low-power arcjet voltage began to change substantially when the surrogate anode was biased and without appreciable currents going to the anode. When the low-power arcjet plume was used to neutralize the Hall thruster, up to 181% of the arc discharge current was extracted.

The operation of the Hall thruster in the hybrid configuration exposed it to high tank pressures. The two helium mass flow rates used in these studies perturbed the operation of the Hall thruster, but in different regions. With a flow rate of 4.5 mg/s, the Hall thruster remained on the typical VI curve up to 250V. Above this value, instead of a large increase in the Hall discharge current, it continued its linear increase. At the 8.6 mg/s flow rate, the Hall discharge current was greater then the typical VI curve up to 260 and they match above 260V. When the arcjet is operational, the VI curves only change at the low voltages. The initial knee of the VI curve is shifted to higher Hall discharge voltages.

In the mission analysis we have examined various cases of a hybrid Hall cluster with arcjet neutralization. Three broad classes of Hall clusters with arcjet neutralizers were examined; helium, hydrogen, and single propellant systems. From these it was determined that in order to maintain reasonable performance characteristics, the arcjet and Hall thrusters would each require a separate propellant system. Examination of the two most promising arcjet concepts (helium and hydrogen), illustrated that the higher propellant density and system thrust to weight ratio of the helium arcjet overcomes the higher specific impulse of the hydrogen arcjet for the sample LEO to GEO spiral transfer mission.

From the analysis it becomes obvious that the hybrid thruster systems have a limited, but very useful capability for orbit transfers early in mission timelines.

This limitation is due to the storage limitations of cryogenic liquid helium at temperatures of 4 K. However, within the limitation of operation early in a mission timeline, hybrid Hall-arcjet thrusters appear capable of putting larger payloads on station within 60 days than either pure Hall thruster systems or chemical systems. This will provide increased mission capability at lower cost for users with large payloads.

Acknowledgements

The work at Stanford University is supported by the Air Force Office of Scientific Research. The authors are grateful to NASA Glenn for providing the arcjet and a new arcjet nozzle. The authors greatly appreciate the assistance provided by Dr. N. Gascon, in operating the Hall thruster used here in the demonstration study.

References

1. Janson, S.W., "The On-Orbit Role of Electric Propulsion," AIAA-93-2220, 29th Joint Propulsion Conference, 1993.
2. Spanjers, G.G., M. Birkan, and T.J. Lawrence, "The USAF Electric Propulsion Research Program," AIAA-2000-3146, 36th Joint Propulsion Conference, 2000.
3. Walker, Q.E. and M.A. Cappelli, "High Density Plasma Neutralization of a Hall Thruster," AIAA-2001-3352, 37th Joint Propulsion Conference, 2001.
4. Schmidt, D.P., et al., "A low-power, linear-geometry Hall plasma source with open electron-drift," *Plasma Source Sci. Technol.*, **9**: 68-76, 2000.
5. Cappelli, M.A., W.A. Hargus, Jr., and N.B. Meezan, "Coherent structures in crossed-field closed-drift Hall discharges," *IEEE Transactions on Plasma Science*, **27**(1): 96-7, 1999.
6. Chesta, E., N.B. Meezan, and M.A. Cappelli, "Stability of a magnetized Hall plasma discharge," *Journal of Applied Physics*, **89**(6): 3099-107, 2001.
7. Choueiri, E.Y., "Plasma oscillations in Hall thrusters," *Physics of Plasmas*, **8**(4): 1411-1426, 2001.
8. Haag, T. and F.W. Curran, "Arcjet Starting Reliability: A Multistart Test on Hydrogen/Nitrogen Mixtures," *Journal of Spacecraft and Rockets*, **29**: 444, 1992.
9. Walker, Q.E. and M.A. Cappelli, "Laser-Induced Fluorescence Measurements of a Helium Arcjet Flow," AIAA-99-3603, 30th Plasmadynamics and Lasers Conference, 1999.
10. Storm, P.V. and M.A. Cappelli, "Laser-Induced Fluorescence Measurements Within An Arcjet Thruster Nozzle," AIAA-95-2381, 31st Joint Propulsion Conference, 1996.
11. Hargus, W.A., Jr. and M.A. Cappelli, "The structure of an expanding hydrogen arcjet plasma," *Physics of Plasmas*, **5**(12): 4488-4497, 1998.
12. Welle, R.P., et al., "One Kilowatt Hydrogen and Helium Arcjet Performance," The Aerospace Corporation, ATR-91(8443)-2, April 1993.
13. Isakowitz, S.J., J.P. Haopkins, Jr, and J.B. Hopkins, *International Reference Guide to Space Launch Systems*. 3 ed. 1999, Reston, CA: AIAA.
14. Pollard, J.E., "Evaluation of Low-Thrust Orbital Maneuvers," AIAA-98-3286, 34th Joint Propulsion Conference, 1998.
15. Welle, R.P., et al., "One Kilowatt Hydrogen and Helium Arcjet Performance," AIAA-91-2229, 27th Joint Propulsion Conference, 1991.
16. Hargus, W.A., Jr., et al., "Preliminary Performance Results of the High Performance Hall System SPT-140," AIAA-2000-3250, 27th Joint Propulsion Conference, 2000.