JOURNAL OF SPACECRAFT AND ROCKETS
Vol. 41, No. 6, November–December 2004

Arcjet Neutralization of Hall Thrusters, Part 2: Experimental Demonstration

Quentin E. Walker,* Nicolas Gascon,† and Mark A. Cappelli‡
Stanford University, Stanford, California 94309-3032
William A. Hargus Jr.§
U.S. Air Force Research Laboratory, Edwards Air Force Base, California 93524
and
John A. Schilling¶
W. E. Research, LLC, Rosamond, California 93560

The use of an arcjet to provide electron current for a Hall thrusters is examined, as such a hybrid concept can fill a performance niche amongst available space propulsion options. We report on experiments that determine how much electron current can be drawn to a surrogate anode from the plume of low-power arcjets operating on hydrogen and helium and 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 arcjet Hall thruster hybrid package was assembled for concept demonstration. When operating on helium with a nominal mass flow rate of 4.5 mg/s and at very low power levels (∼70–120 W), the arcjet was able to effectively neutralize the ∼200–900-W xenon Hall thruster causing little measurable departure from the hollow-cathode neutralized Hall thruster I-V characteristics up to 250 V. At higher helium mass flow rates, the Hall discharge current was slightly perturbed from its expected values, most likely because of the ingestion of helium in the chamber background.

I. Introduction

HALL thrusters, or closed electron-drift Hall plasma accelerators, are high-specific-impulse and high-thrust-efficiency space propulsion devices. This technology has reached a relatively high level of maturity in the medium-power range (500 W–5 kW),[1,2] and Hall thrusters are favored over other competing space rockets for a number of commercial and military spacecraft that require stationkeeping, rephasing and orbit topping. This success has spawned an interest in higher power (100–150-kW) Hall-thruster-based propulsion systems, which will extend applications to orbit transfer vehicles and rescue vehicles capable of the repositioning marooned space assets. The availability of this higher power range is based on that expected from proposed U.S. Air Force programs using deployed sails of thin-film solar arrays. One approach to exploiting this higher power for near-term propulsion options involves the clustering of Hall thrusters.[3] The clustering of low-power thrusters to achieve a high total system power will simplify ground testing and space qualification and will accelerate deployment, provided multiple thruster interactions are well understood.

One important thruster interaction involves the problem of cluster plume neutralization. The use of independent cathodes tied to a common ground potential can lead to cathode current stealing, with one cathode dominating over all of the others in supplying the required current to neutralizer the entire cluster plume. Such a scenario will lead to the premature consumption of that cathode. This failure mode can be avoided by independently powering each cathode to electrically isolated power processing units, a solution that is less desirable from the standpoint of system cost, design, and integration. An option that can overcome this limitation is the use of a single, robust cathode that operates at a high power and with high electron emission current. Recently, we proposed that a high-power xenon Hall cluster could be neutralized by a single, moderate-power arcjet.[4] Such a hybrid concept can fill propulsion performance gaps to provide moderate specific impulse (900–1600 s) at high thrust, while maintaining a high overall propulsion efficiency (>55%). In preliminary studies, it was shown that a hybrid Hall thruster–arcjet neutralizer package could meet such performance criterion if the two sources can operate simultaneously without interactions that compromise the operation of any one individually.[5] The potential performance of this hybrid propulsion scheme was compared to other competing propulsion options in a companion paper.[6] In that paper, we examined a reference mission where a 2000-kg payload traverses from low Earth orbit (400 km, 28-deg inclination) to geosynchronous Earth orbit (35,786 km, 0-deg inclination). It was shown that hybrid Hall effect clusters neutralized by a single medium power helium arcjet appear capable of putting larger payloads on station within 60 days than either pure Hall thruster systems or chemical upper stages. The requirement for helium as an arcjet propellant (to obtain high overall thruster package efficiency) does restrict the use of such a system to short-term missions (less than 120 days) because of the issues associated with the on-orbit liquid-helium storage. Despite the need for dual-propellant storage and management, the results of the mission analysis prompted laboratory investigations.

This paper describes the results of these laboratory demonstrations of arcjet neutralization of a Hall thruster, though the experiments are carried out at significantly reduced power levels because of pumping limitations. The experiments were performed at Stanford University using a specially designed low-power (70–120-W) helium arcjet neutralizing a moderate-power (∼300-W) Hall thruster. Larger-scale studies (>3-kW clusters) are planned in the future, but these will push the present capabilities of many available ground-test

Received 20 June 2003; revision received 29 October 2003; accepted for publication 5 November 2003.

*Ph.D. Candidate Student, Thermosciences Division, Mechanical Engineering Department, Building 520; qwalker@stanford.edu. Student Member AIAA.

†Postdoctoral Fellow, Thermosciences Division, Mechanical Engineering Department, Building 520; nicolas@navier.stanford.edu. Member AIAA.

‡Associate Professor, Thermosciences Division, Mechanical Engineering Department, Building 520; cap@stanford.edu. Member AIAA.

§Research Engineer, Spacecraft Propulsion Branch; william.hargus@edwards.af.mil. Senior Member AIAA.

¶Chief Scientist; schillin@spock.usc.edu. Member AIAA.

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.

Because 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 providing the needed electron current flow from its plume to neutralize a cluster of Hall thrusters. The performance advantage of an arcjet Hall thruster hybrid concept depends critically on the efficiency that can be achieved by the arcjet. Helium arcjets are capable of efficiencies greater than 60% because of the absence of frozen flow losses.[7] 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, if such high arcjet efficiencies are attainable.

As important, the preliminary performance estimates of the hybrid thruster concept assume that the arcjet and Hall thrusters operate without performance penalties when working together. It is known that each thruster exhibits instabilities that can impede performance when they are operated simultaneously. In this paper, we examine if there are any undesirable synergistic effects associated with the possible interactions of their dynamical behavior. When operating on helium, the two arcjets used in these studies were found to exhibit arc voltage fluctuations in the hundreds of kilohertz range and drifts in the average arc voltage over timescales of seconds (the latter, most likely caused by thermal instabilities). The Hall thruster employed also exhibited fluctuations in the 10–200-kHz region, which are attributed to circuit, ionization, and drift-type instabilities among others.[8] It is expected that an interaction between instabilities in either plasma source can occur. Furthermore, prior to our studies it was not known if (and how) the drawing large levels of electron current from the arcjet plume will compromise the performance of the arcjet itself. Reduced arcjet efficiency would result in lower cluster performance, making the concept less competitive with alternative propulsion packages.

As just mentioned, the development of this hybrid thruster concept around a helium arcjet 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 this paper we describe 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 higher-power studies. Proof-of-concept experiments were performed, first with surrogate anodes (which take the place of a Hall thruster anode, but do not require propellant flow) and a moderate-power arcjet and then with a single low-power (~300-W) Hall thruster, operating in tandem with a specially developed ultra-low-power (70–120-W) 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. We believe that this paper presents the first description of such a hybrid thruster package and the first comparison of the hybrid Hall thruster operating characteristics to that of the Hall thruster neutralized with a hollow cathode.

II. Experimental Setup

The nominally 1-kW arcjet thruster used to study the basic problem of current draw from arcjet plumes to a surrogate anode is a radiatively cooled, laboratory-type thruster designed and built at NASA Glenn Research Center.[9] (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.) This is the same thruster that has been extensively studied and characterized with various diagnostics while operating on helium and other propellants.[10–12] The tungsten nozzle has a 0.635-mm-diam throat and a conical diverging section with an area ratio of 225 (9.53-mm exit diameter).

A second, low-power (70–120-W) arcjet needed for the concept demonstration was specially designed and fabricated for these experiments. A schematic of the thruster is shown in Fig. 1. The nozzle is composed of tungsten with a 0.30-mm-diam throat, a conical diverging section with an area ratio of 286 (5-mm exit diameter), and diverging angle of 15 deg. 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.

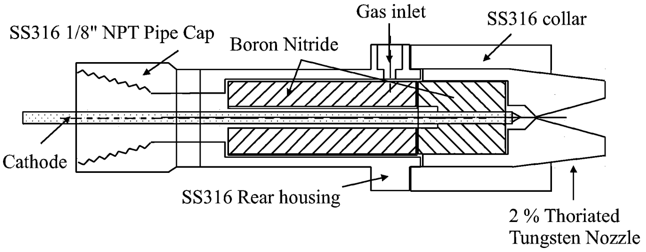

Fig. 1 Schematic of the low-power helium arcjet used in the neutralization studies.

The Hall thruster used in the demonstration experiments is of a conventional coaxial geometry consisting 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 and designed to operate in the 300–700-W range. It was initially developed to study the effects of varying channel geometry (width) on Hall thruster performance, with a peak magnetic field of about 150 G near the discharge exit. For comparison purposes, the Hall thruster was also operated with a commercial hollow cathode (Ion Tech HCN-252), with its body kept at the vacuum chamber ground potential.

The first experiments reported on next involve a series of studies aimed at determining the adverse effects, if any, that drawing substantial electron current from an arcjet plume can have on arcjet operation and/or 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-diam 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 was a 15-cm-diam circular copper plate, recessed into a boron nitride insulator, placed 15 cm from the center of the arcjet. An alumina ring secures the insulator and copper plate together. The surrogate anode is connected to a dc power supply capable of providing up to 20 A of current when biased to 300 V. The current drawn by the power supply is measured across a shunt resistor with a dc multimeter.

Impact Pressure Probe

The thrust of the 1-kW arcjet is measured with a cooled impact pressure probe with a capacitance manometer pressure sensor. Previous studies have shown that the thrust inferred by integrating the impact pressure profile across the exit region of the plume is in reasonable agreement (within 5%) with that measured with a thrust stand.[4] A detailed description of the probe, as used in studies of the same arcjet operating on hydrogen, is given in Ref. 12. Briefly, 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 water-cooling connections and placed on a multi-axis translation stage for translation across a fixed arcjet plume.

Hybrid Arcjet Hall Thruster Demonstration

Figure 2 shows the schematic of the setup of the hybrid arcjet Hall thruster demonstration. The anode of the arcjet was held at ground

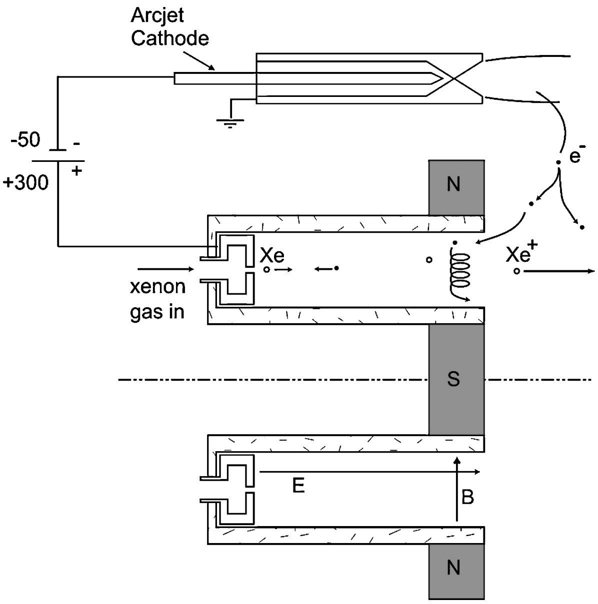

Fig. 2 Schematic of the hybrid arcjet Hall thruster.

potential while the cathode was biased negatively relative to ground. Within the vacuum chamber, the center-to-center distance between the arcjet and Hall thruster was 12 cm. The arcjet exit plane was parallel to the front plate of the Hall thruster, and no attempt was made to study the sensitivity of operation to this positioning, or to the relative jet angles. Separate power supplies were used to power the arcjet and the Hall thruster anode. The hybrid thruster demonstration was conducted in a 1-m-diam cylindrical nonmagnetic stainless steel chamber 1.5 m in length. Two 50-cm-diam elbow sections were attached on either end of the main section to support 50-cm diffusion pumps. The pumping speed of the test facility was 9000 l/s (on xenon). An ionization gauge was used to measure the pressure within the vacuum chamber during the experiments, and a thermocouple gauge was used to continually monitor the backing line pressure for the diffusion pumps.

III. Results and Analysis

The 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 3 depicts the measured variation in the extracted current from the helium arcjet plume vs the surrogate anode bias. In this experiment, the mass flow rate was fixed (36.2 mg/s) while the arcjet is operated at various arc discharge current levels ranging from 6–12 A. It is apparent that in almost all cases studied currents greater than the arc current itself (designated by the dashed horizontal lines) can be extracted from the arcjet plume. Specifically, the extracted electron current can be as large as 134% of the arc current. However, it is noteworthy that these appreciable currents are not extracted until the anode voltage is above 40 V. As the surrogate anode voltage is increased, the amount of extracted current is found to increase nearly exponentially between 40 and 50 V and then saturating at an anode bias between 50–60 V.

As shown in Fig. 4, the arc discharge voltage was found to generally decrease as the surrogate anode bias voltage was increased. Surprisingly, this resulted in a drop in the power dissipated in the arcjet, by as much as 50%. It appears that the application of an external bias on a surrogate anode serves to remove the voltage demand placed on the primary discharge to sustain the arc. Indeed, the power dissipated in the surrogate anode circuit makes up the difference between the arc discharge power without and with the applied bias. It is interesting, however, that at least in the highest arc currents studied the arcjet first responds with an increase in discharge. The reason for this increase, which is persistent only for the highest arc current cases, is not yet understood.

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	8.3
27	−32	7.6

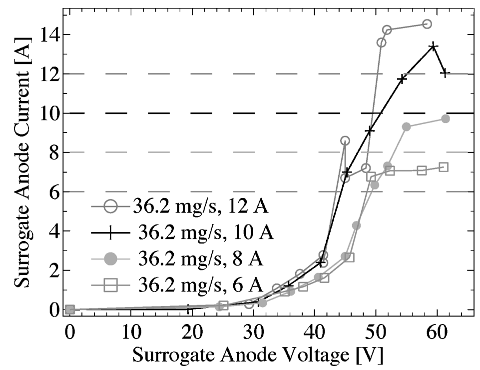

Fig. 3 Helium arcjet neutralization current provided as the surrogate anode voltage increases.

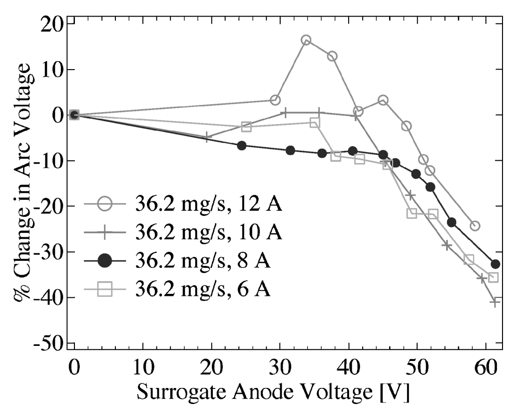

Fig. 4 Helium arcjet voltage change as the surrogate anode voltage increases.

Although the precise source of the extracted current is difficult to identify, its origin is attributed to a combination of 1) the arcjet cathode, 2) the arcjet anode (note that it is grounded, and so it can provide current to a positively biased anode), or 3) the plasma jet itself, through volume ionization. The decreasing arc voltage at a constant arc current suggests that the plasma conductivity is increasing with increased levels of anode bias, possibly because of increased temperature and hence ionization in the plume. This increase in volume ionization acts as an electron current multiplier to levels substantially beyond those needed to sustain the primary discharge.

In another set of experiments, the arcjet current was maintained at a fixed level of 6 A while the helium mass flow rate was varied. Table 1 presents the results of these limited studies, illustrating the resulting change in the arc voltage and the maximum amount of current drawn to the anode. The maximum extracted current was found to decrease with increasing mass flow rate.

It is apparent that the moderate-power (∼500-W) helium arcjet used here can provide the currents needed to neutralize a high-power (5-kW, typically 12–15-A) Hall thruster and, quite possibly, a cluster of four or five low-power (1-kW, typically 3-A) clusters. However, as already mentioned, the arc voltage instabilities occur near the same range in frequency as instabilities that are known to persist in typical Hall thrusters. Furthermore, the performance of the arcjet can be adversely affected by the action of extracting current from its plume. In the following sections, we address these two issues by further experimental investigations.

The 1-kW Arcjet Voltage Fluctuations

Previous studies of arcjets operating on helium noted that the arc voltage fluctuation is somewhat higher than that seen in comparable thrusters operating on hydrogen.[7] In this study, the arc voltage was monitored with a Tektronix P5200 high-voltage differential probe and acquired into a DAQ5120 data acquisition card in a laboratory computer. We examined fluctuations in frequencies as high as 10 MHz and compared them to those seen in the same thruster operated on hydrogen. Figure 5 shows part of the spectral amplitude (logarithmic scale) of the voltage 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. Under these conditions, the specific power is comparable, as the hydrogen arc voltage is 150 V and the helium arc voltage is near 65 V. When operating on helium, the arcjet voltage spectrum shows a distinct feature near 120 kHz with an apparent harmonic near 240 kHz. The hydrogen arcjet exhibits a single broad feature near 300 kHz, which is much weaker in amplitude, than the features seen with hydrogen. At the higher frequencies (not shown in the figure), helium operation results in a broadband feature centered near 2 MHz that is not present when operating on hydrogen. When operating on helium, the arcjet voltage drifts by as much as 10% over the course of minutes, which we attribute to thermal instabilities associated with the electrode arc attachment.

The discharge voltage fluctuations changed somewhat when the arcjet provided electron current to the surrogate anode. With hydrogen, the low-frequency fluctuations below 300 kHz increased slightly in strength, with no substantial differences seen at the higher frequencies. The changes in the spectra for the case of helium were somewhat more dramatic, as seen in Fig. 6. For the case shown, the arc current is 10 A, and the surrogate anode current is 13 A. Surprisingly, the intensity of the fluctuations decreased across the entire spectrum from 5 MHz to almost near dc, although there is the emergence of a weak feature at about 450 kHz.

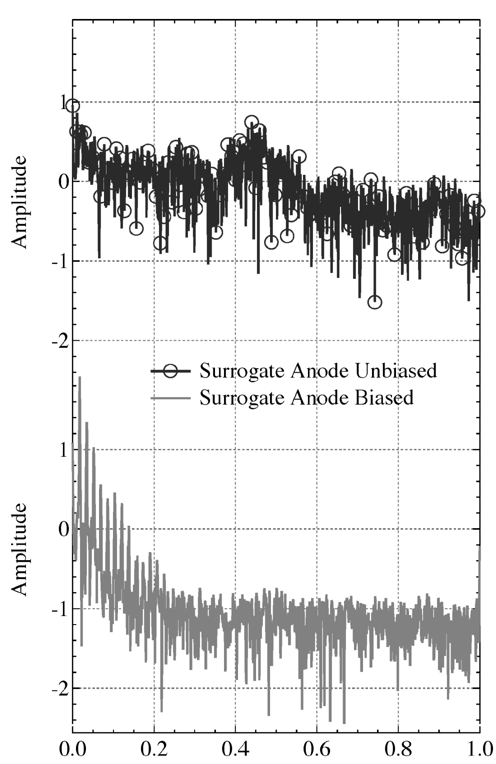

Fig. 5 Comparison of the arc voltage power spectra for the hydrogen (13.7-mg/s, 10-A) and helium (36.2-mg/s, 10-A) 1-kW arcjets.

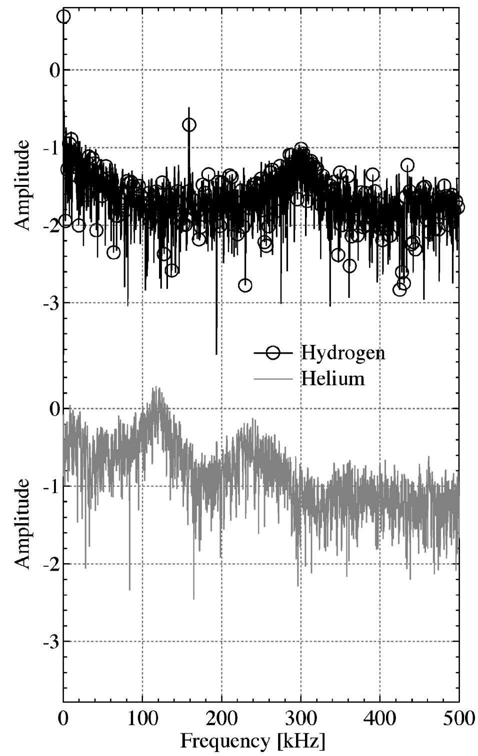

Fig. 6 Helium arc voltage fluctuations with and without the surrogate anode biased to draw 13 A. In both cases, the arc discharge current is 10 A.

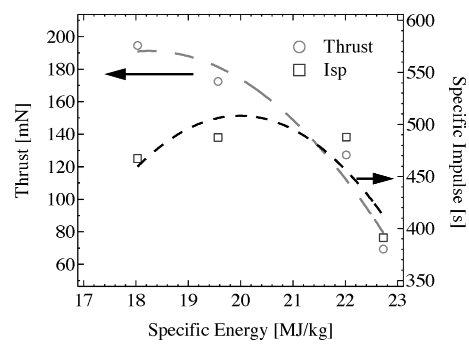

Fig. 7 Thrust and specific impulse for the 1-kW helium arcjet with a current of 10 A and various mass flow rates.

Impact Pressure Measurements

In addition to monitoring changes in the fluctuating nature of this arcjet undergoing electron supply to the surrogate anode, we also monitored performance changes as inferred from impact pressure probe measurements of the momentum flux of the jet. Figures 7 and 8 show the measured variation in the thrust, specific impulse, and thrust efficiency at 10-A discharge current with varying helium mass flow rate (no bias on the surrogate anode). As expected, the thrust increased with the increase in mass flow rate, with the specific impulse and thrust efficiency exhibiting a maximum at a specific energy of 20 MJ/kg. The same measurement was conducted with the surrogate anode biased. Table 2 shows the results with the arcjet current at 10 A and helium flow rates of 27 and 36.2 mg/s. The striking result is that the thrust does not change significantly when current is extracted from the arcjet, even though the arc voltage drops slightly (10–15%). The differences between the measurements are within the uncertainty of the measurement, that is, ± 6 mN.

Some comments on the intrusive nature of this impact probe during collection to the surrogate anode are warranted. The copper impact probe was grounded during the scans and was found to noticeably disrupt the current extraction from the arcjet when the probe came very close to the center of the arcjet plume (within ~ 1 mm).

Table 2 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	460
36.2	55	10	50	13	157	445
27	55	10	0	0	122	460
27	49	10	50	13	124	470

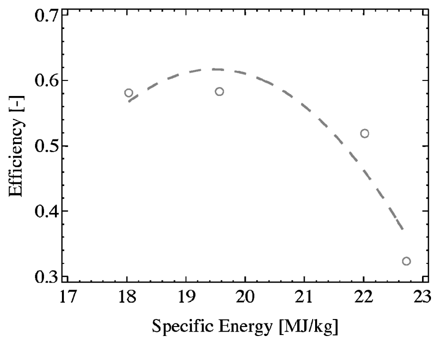

Fig. 8 Thrust efficiency of the helium arcjet with a current of 10 A and various mass flow rates.

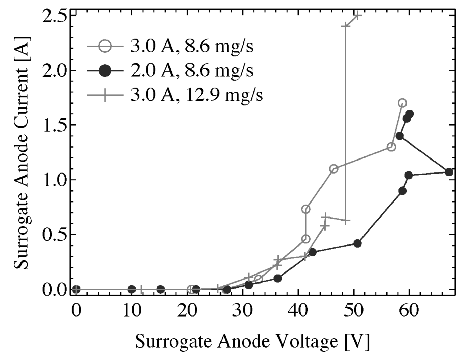

Fig. 9 Neutralization current provided by the low-power helium arcjet.

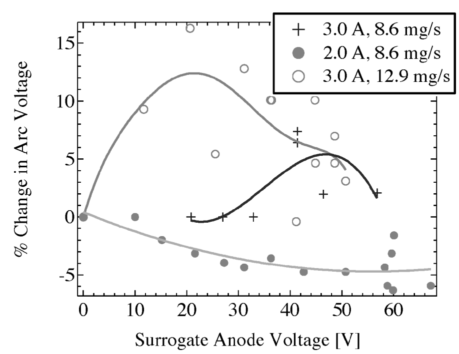

Fig. 10 Low-power arcjet voltage change as the surrogate anode voltage increases.

The interference of the probe led to as much as a 10-A drop in the surrogate anode current. We suspect that the drop in current is a result of the shadowing of the available plasma area from which current can be drawn by the water-cooled probe. The impact that this interference has on the overall thrust determination is not significant, however, because the pressure is integrated across the exit plane to derive the overall thrust, and the pressure near the periphery of the arcjet nozzle radius is more heavily weighted than the pressure near the center. Preliminary nonintrusive measurements of arcjet velocity using laser-induced fluorescence[10] also indicate that the perturbation on the flow by the drawn current is not significant, in agreement with these probe measurements.

Low-Power Arcjet Surrogate Anode

The results obtained with the higher power (1-kW) thruster demonstrated that the arcjet could be used as a source of substantial electron current, without significant degradation in its performance. A natural extension of these experiments would be a lab demonstration of the hybrid thruster concept. As already mentioned, one of the biggest obstacles in carrying out such a demonstration is finding a ground-test facility that is capable of simultaneously supporting the operation of both thrusters. To partially circumvent this challenge, we built a very low-power arcjet that operates at significantly lower mass flow rates (<10 mg/s) permitting simultaneous operation with a Hall thruster within one of our vacuum chambers. Prior to carrying out demonstrations with this low-power arcjet, we subjected it to similar surrogate anode tests to those just described.

Figures 9 and 10 depict the variation in the extracted current and change in arc voltage, respectively, with varied bias on the surrogate anode. In these experiments, the arc discharge current was either 3 or 2 A with a mass flow rate of either 12.9 or 8.6 mg/s. In contrast to the results of the 1-kW arcjet, maximum extracted currents were generally less than the arc, ranging from 75–85% of the arc discharge current. Just as with the 1-kW arcjet, appreciable currents are not extracted until the anode voltage is above 40 V. As seen in Fig. 10, the concomitant decrease in the arc voltage is also not so severe. Whereas the 1-kW arcjet arc discharge voltage decreased up to 40%, the low-power arcjet voltage decreased by only about 7%, with increases in some cases well above those seen at the higher power case, for an arc discharge current of 3 A.

Hybrid Arcjet Hall Thruster Demonstration

Because of the limited pumping speed of the ground-test facility, the demonstration of the hybrid thruster concept was carried out at a chamber pressure that was higher than the level necessary for unambiguous evaluation of thruster performance. With a xenon flow of 2 mg/s through the Hall anode and 0.3 mg/s through the hollow cathode and without the flow of helium through the arcjet, the chamber pressure measured at the wall of the vacuum tank (using a xenon-corrected ion gauge) was 6×10^{-4} torr. With an additional helium mass flow rate of 4.5 mg/s, the ion gauge remained at 6×10^{-4} torr, whereas with a flow rate of 8.6 mg/s the reading increased substantially to 2.4×10^{-3} torr. Although these pressures might be too high to obtain reliable thrust data, they are sufficiently low to examine, at least qualitatively, interactions between the Hall thruster and arcjet in this hybrid package.

To isolate possible chamber pressure effects on the Hall discharge operation, current–voltage I-V characteristics were recorded of the Hall thruster operating with the external hollow cathode and with a nominal flow of helium introduced into the arcjet (without the arcjet ignited). These I-V traces are presented in Fig. 11. A lower helium mass flow rate of 4.5 mg/s did not appear to significantly affect the I-V characteristics at voltages below about 200 V. However, the addition of even this small amount of helium did virtually eliminate the persistence of the strong jump at high discharge voltage, the origin of which is still the subject of debate. It is apparent that at the higher helium mass flow rate of 8.6 mg/s the Hall discharge current departs significantly from that taken in the absence of helium within the chamber. In fact, when operating at above 210 V a glow discharge appeared behind the Hall thruster rendering high voltage data to be unreliable.

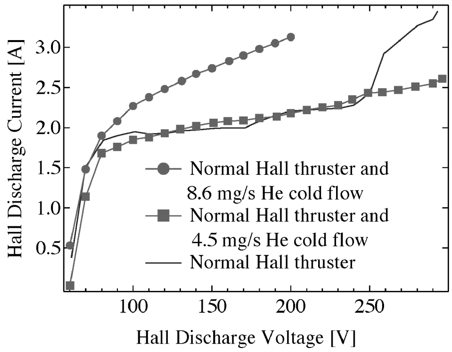

Fig. 11 Comparison of the Hall thruster I-V curves for different helium flow rates into the vacuum chamber. The normal Hall thruster refers to the Hall thruster neutralized with the hollow cathode.

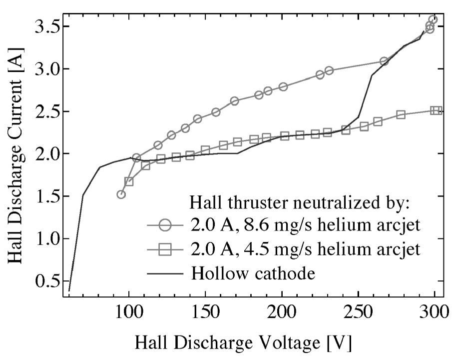

Fig. 12 Comparison of the I-V curves for the hybrid and hollow cathode neutralized Hall thrusters.

Although the changes in I-V characteristics are undoubtedly caused by the ingested helium, these results cannot conclusively separate the effects associated with either ground-test pumping imitations or with the underexpanded arcjet plume. Even in the presence of the high vacuum of space, the arcjet plume will have a significant particle density within the near field and will lead to the possible ingestion of helium by the Hall thruster cluster. Only further experiments carried out under much higher vacuum conditions will resolve these important issues.

Figure 12 compares the I-V characteristics of the hybrid-operating mode to the Hall thruster neutralized with a hollow cathode. Note that in the hybrid thruster the hollow cathode is not used at all, and there is neither power nor mass flow through it. A striking feature of the hybrid operation is that the ionization branch—that is, the low-voltage region of the I-V curve where current rises sharply with increases in voltage—is shifted to higher voltage values. As seen in the cold helium flow case, the hybrid discharge does not display the voltage jump at above 250 V. Also, compared to the Hall thruster operating with the hollow cathode and 4.5 and 8.6 mg/s of cold helium, the I-V curves are shifted to the right, that is, they operate at a consistently lower discharge current at a given voltage.

The surrogate anode tests attempted to determine the maximum current that could be extracted from the arcjet plume. According to the results just shown, only 1.5 A of current could be drawn from the low-power arcjet plume with an arc discharge current of 2.0 A and a helium mass flow rate of 8.6 mg/s. Surprisingly, in the hybrid configuration with the same arc discharge current and mass flow rate the arcjet plume was able to provide the electron current to support a Hall discharge requiring 3.5 A! This suggests that the surrogate anode tests provided a highly conservative lower bound and that under actual neutralization environments a substantially greater (by at least a factor of 2) neutralization current can be expected.

To determine limits to how much electron current can be extracted from the arcjet plume, the arc discharge current was decreased at a fixed arcjet mass flow rate until the arcjet was no longer able to support the current demanded by the Hall thruster (followed by the extinguishing of the discharge). Figures 13–15 illustrate graphically the resulting changes in the arc voltage with changing arc current for three combinations of helium mass flow rate and Hall discharge current. It is noteworthy (not illustrated in the figures) that in almost all cases the arc discharge voltage decreased immediately following the initiation of the Hall discharge. As shown in Fig. 13, with the voltage of the Hall thruster regulated to 115 V and with initially 2 A of arc current and 8.6 mg/s of helium through the arcjet, the Hall discharge current established was about 2 A. At an arc current of 1.5 A, a maximum of 133% of the arc discharge current could be extracted from the arcjet plume. In Fig. 14, the Hall discharge voltage is set to 300 V, and with initially 2-A, 8.6-mg/s arcjet the Hall discharge current is 3.1 A. Up to 181% of the arc current was extracted at a limiting arc discharge current of 1.1 A. Figure 15 is similar to that of Fig. 14, except at a lower flow rate of 4.5 mg/s. The Hall discharge was 2.5 A, and the maximum extracted current was 133% of the arc discharge current. When the arcjet plume could not provide the neutralizing and Hall discharge current needed, the Hall thruster would shut off, the arcjet would remain operational, and the arc discharge voltage would suddenly increase slightly. In all cases the low-power arcjet could provide much more current than anticipated by results of the surrogate anode studies.

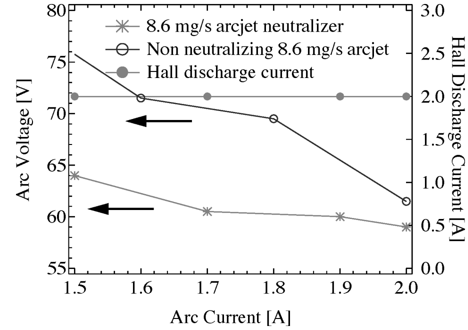

Fig. 13 Low-power arcjet (8.6-mg/s mass flow rate) I-V curve while neutralizing the Hall thruster (2 A, 115 V).

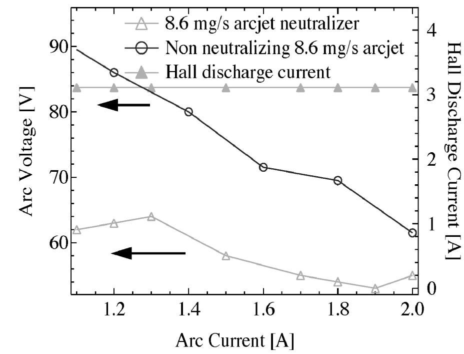

Fig. 14 Low-power arcjet (8.6-mg/s mass flow rate) I-V curve while neutralizing the Hall thruster (3.1 A, 300 V).

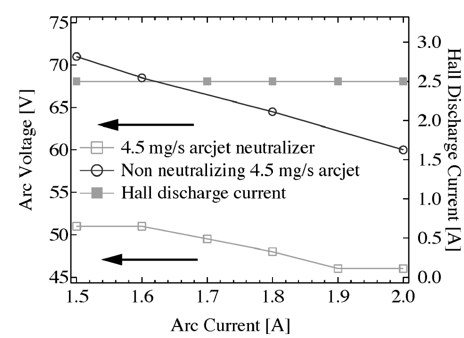

Fig. 15 Low-power arcjet (4.5-mg/s mass flow rate) I-V curve while neutralizing the Hall thruster (2.52 A, 301 V).

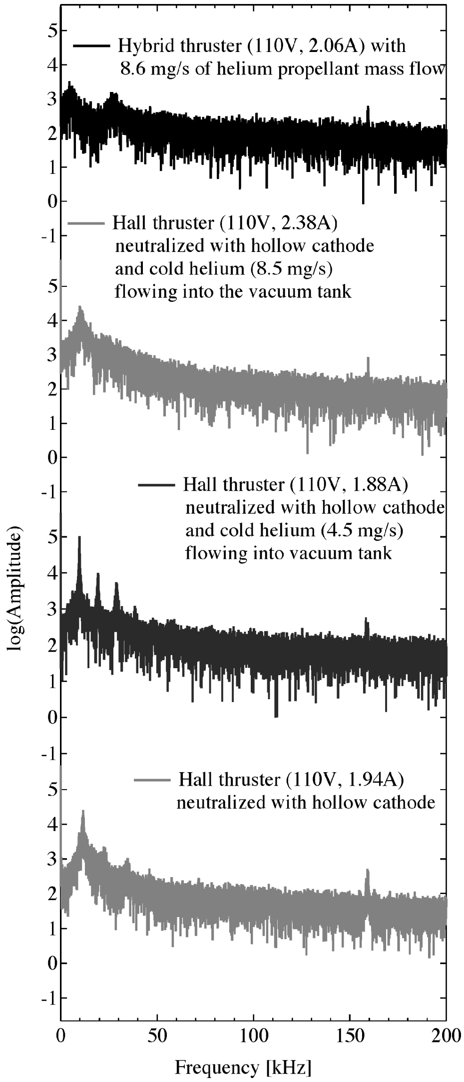

Fig. 16 Comparison of Hall discharge current fluctuations with a Hall discharge voltage of 110 V.

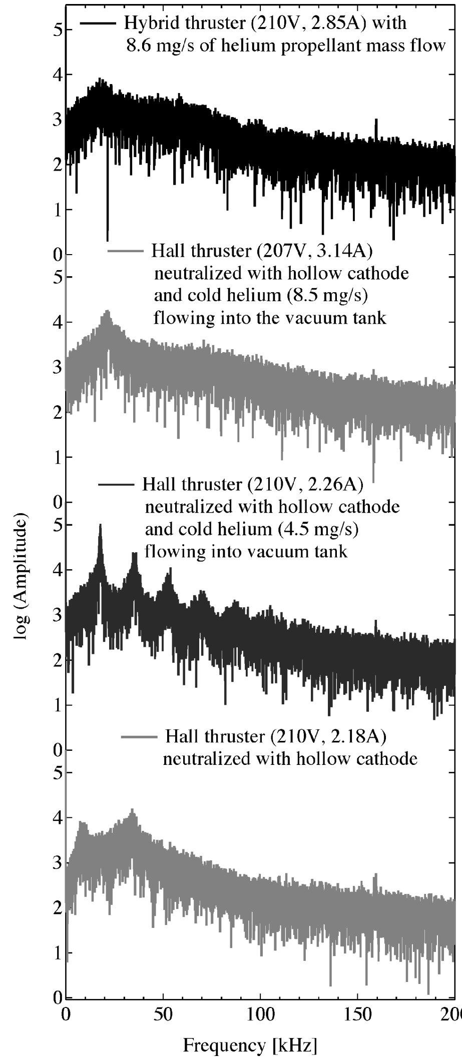

Fig. 17 Comparison of Hall discharge current fluctuations with a Hall discharge voltage of 210 V.

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. Figures 16 and 17 show the amplitude of Hall discharge current oscillations for a range of up to 200 kHz in frequency, for a Hall discharge voltage of 110 and 210 V, respectively. At the lower voltage (Fig. 17), the Hall thruster neutralized with the hollow cathode shows a characteristic feature often attributed to the so-called "breathing mode" near 11.6 kHz and its associated harmonics. At the higher voltage, this breathing mode shifts to higher frequency (34 kHz), and a second, weaker mode emerges near 7.3 kHz. This lower-frequency mode is the subject of much debate and is perhaps associated with tilted ionization "spokes"[8] and/or interactions with the external discharge circuit (so-called "loop" instability). The addition of small amounts of cold helium to the vacuum chamber (4.5 mg/s) appears to lead to a shift in the breathing mode frequency and to a dramatic increase in the fluctuation intensity—so much so that harmonics can be seen at frequencies as high as 100 kHz or higher. The current oscillations were found to be nearly sinusoidal at 110 V, whereas the thruster was operating in a pulsed mode at 210 V. At 8.5 mg/s, of cold helium, the overall intensity of these oscillations increased slightly, but the pulsed nature of the oscillations at 210 V diminished. The dominant instability still attributed to the breathing mode shifted to 9 and 21 kHz for the 110 and 210 V cases, respectively, with no harmonics present. With the arcjet ignited at 8.5 mg/s and operated in the hybrid mode, the Hall thruster oscillations were even further reduced in intensity, with only minor differences seen in the spectra, in comparison to that of the Hall thruster and 8.5 mg/s of cold helium introduced into the chamber. Although this study of the fluctuations in the hybrid mode is by no means exhaustive, it does indicate that there should be no obvious adverse interactions encountered in ground tests with improved vacuum that would prevent the operation of the Hall thruster in this hybrid configuration.

IV. Conclusions

The results presented here, together with those of its companion paper,[6] provide support for the continued development of helium arcjet sources as potential 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 with other propulsion options. This study demonstrated that substantial current can be drawn from an arcjet thruster plume, estimated the impact that drawing current can have on the operation and performance of the arcjet thruster, and demonstrated the feasibility of using an arcjet thruster plume to neutralize a Hall thruster. In the companion paper of Hargus et al.,[6] it seems that the hybrid thruster system has a limited, but very useful capability for orbit transfers early in mission timelines. This limitation is because of 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.

Studies carried out with a surrogate anode and with a nominally 1-kW helium arcjet demonstrated that arcjets could provide the necessary neutralization current for a cluster that is operating at about five times the arcjet power, with only a minor effect on arcjet performance, even though there is a noticeable effect on arcjet voltage. At the extracted current saturation limit (typically 120% of arc discharge current), there is a 40 to 30% decrease in 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. Similar surrogate anode studies on an even lower-power arcjet, specially designed for the hybrid demonstration experiments, showed similar results, although the ratio of extracted current/discharge current were not as high as those seen in the 1-kW arcjet case.

Surprisingly, in the concept demonstrations carried out with the low-power arcjet the plume provided more current than expected on the basis of the surrogate anode studies. In the hybrid concept demonstration, up to 181% of the arc discharge current was extracted from the arcjet plume to service the Hall discharge and beam neutralization. If we use a ratio of 2 for the extracted to arc discharge current to guide our high-power Hall cluster design, we could anticipate that about 1 kW (15 A, 63 V) of helium arcjet power could service a 10-kW (30-A, 333-V) Hall thruster cluster.

The operation of the Hall thruster in the hybrid configuration exposed it to relatively high chamber pressures ($\sim 10^{-3}$ torr). Noticeable departures from the usual Hall thruster I-V characteristics were apparent, not just in the hybrid-thruster mode, but also when the Hall discharge was operated in the usual mode with an external hollow cathode and when the helium is introduced through through unignited arcjet. At this point, it is difficult to determine how such helium in the near field will affect the operation of this hybrid thruster because the impact of ground-test limitations is difficult to quantify. Future experiments should include studies to assess these facilities affects in larger chambers capable of supporting lower background pressures during thruster operation.

Acknowledgments

The work at Stanford University is supported by the U.S. Air Force Office of Scientific Research. The authors are grateful to the NASA Glenn Research Center On-Board Propulsion Branch for originally providing the 1-kW arcjet and components.

References

[1] Janson, S. W., "The On-Orbit Role of Electric Propulsion," AIAA Paper 93-2220, June 1993.

[2] *1998 Strategic Master Plan*, Air Force Space Command, Dept. of the Air Force, Los Angeles AFB, CA, 1998.

[3] Spanjers, G. G., Birkan, M., and Lawrence, T. J., "The USAF Electric Propulsion Research Program," AIAA Paper 2000-3146, July 2000.

[4] Walker, Q. E., and Cappelli, M. A., "High Density Plasma Neutralization of a Hall Thruster," AIAA Paper 2001-3352, July 2001.

[5] Walker, Q. E, Gascon, N., Cappelli, M. A., Hargus, W. A., Jr., and Schilling, J. A., "Preliminary Study of Arcjet Neutralization of Hall Thruster Clusters," International Electric Propulsion Conf., Paper IEPC-01-63, Oct. 2001.

[6] Hargus, W. A., Jr., Schilling, J. A., Walker, Q. E., and Cappelli, M. A., "Arcjet Plasma Neutralization of Hall Thrusters Part 1: Hybrid Thruster Mission Analysis," *Journal of Spacecraft and Rockets*, Vol. 41, No. 6, 2004, pp. 1016–1022.

[7] Welle, R. P., Pollard, J. E., and Janson, S. W., "One Kilowatt Hydrogen and Helium Arcjet Performance," Aerospace Corp., ATR-91(8443)-2, Los Angeles, April 1993.

[8] Choueiri, E. Y., "Plasma Oscillations in Hall Thrusters," *Physics of Plasmas*, Vol. 8, No. 4, 2001, pp. 1411–1426.

[9] Haag, T., and Curran, F. W., "Arcjet Starting Reliability: A Multistart Test on Hydrogen/Nitrogen Mixtures," *Journal of Spacecraft and Rockets*, Vol. 29, No. 4, 1992, p. 444.

[10] Walker, Q. E., and Cappelli, M. A., "Laser-Induced Fluorescence Measurements of a Helium Arcjet Flow," AIAA Paper 99-3603, July 1999.

[11] Storm, P. V., and Cappelli, M. A., "Laser-Induced Fluorescence Measurements Within an Arcjet Thruster Nozzle," AIAA Paper 95-2381, June 1996.

[12] Hargus, W. A., Jr., and Cappelli, M. A., "The Structure of an Expanding Hydrogen Arcjet Plasma," *Physics of Plasmas*, Vol. 5, No. 12, 1998, pp. 4488–4497.

I. Boyd
Associate Editor