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John E. Foster, Michael Patterson, Eric Pencil, Heather McEwen, and Esther Diaz
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Abstract

Neutralizers in a multi-thruster array configuration were characterized using conventional diagnostics such as peak-to-peak keeper oscillation amplitude as well as unconventional methods which featured the application of electrostatic probes. The response of the array local plasma environment to neutralizer flow rate changes were documented using Langmuir probes and retarding potential analyzers. Such characterization is necessary for system efficiency and stability optimization. Because the local plasma environment was measured in conjunction with the neutralizer characterization, particle fluxes at the array and thus array lifetime impacts associated with neutralizer operating mode could also be investigated. Neutralizer operating condition was documented for a number of multithruster array configurations ranging from three-engines, three-neutralizers to a single engine, one-neutralizer all as a function of neutralizer flow rate.

I. Introduction

Neutralizer performance and lifetime are intimately connected to neutralizer gas flow rate (ref. 1). Minimizing neutralizer flow rate to values as low as practically achievable can lead to thruster total efficiency improvements as well as reduce the total propellant required for a given mission (refs. 2 to 4). The minimization of neutralizer flow rate for system performance gain must be tempered with lifetime considerations. Normally, this usually translates into operating the neutralizer at flow rates above the threshold of the spot-to-plume mode onset. The hollow cathode spot mode is a quiet, low voltage discharge condition characterized by the presence of a luminous "spot" of intense ionization and excitation in the orifice of the cathode. Plume mode operation is associated with the presence of a luminous plume emanating from the hollow cathode and projecting downstream. The luminous plume is produced by energetic electrons exciting gas escaping the cathode orifice. This discharge mode is electrically noisy and associated with higher keeper voltages. The plume mode typically arises at fixed emission current as the flow rate is reduced below a threshold value. Operation in the plume mode state can give rise to neutralizer cathode erosion (ref. 5). The relative distance between this threshold flow rate and the actual operating condition is referred to as flow margin (refs. 6 and 7). Estimating the magnitude of neutralizer flow margin requires knowledge of the evolution of the neutralizer operation over time. As a neutralizer undergoes normal wear over time, the minimum flow rate required for the onset of plume mode operation can increase (ref. 8). The nominal operating flow rate that is usually selected is the sum of the flow rate at the threshold of spot-to-plume mode transition and the margin necessary to allow the neutralizer to operate over the duration of the mission in a quiescent state. It follows then that determination of this transition flow that leads to plume mode operation is important. This determination process is known as neutralizer characterization.

A number of different diagnostics have been used to characterize the neutralizer. By far, the most common has been the examination of the magnitude of the peak-to-peak oscillation on the neutralizer keeper voltage (refs. 6, 8, and 9). Here, the transition from spot mode to plume mode has been previously defined as the condition in which the peak-to-peak keeper voltage oscillation has reached 5 V (ref. 9). Keeper voltage variations have also been used to a limited degree (ref. 5). Changes in the neutralizer coupling voltage have also been used as a transition indicator (ref. 6). These diagnostic approaches are not direct measurements of changes in the plasma conditions at the neutralizer that ultimately lead to the spot-to-plume transition. Instead, they are indirect measurements whose functional behavior in part depends on the response of the power supply to changes in the plasma load. This power supply response may or may not be linear. The most direct way to access the state of the neutralizer plasma and thus the operating state of the neutralizer is to actually probe the neutralizer plasma using electrostatic plasma probes (ref. 6). In this respect, the probe response is a direct measure of changes occurring at the neutralizer.

The approach of using electrostatic probes to characterize neutralizer operating condition was successfully applied to the NASA's Evolutionary Ion Thruster (NEXT) and the High Power Electric Propulsion thruster (HiPEP) (refs. 6 and 10). The approach of using electrostatic probes to characterize hollow cathode transition from spot-to-plume mode was validated in the late 60s (refs. 11 to 13). This work coupled with more recent application of electrostatic probes such as retarding potential analyzers (RPAs) on the Deep Space spacecraft to monitor neutralizer operating mode changes motivated the application of this diagnostic in addition to Langmuir probes for the evaluation of the neutralizer flow margin for the NEXT multi-thruster array (refs. 5 and 6).

Thruster array performance can be optimized by minimizing neutralizer flow rate to individual neutralizers or by reducing the number of neutralizers active during engine operation. Because each neutralizer has the capacity to supply significantly more current than that which is associated with the ion beam, operation of multiple thrusters with a reduced neutralizer count is possible (ref. 14). Indeed, the use a of a single neutralizer to neutralize multiple beams has been demonstrated in the past with no detrimental effects on array operation (refs. 13 and 14). The impact of such operation on neutralizer lifetime due to higher emitter temperatures associated with higher current operation, however, was not assessed. Because plasma conditions within the neutralizer at a fixed flow rate will change if its emission current doubles or triples, for example, the flow margin for a neutralizer neutralizing multiple beams is expected to change with neutralizer configuration. Additionally, even with n-neutralizers neutralizing n-ion beams, where n is the number of thrusters in the array, the effective conductivity of the plasma bridge can be expected to change due to the presence of increased charge exchange ions (CEX) and an elevated background plasma density associated with simultaneous operation of the thrusters. Characteristics of the background plasma should change with power level as well. Such effects have been documented in the past (ref. 15). Depending on the capabilities of the vacuum system, the elevated background plasma due to inadequate pumping speed could potentially obscure the actual transition point leading to uncertainty in the estimated neutralizer margin. It is expected that background plasma levels have a first order impact on macroscopic parameters such as keeper voltage and keeper oscillating voltage magnitude. This is due the presence of charge carriers that can significantly affect impedance. All of these effects affect neutralizer operation as well as potentially neutralizer flow rate margin. Because the neutralizers contribute to the background plasma character, probe measurements of this plasma are expected to reflect neutralizer operating condition. In this regard, measurements in the general vicinity of the neutralizer and those made in the near field plume should reflect the neutralizer operating condition.

Using Langmuir, RPA, and voltage probe diagnostics, the neutralizer was characterized as a function of flow to elucidate the effect such flow rate changes have on neutralizer flow margin and on the near field multi-thruster array plasma.

II. Experiment Configuration

Multi-thruster array testing took place in the NASA Glenn Vacuum Facility 6 (VF6) space simulation chamber. This vacuum facility measures 22.9 m long and 7.6 m in diameter. After the facility is roughed down using three mechanical pumps and four root blowers (10^{-3} Torr), the background pressure is reduced to base pressure through the operation of twelve cryopumps. On xenon, the pumping speed of the facility is approximately 400,000 l/s. The zero load base pressure was approximately 1×10^{-7} Torr.

The thruster array, shown in figure 1, consisted of 3 active NEXT, engineering model (EM) ion thrusters along with an inactive engine that served as the array "flight spare" (ref. 16). This arrangement, shown in figure 1, constituted the so-called "3+1" configuration. EM1 and EM5 featured 40 cm diameter ion optics, whereas EM4's optics were masked down to 36 cm. The array was operated at power levels ranging from 1.1 kW (one thruster active)to 20.4 kW (3 thrusters at full power, 6.8 kW each). Additional details on the array and the array engineering demonstration test may be found in reference 16.

Integrated onboard the multithruster array was a number of electrostatic probes as indicated in figure 1. A number of these probes were utilized in this investigation. Located atop each neutralizer was a planar, molybdenum 6.37 mm diameter Langmuir probe (LP). These probes are labeled LP2, LP3, LP4, and LP5. Co-located with the Langmuir probes at the neutralizers of EM1 and EM2 were also retarding potential analyzers (RPAs). These probes, RPA4 and RPA5, feature 3 grids and a collector electrode. Also used in this investigation were two planar Langmuir probes (11.2 mm in diameter) and two RPAs located between EM1 and EM4 (LP6, RPA3), and between EM2 and EM5 (LP7, RPA2), respectively. Additionally, a centrally located Langmuir probe and RPA were located on the biasable accelerator grid of dormant thruster EM2 (LP1 and RPA1). This collection of probes was used to characterize not only the local plasma response to neutralizer flow rate changes but also to detect global plasma changes remote to the neutralizer brought on by changes in the operating mode of the neutralizer.

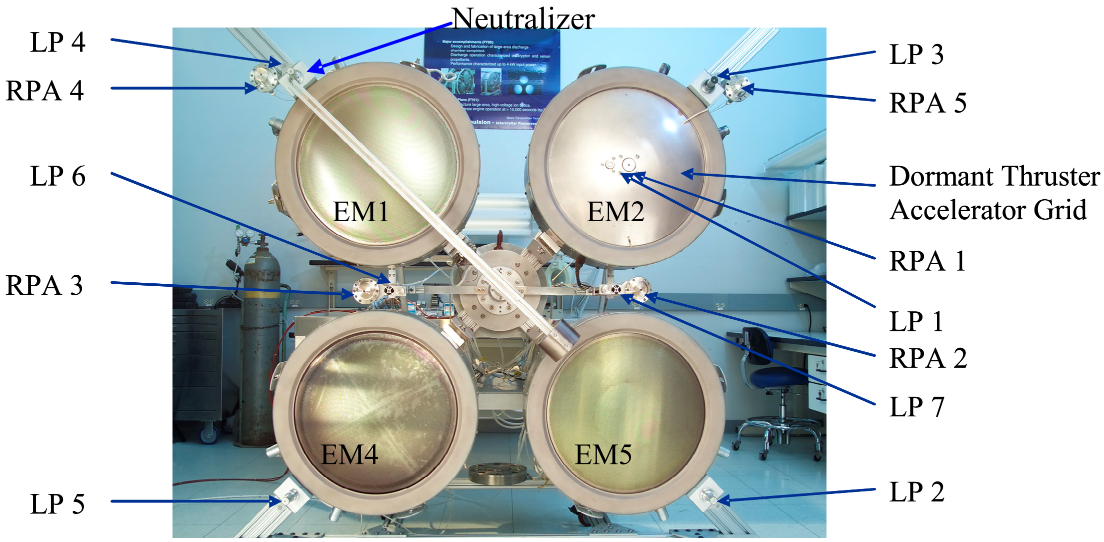

Figure 1.—Schematic of diagnostics used during the multi thruster array test. Labeled electrostatic probes were used to monitor variations in the plasma properties in response to neutralizer flow rate changes.

From the Langmuir probe current-voltage (IV) characteristic, electron temperature, electron number density and plasma potential were extracted. Thin sheath theory was used in the Langmuir probe analysis (ref. 17). This approach is justified provided the sheath thickness is small compared with the probe's radius. This requirement assures a nearly planar sheath at the probe thereby avoiding orbital effects. In most cases, (intermediate through full power) this condition was well satisfied. The analysis of the I-V characteristics required first locating the plasma potential. The plasma potential was obtained by using the zero crossing point of the I-V characteristic (ref. 18). In cases where this function was not readily interpretable (low signal to noise), the plasma potential was selected from the knee of a logarithmic plot of the I-V characteristic. Probe data presented herein is of electron temperature variations with neutralizer flow rate. The uncertainty of this measurement was approximately 25 percent. The RPA was used to obtain the average energy and spread in energy of ions falling back onto the array. Here the energy distribution is obtained by taking the derivative of the ion current relative to the ion retarding grid (ref. 19):

$$f(E) \propto -\frac{dI_c}{dV_{ir}} \tag{1}$$

Here, I_c is the collector current, V_{ir} is the bias voltage on the ion repeller grid, E is the ion energy, and $f(E)$ is the ion energy distribution function. The entrance grid was grounded. The second grid, the ion repeller grid, was ramped from approximately 0 to 10 V. In almost all cases, the current signal measured at the collector electrode, which was biased at –35 V, went to zero well before reaching the 10 V on the ion repeller grid. In this respect, ions incident onto the array were low energy. The third grid, the secondary electron suppression grid was biased at –25 V. In this work, the I-V characteristic acquired from the RPA is presented as a function of neutralizer flow rate. The location of the "knee" in the acquired I-V characteristic indicates the position of the most probable ion energy. The shifts ion energy with operating condition can therefore be measured by tracking the shifts in the "knee" of the I-V curve.

Neutralizer characterization was carried out by acquiring keeper voltage data and electrostatic probe I-V characteristics as the flow rate of the neutralizer was varied. The neutralizer flow rate was typically varied from 6 standard cubic centimeters per minute (sccm) down to 2.5 sccm. Data was not acquired until the neutralizer flow rate stabilized at each set point (~10 min.). This stabilization time was in part related to the gas feed system response time associated with gas tubing length. The data acquisition process was completely automated. Langmuir probe IV characteristics were obtained using a commercially available probe driver and software. The RPA ion repeller grid voltage was varied using a high precision voltage source. Ion current to the collector of the RPA was measured using a precision pico-electrometer.

The sections that follow present the response of the aforementioned diagnostics to neutralizer flow rate changes for a number of different thruster array operating modes. These operating conditions are summarized in table I.

TABLE I.—INTERROGATED OPERATING CONDITIONS

Configuration	Thruster	Pressure, torr	Input power, kW	Beam voltage, V	Accelerator voltage, V	Beam voltage, A	Accelerator current, mA	Coupling voltage, V	Keeper voltage, V	Neutralizer flow rate, sccm
3 engines, full power, 3 neutralizers	EM1	2.86×10^{-6}	6.821	1791	–210	3.55	18.2	–10.2	11.2	4.0
	EM4	2.86×10^{-6}	6.87	1789	–209	3.53	18.9	–10.7	12.4	4.0
	EM5	2.86×10^{-6}	6.85	1790	–210	3.53	22.2	–10.3	12.2	4.0
2 engines, two neutralizers, low power	EM1	8.16×10^{-7}	1.13	670	–115	1.21	3.7	–8.8	15.6	3.0
	EM5	8.16×10^{-7}	1.09	670	–115	1.20	3.9	–9.3	15.1	3.0
2 engines, one neutralizer, low power	EM1	7.47×10^{-7}	1.11	669	–115	1.20	3.9	–10.3	12.9	3.0
	EM5	7.47×10^{-7}	1.05	669	–115	1.20	3.4	–10.2	NC	0
1 engine (EM5) low power with a remote neutralizer (EM1)	EM5	4.68×10^{-7}	1.05	670	–115	1.20	3.4	–9.0	15.7	0
2 engines, 2 neutralizer, full power	EM1	2.04×10^{-6}	6.86	1790	–210	3.52	17.5	–10.1	11.4	4.0
	EM5	2.06×10^{-6}	6.84	1811	–115	3.53	18.2	–10.7	15.2	4.0
2 engines, full power , 1 neutralizer	EM1	1.88×10^{-6}	6.85	1789	–210	3.53	18.1	–11.3	11.2	4.0
	EM5	1.88×10^{-6}	6.80	1789	–210	3.52	18.3	–11.3	NC	4.0
EM 4at low power	EM4	5.29×10^{-7}	1.13	668	–115	1.20	3.4	–9.4	18.9	3.0
EM4 at intermediate power	EM 4	7.03×10^{-7}	2.74	1169	–200	2.00	5.7	–10.1	17.1	2.5
EM 4at full power	EM4	1.16×10^{-6}	6.84	1788	-21	3.52	13.6	-11.2	12.6	4.0
EM 1, EM 4, and EM 5 at low power, single neutralizer	EM 1	1.05×10^{-6}	1.10	668	-115	1.20	5.6	-12.0	11.8	3.0
	EM 4	1.05×10^{-6}	1.06	666	-115	1.20	4.2	-13.7	NC	0
	EM 5	1.05×10^{-6}	1.04	665	-115	1.20	4.2	-13.7	NC	0

*NC = not connected

III. Neutralizer Characterization Results

A. Neutralizer Characterization of One Thruster Active With Local Neutralizer

The EM4 neutralizer was characterized with the EM4 thruster operating alone using the diagnostics described above. It is anticipated that single thruster operation at the lowest power condition would be most reflective of space-like conditions since the background pressure would be minimized at fixed pumping speed. The neutralizer characterization curves were acquired over a power level ranging from 1.1 to 6.8 kW. The variation in flow rate margin with power level was investigated.

1. EM4, Low Power Operation (LP)

Electrostatic probe I-V characteristics acquired at low thruster power (1.1 kW) were somewhat noisy. The low signal to noise ratio was attributed to the low plasma density at the thruster array. The Langmuir probe that was most sensitive to changes in EM4 neutralizer flow which also had a reasonable signal to noise ratio was located between EM1 and EM4, LP6. Apparently, the neutralizer Langmuir probe mounted atop the EM4 neutralizer enclosure, LP5, was located too far behind the neutralizer orifice to sample appreciable plasma signal at this low power level. Presented in figure 2 are variations in the electron temperature and the neutralizer keeper peak-to-peak oscillation voltage as EM4 neutralizer flow rate was varied. As can be seen in the figure, both parameters are relatively flat up until 4 sccm. Below 4 sccm the slope of both functions increase significantly. The measured magnitude of the electron temperature was relatively high at this low thruster power operating condition. In part, a somewhat elevated temperature is to be expected because the measuring probe is located outside the beam. The probe therefore samples those electrons that are energetic enough to escape the potential well of the ion beam. Reduced signal to noise is also a contributor to the measured magnitude of the electron temperature at this low power condition. Ignoring absolute magnitude, it should be pointed out however that the systematic increases in the electron temperature are a real effect since it is a measure of the variation in the slope of the electron retarding region of the I-V characteristic with decreasing flow rate. Altogether, the data suggest a change in neutralizer operating mode at flow rates below 4 sccm. Apparently, at this point the neutralizer begins its transition into plume mode operation. The measured RPA signals at this low power operating condition were very noisy and in this case could only be interpreted qualitatively. The RPA that was most sensitive to changes at this low power condition was RPA1 located at the exit plane of the dormant thruster. Obvious in the series of traces taken as a function of flow rate was a significant degradation in function structure below 4 sccm. This finding is consistent with the detected increase in plasma noise levels in Langmuir probe I-V characteristics as well as in the precipitous rises in neutralizer keeper peak-to-peak voltage with decreasing flow rate. Such signal degradation at this somewhat remote probe indicates that neutralizer flow rate changes have an impact on plasma conditions far removed from the neutralizer itself.

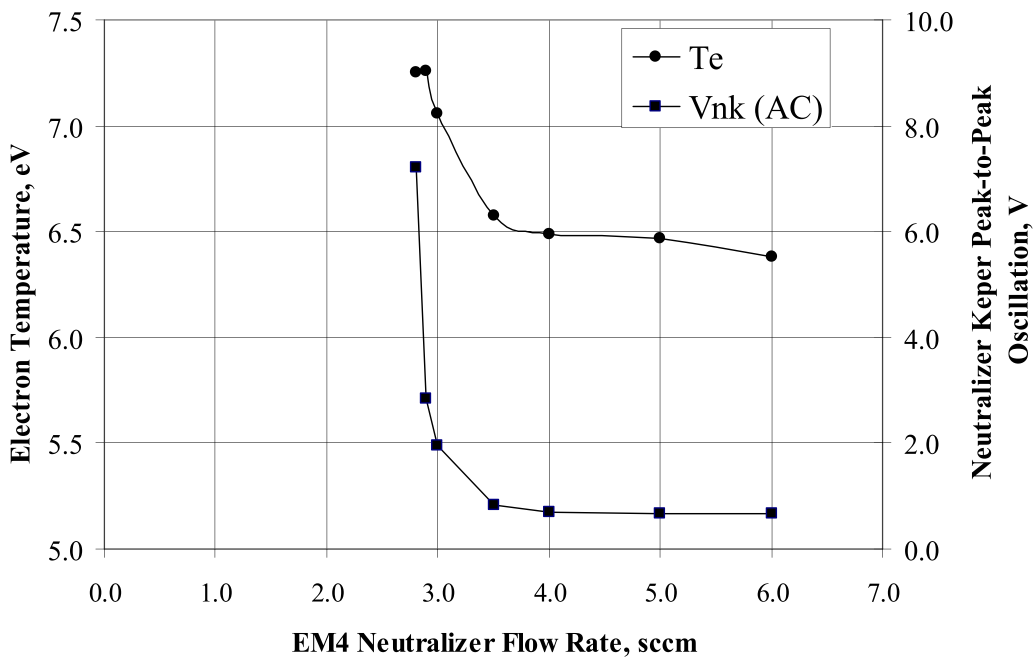

Figure 2.—Electron temperature, Te, as measured with LP6 and keeper peak-to-peak voltage, Vnk (AC), variations as a function of EM4 neutralizer flow rate at low thruster power.

2. EM4, Intermediate Power (IP)

Figure 3(a) illustrates the variations in the electron temperature and the neutralizer keeper voltage AC component with flow rate for during EM4 neutralizer characterization at intermediate power (2.74 kW). Data was acquired from a Langmuir probe located between EM1 and EM4, LP6. Again, the probe signal was too noisy at the Langmuir probe located atop the EM4 neutralizer housing box. As can be seen in the figure, the electron temperature and the peak-to-peak keeper voltage oscillation magnitude both start to rise moderately at flow rates below 3 sccm. The measurements are quite consistent each confirming the utility of each as a means to track the transition to plume mode. RPA data was also consistent with the variations in the electron temperature with flow rate. Figure 3(b) illustrates changes in the RPA signal with decreasing flow rate at a probe location between EM1 and EM4, RPA3. Smoothing was applied to this plot to capture qualitative trends. At this higher power, the RPA signals were less noisy and more amenable toward interpretation. As can be seen in the figure, the energy distribution function is does not change over a wide flow rate range. Although at 2.5 sccm, the current signal began to increase and shift toward higher energies, it was only at the lowest flow rate investigated that there was a significant change in the RPA signal. Here the signal became quite noisy and chaotic. The well structured low energy peak disappeared altogether at 2.3 sccm which is consistent with figure 3(a). The noisy but relatively flat signal at this low flow rate suggests that the neutralizer is likely in plume mode.

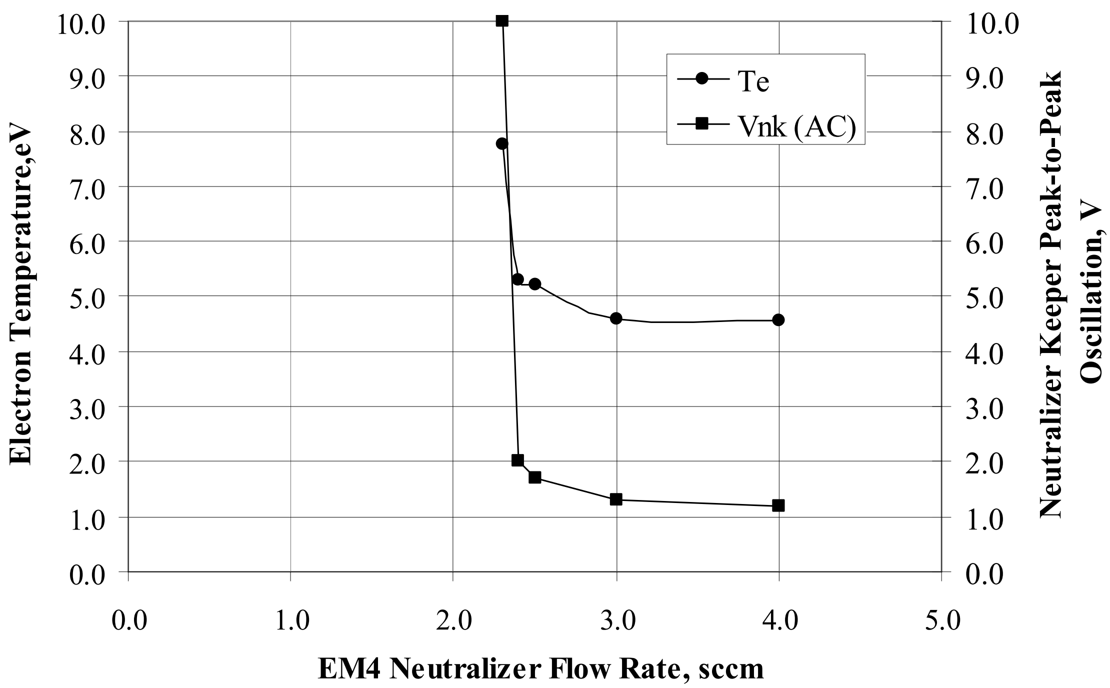

Figure 3(a).—Electron temperature, Te, as measured with LP6 and keeper peak-to-peak voltage , Vnk (AC), variations as a function of EM4 neutralizer flow rate at intermediate thruster power (IP).

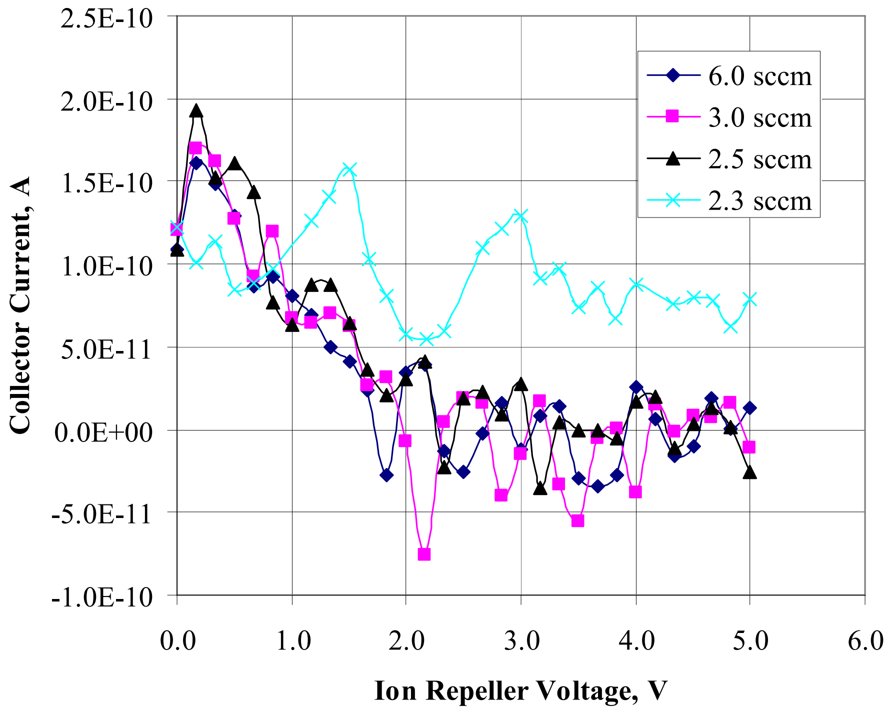

Figure 3(b).—The variation in RPA3 signal with changes in EM4 flow rate at intermediate power.

3. EM4 Full Power Neutralizer Characterization

Figure 4(a) illustrates the behavior of the electron temperature and the magnitude of neutralizer keeper peak-to-peak oscillations at EM4's neutralizer as a function of flow rate while at full power (6.8 kW). The electron temperature variation with flow rate is consistent with the changes in the AC component of neutralizer keeper voltage. Both indicate the transition to plume mode for flow rates under 3 sccm. The electron temperature is significantly larger below 3 sccm. It should be pointed out that again at this operating condition, the probe atop the neutralizer box signal was too noisy to make an assessment of local plasmas environment. Here again, the probe located between EM1 and EM4, LP6, was used. It should also be pointed out that in general, as the neutralizer flow rated decreased, the noise level or "hash" on the I-V Langmuir probe characteristics increased. Figure 4(b) illustrates the behavior of the ion energy signal as measured using an RPA at different neutralizer flow rates. Again, the RPA utilized was RPA3. The data indicates that with decreasing flow rate, the ion signal turns more noisy and chaotic. There also appears to be a shift toward higher energies. At the transition flow of 3 sccm, there is a marked increase in the noise level on the trace. There is also a noticeable shift toward higher energies. At flow rates below 3 sccm, the RPA signal is virtually flat indicating an absence of well organized ion back flux. This behavior is likely due to modifications in the potential distribution downstream of the probe brought on by noisy neutralizer operation.

To summarize, for single thruster operation, the electron temperature in the beam plasma underwent transitions consistent with observed changes in peak-to-peak keeper voltage over a broad thruster power range (1.1 to 6.8 kW). This correlation of these independent measurements suggests that at least with a single NEXT thruster operating, the determination of spot-to-plume transition can be made with similar sensitivity whether using a Langmuir probe or simply observing slope changes in the keeper voltage peak-to-peak oscillation magnitude plotted versus flow rate as was observed earlier (ref. 10). More interesting however is the rather global nature of the Langmuir probe measurement. Local changes at the neutralizer in response to flow rate variations are apparently well reflected in the measured response to plasma conditions located both local and remote to the neutralizer. This behavior supports the notion that the nature of the electron energy distribution function in the ion beam (at least in the near field) is strongly influenced by the operating state of the neutralizer.

The neutralizer characterization data indicated that neutralizer margin increases with increasing thruster power level. The margin is attributed to not only increased plasma production local to the neutralizer due to the higher emission requirement, but also increased background charge exchange plasma density which would tend to improve the conductivity of the neutralizer plasma coupling bridge.

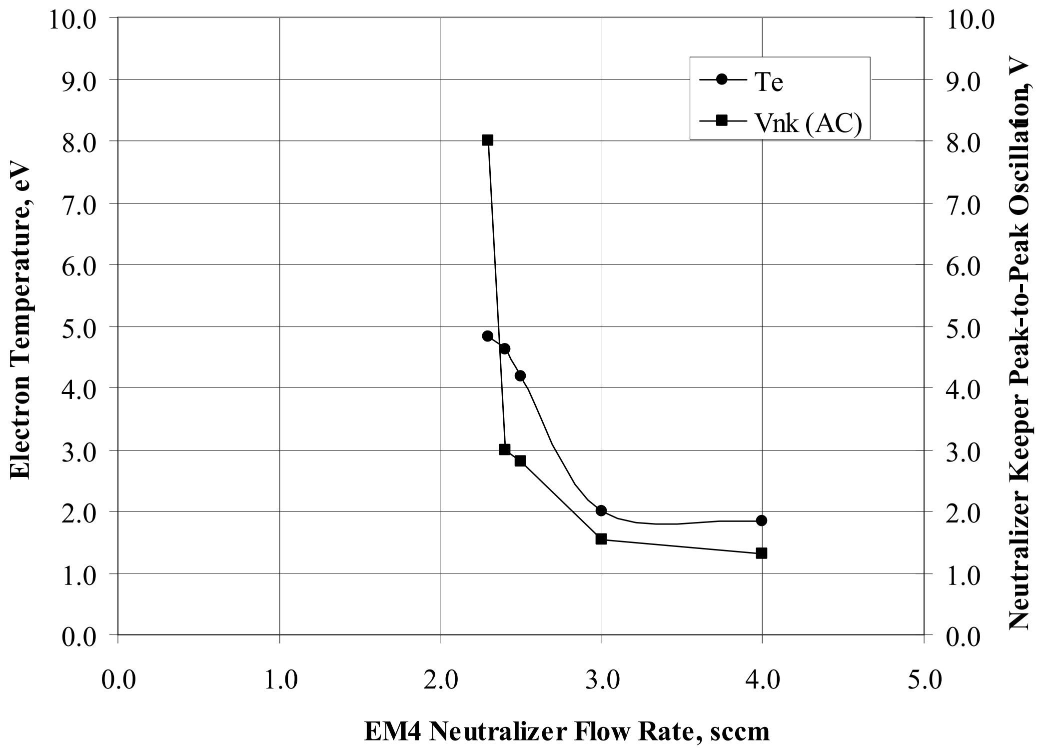

Figure 4(a).—Electron temperature as measured with LP6 and neutralizer keeper peak-to-peak voltage variations with flow rate changes during EM4 operation at full power.

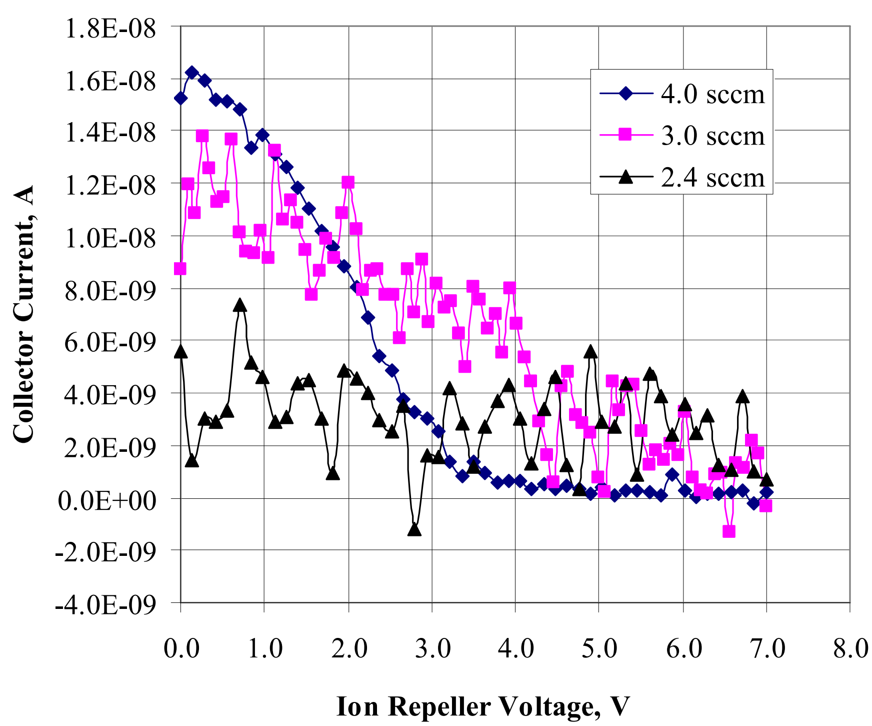

Figure 4(b).—Variations in ion energy as measured with RPA3 with neutralizer flow rate changes during EM4 operation at full power.

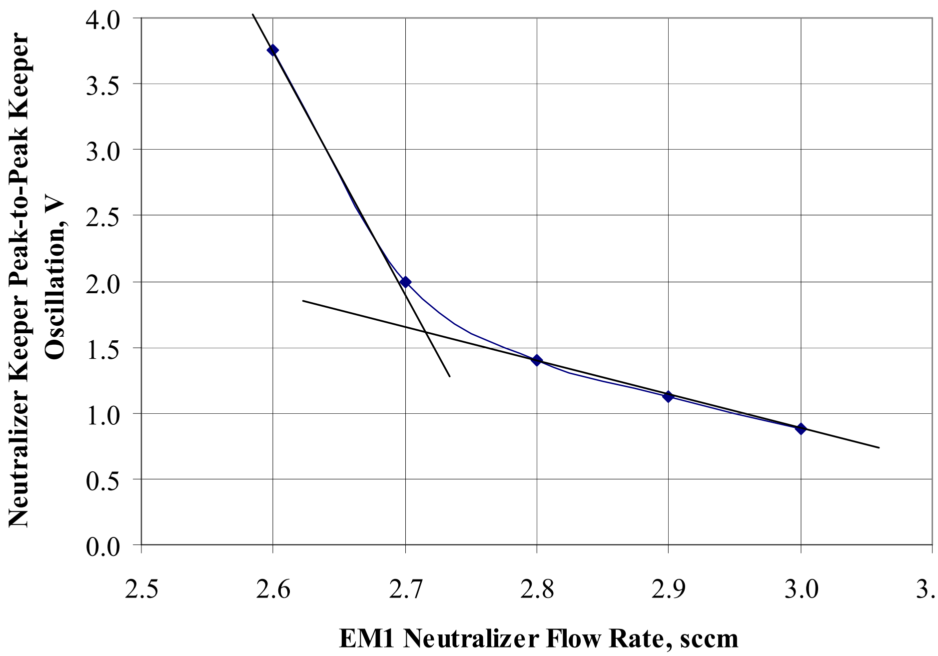

Figure 5.—Variation in keeper peak-to-peak voltage oscillation with decreasing neutralizer flow rate for EM5 operating with EM1's neutralizer.

B. One Thruster Active With a Remote Neutralizer

Remote neutralizer operation was demonstrated with EM5 operating at low power. EM5's ion beam was neutralized with EM1's neutralizer. In this case, EM5's neutralizer was not active. The RPA and Langmuir probe characteristics were too noisy to draw meaningful conclusions regarding a mode transition during neutralizer characterization of this configuration. The background plasma density was simply to low. Figure 5 illustrates the variations in the neutralizer keeper peak-to-peak oscillation voltage with flow rate. The voltage rises monotonically with decreasing flow rate with a moderate slope change occurring just under 2.75 sccm. The monotonically increasing behavior of this function suggests that the neutralizer may have been operating in a transitional mode for flow rates between 2.75 and 3 sccm. This would explain noise in the Langmuir probe I-V characteristics which increased with decreasing flow rate. The flow rate indicating transition to the plume mode as inferred from the slope change is lower than that which was observed when EM1 was operated at low power with a co-located neutralizer. In that case, the transition began at flow rates just under 4 sccm. The increase in flow rate margin for the remote neutralizer case is presently not well understood. It is speculated that the increased coupling distance afforded the opportunity for additional ionization by neutralizer electrons along the line of sight to the ion beam.

C. Two thrusters active with one or two neutralizers

Neutralizer characterization for two thrusters operating on one and two neutralizers respectively was investigated at both low and high thruster power conditions. The thrusters operated for this investigation were EM1 and EM5. In all cases, the neutralizer characterization was done on the EM1 neutralizer. For the two thrusters, single neutralizer case, EM5's neutralizer was turned off. The electron temperature and neutralizer peak-to-peak oscillation voltage magnitude were plotted as a function of flow rate to locate the spot-to-plume transition point. RPA profiles were also acquired to quantify shifts in ion energy as a function of neutralizer operating condition. Such changes can occur due to either modification of the potential distribution in the plume or to local energetic ion production at the neutralizer during operating mode transition.

1. EM1 and EM5, Low Power, Two Neutralizers

Figure 6(a) presents a comparison of the electron temperature and the keeper peak-to-peak oscillations as a function of EM1 neutralizer flow rate. Here, the electron temperature measurements were acquired from a planar probe located between EM1 and EM4, LP6. LP6 was the closest probe to the EM1 neutralizer that yielded a

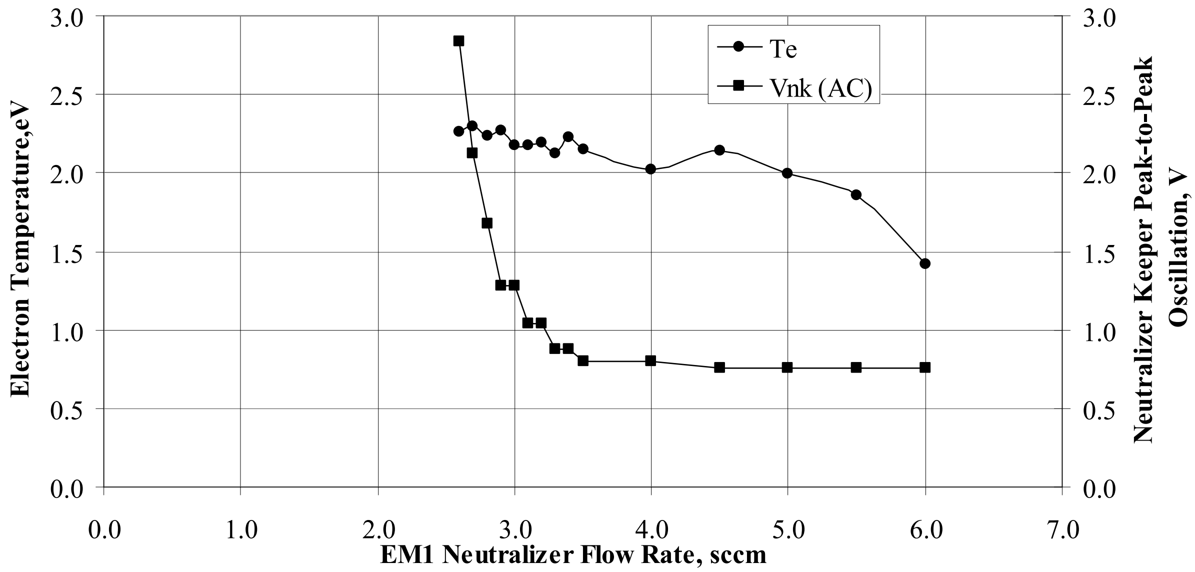

Figure 6(a).—Electron temperature as measured with LP6 and neutralizer keeper peak-to-peak voltage variations with flow rate changes during operation with EM1 and EM5 operating at low power with two neutralizers.

sufficiently high signal to noise ratio (uncertainty in slope < 25 percent). As can be seen in the figure, the peak-to-peak voltage oscillation exhibits a rather sharp increase in magnitude below 3.5 sccm suggesting the onset of plume mode operation. The electron temperature variations on the other hand were rather slowly varying with decreasing flow, rising initially and then saturating. This functional behavior was different from that observed in the electron temperature at low power operation with a single engine running as seen in figure 2(a). The magnitude of the measured temperature was also higher in this former case. The presence of the additional neutralizer may be impacting the sensitivity of the electron temperature measurement. In this case, two electron populations would be present: (1) population associated with the neutralizer under characterization and (2) population associated with the active, nominally operating neutralizer. The mixing of these electrons may act to smear sharp variations and result in a lower sensitivity function. This is certainly possible since the probe (located between EM1 and EM4) samples diffusing plasma from both thrusters. The Langmuir data indicates that a significant change in the slope occurs below 4 sccm. In this regard, there is about a 0.5 sccm disparity between the keeper peak-to-peak voltage oscillation and Langmuir probe measurements. It should also be pointed out that a neutralizer is said to be in the plume mode when the peak-to-peak voltage oscillations are at least 5 V (ref. 9). As can be seen in the figure, even at those flow rates below 3 sccm, the neutralizer signal never reached 3 V, suggesting also reduced sensitivity in the keeper peak-to-peak voltage measurement as well. The transition slope however was steep.

Ion energy data as acquired at RPA3 located just below EM1 appears to follow general trends observed in Langmuir probe data. This data is plotted in figure 6(b). The data indicates a small shift toward higher energies as the flow is reduced from 6 to 4 sccm. Below 4 sccm, there appears little change in the energy of the ions or even noise level of the signal. Because the RPA faces downstream, the measured energy scans reflect changes in plasma potential downstream of the array. Such changes are brought on by variations in the electron temperature. The fact that between 2.7 and 4 sccm, the RPA characteristic does not change appreciably suggests that similar to the electron temperature shown in figure 6(b), the average ion energy also does not vary much either over this flow rate range at least at this measurement location. Possible modification to the downstream plasma potential profile in response to changes in the operating condition of the EM1 neutralizer may be compensated for by the EM5 neutralizer operating at its nominal set-point.

2. EM1 and EM5 Operating at Low Power With One Neutralizer

Figure 7 illustrates the changes in the measured electron temperature and the peak-to-peak oscillation voltage as a function of EM1 neutralizer flow rate with EM5's neutralizer turned off. The Langmuir probe utilized here again is located between EM1 and EM4, LP6. The electron temperature rises sharply with decreasing flow rate indicating

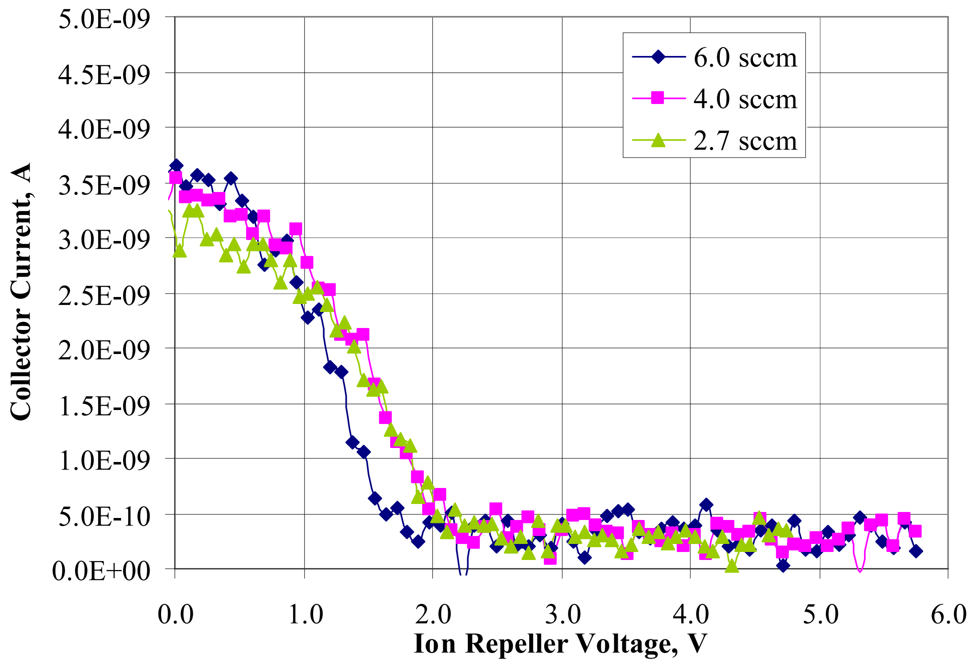

Figure 6(b).—Variations in the ion energy as measured with RPA3 with neutralizer flow rate changes during EM1 neutralizer flow rate changes.

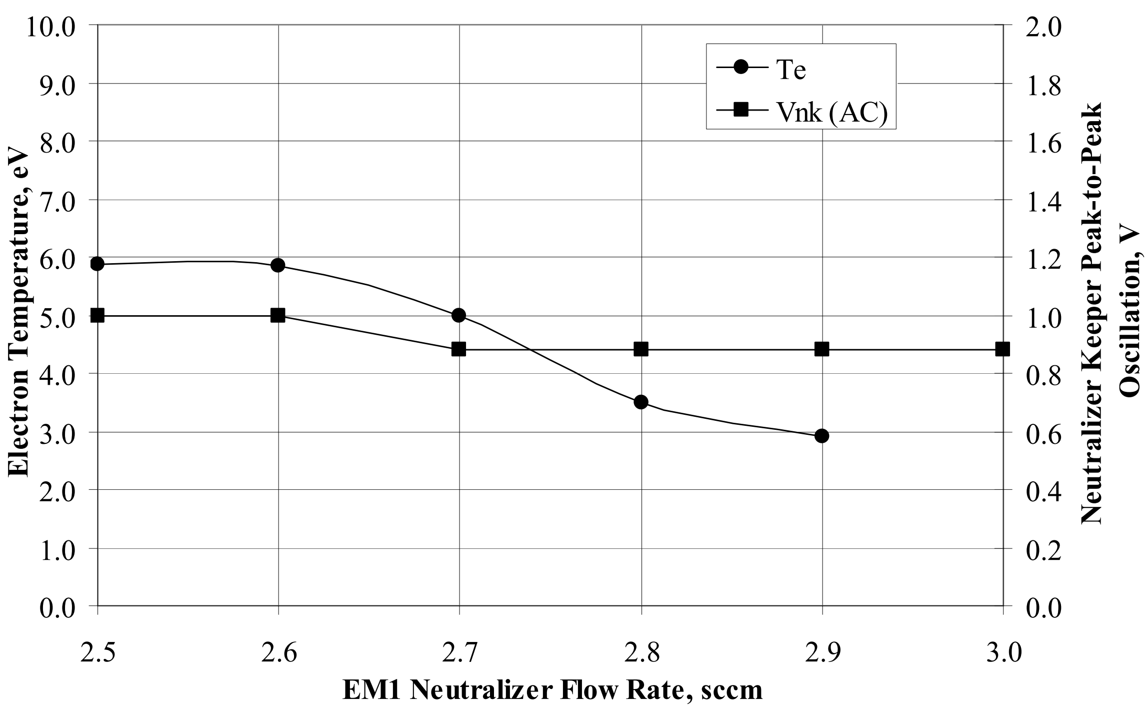

Figure 7.—Electron temperature as measured with LP6 and neutralizer keeper peak-to-peak voltage variations with flow rate changes during EM1 and EM5 active at low power. EM1 neutralizer active, EM5 neutralizer shut off.

that even at the largest flow rate for which there was a Langmuir probe measurement, the neutralizer is likely operating near the transition threshold leading to plume mode operation. Note that the functional behavior of the electron temperature with decreasing flow rate is quite different from the slowly varying function observed with two neutralizers active. In this present case, the sensitivity to flow rate changes is much greater. It should be noted that the keeper peak-to-peak voltage was very insensitive to changes in the flow rate over a wide range with a detectable change occurring just below 2.7 sccm. Even this change was fairly small (~10 percent). This data indicates the lack of sensitivity of this measurement to plume mode detection at least for this operating condition. Even at very low flow rates, the keeper peak-to-peak voltage did not rise appreciably and based on the criteria that the neutralizer oscillation voltage is greater than 5 V, does not indicate plume mode. It should be pointed out that with decreasing flow rate the Langmuir probe IV characteristics became noisier, which is also consistent with the transition to electrically noisier plume mode operation.

The transition from spot to plume mode as inferred from the electron temperature plot appears to be more dramatic than that displayed in the two neutralizer case. This higher sensitivity is likely due to the fact that the nature of the electron population is due to changes at one source, the neutralizer under test. This point is to be contrasted with the two neutralizer active condition where only one is characterized while the other operates at nominal conditions. Under these conditions, two distinct populations can be expected and the subsequent mixing in the array near-field should smear out gross changes in the distribution of electrons due to changes in operating condition of neutralizer under test. This would tend to reduce overall sensitivity of the measurement to changes at the neutralizer itself. The sensitivity could be recovered provided the electrostatic probe is sufficiently close to the neutralizer plume. This was not always possible in this investigation due to the low signal to noise ratios for neutralizer co-located Langmuir probes during operation at low power. Finally, it should be pointed out that in contrast to the two neutralizer active case, the system appears to have better neutralizer margin when only one neutralizer is operating. This finding is somewhat surprising because the single neutralizer must supply twice the current. This behavior may be related to the same phenomena giving rise to improved flow rate margin in the remote neutralizer configuration (see section III. B.)

RPA profiles taken at the single neutralizer, low thruster power conditions were quite noisy. Qualitatively, there was general degradation in signal definition with decreasing flow rate. The magnitude of the signal also tended to degrade with decreasing neutralizer flow rate. The lack of signal definition may be due to a degradation of potential structure downstream of the array.

3. EM1 and EM5 Operating at Full Power With Two Neutralizers

A neutralizer characterization curve for the condition of two thrusters (EM1 and EM5) operating at full power with respective neutralizers active was acquired. As the flow rate in the EM5 neutralizer was varied, the response was monitored by acquiring I-V characteristics at array Langmuir probes and by recording the neutralizer peak-to-peak voltage oscillation. As can be seen in figure 8, the Langmuir probe at the neutralizer being characterized and the peak-to-peak voltage oscillation were most sensitive to these flow rate changes. The Langmuir probe located between EM2 and EM5 (LP7) was fairly unresponsive to changes in EM5 neutralizer flow rate. This observation is consistent with findings mentioned earlier. The plasma conditions associated with two thrusters and two neutralizers operating smooth out changes in plasma conditions for probes located remote to the neutralizer under test. On the other hand, the probe most sensitive to neutralizer flow rate changes is the one co-located with the neutralizer under test (LP2). The co-located probe directly samples local plasma changes occurring at the neutralizer. In figure 8 it can be seen that below 3 sccm both the electron temperature and the peak-to-peak voltage oscillation increase significantly. This finding seems to indicate a transition into the plume mode for flow rates below 3 sccm. It should be pointed out that even though the peak-to-peak oscillation voltage begins to take off below 3 sccm, the maximum voltage recorded for this parameter at the lowest flow rate investigated was still less than 5 V, the traditional criterion for plume mode operation. Its remarkable that the neutralizer keeper voltage over this flow rate range only increased by only one volt despite the dramatic changes in the electron temperature and peak-to-peak voltage oscillation amplitude. Over this same flow rate range the coupling voltage increased by nearly 9 Volts. The coupling voltage, which reflects the relative conductivity of the path from neutralizer to beam, in this case reflects well the changes in plasma condition at the neutralizer. The potential difference between the keeper and neutralizer cathode however are apparently completely decoupled from plasma bridge processes, making it a relatively low sensitivity diagnostic.

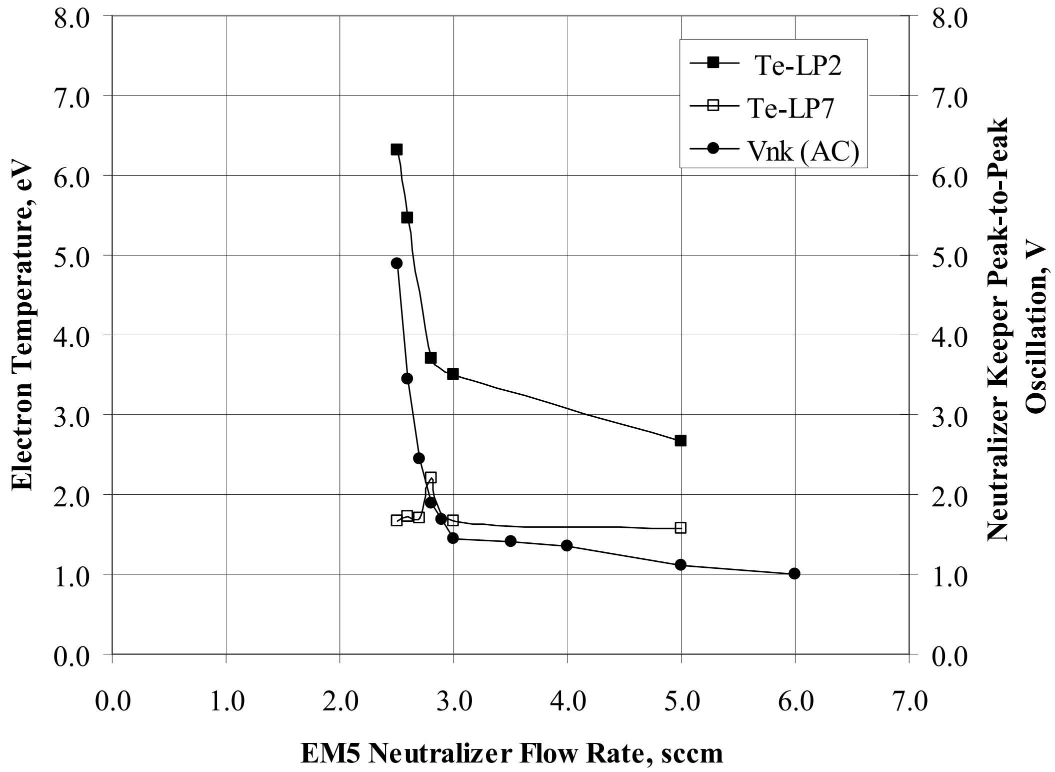

Figure 8.—Electron temperature as measured with LP2 and LP7 and neutralizer keeper peak-to-peak voltage oscillation changes with flow rate changes during EM1 and EM5 operation at full power.

4. EM 1 and EM 5 Operating at Full Power With One Neutralizer

Langmuir probe data was also acquired for EM1 and EM5 operating at full power with a single neutralizer (EM 1). Generally signal to noise ratios were better at the higher power levels owing to the higher associated plasma density. Probe data presented here were acquired from the Langmuir probe located between EM1 and EM4, LP6. While the signal strength at the probe at EM1 neutralizer was considerably higher, at flows below 3.2 sccm, the traces became quite noisy and difficult to interpret. It should be pointed out that the change in the EM1 neutralizer Langmuir IV characteristic from well defined to incoherent is a sign of a local change in plasma conditions and also suggests the onset of plume mode operation. This conjecture is supported by additional Langmuir probe data acquired remote to the neutralizer that also indicated a transition in operating mode at neutralizer flow rates below 3.2 sccm. Figure 9(a) illustrates variations in the measured electron temperature and the peak-to-peak voltage oscillation of the neutralizer keeper as a function of flow rate. As can be seen in the figure, while both signals increase with decreasing flow, an increase in the growth rate of the peak-to-peak voltage occurs at flow rates less than 3 sccm while the electron temperature measurement indicates a slope change at flow rates less than 3.2 sccm as indicated in the figure. These transition points determined from the two different diagnostics are similar to those observed when two neutralizers were operating at full power, suggesting no significant change in neutralizer flow margin. This finding is to be contrasted with changes observed in neutralizer flow margin with one and two neutralizers operating, respectively at the low power condition. In the low power case, single neutralizer operation resulted in flow margin gain.

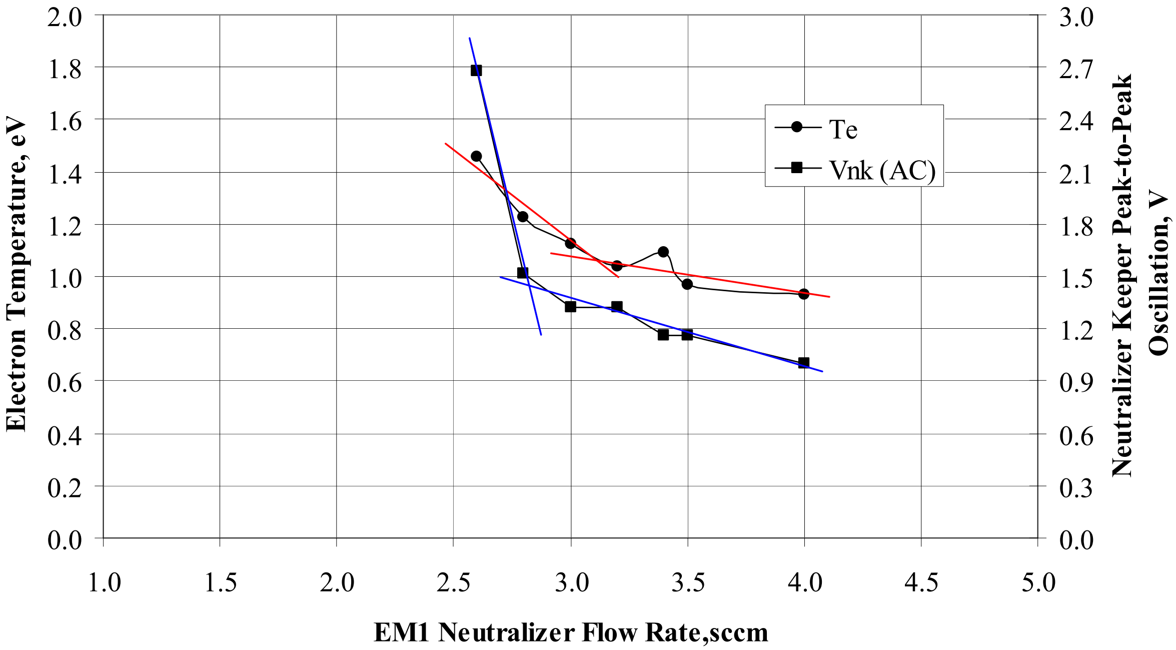

Figure 9(a).—Variations in electron temperature as measured with LP6 and peak-to-peak keeper voltage with flow rate with EM1 and EM5 at full power operating on EM1's neutralizer.

RPA data was also acquired during this test. RPA IV profiles at 3 sccm and below for the RPA co-located with the EM1 neutralizer (RPA4) are presented in figure 9(b). As mentioned earlier, the neutralizer transition to plume mode occurs at flow rates possibly as high as 3.2 sccm as inferred from electron temperature variations. RPA4 profiles show rather significant shifts in the "knee" with reducing flow rate. The knee shifts from approximately 3 eV at 3 sccm to nearly 5 eV at 2.6 sccm. The profiles suggest that the ion population is increasing in average energy as the neutralizer moves further into the plume mode. Beyond the knee, the profile extends to higher energies suggesting an overall broadening of the profile toward higher energies as well. The presence of the more energetic ions is an indicator of a neutralizer operating mode change.

Figure 9(c) illustrates the variations in the RPA3 (located between EM1 and EM4) IV characteristic as neutralizer flow rate is reduced. As can be seen here, with decreasing flow rate, the ion energy shifts to higher values. The relative increases are modest even though the RPA is far removed from the neutralizer. Again, this non-local sensitivity to neutralizer flow changes at this particular RPA demonstrates the global impact that the neutralizer operating condition has on plasma properties at the exit plane of the thruster array. As discussed earlier, this sensitivity is heightened when only one neutralizer is active. In this case, there are no averaging processes present to mute the changes in the electron distribution which in term establishes the potential distribution downstream. In this case, the near-field plume plasma properties directly reflect electron conditions at the neutralizer. It should be also mentioned that the current signal at RPA3 tended to increase with decreasing flow rate as well. This increase can only occur if the local plasma density is increasing or if the plasma potential structure changes in a manner that better focus ion flux to the array. Increases in the magnitude of the plasma potential in the exit plane of the array suggests that it is this latter effect that may be giving rise to the increased ion current signal at RPA3. Thruster array Langmuir probe plasma potential measurements indicate that the potential difference between the RPA entrance grid and the plasma potential at the exit plane increases monotonically with decreasing neutralizer flow rate.

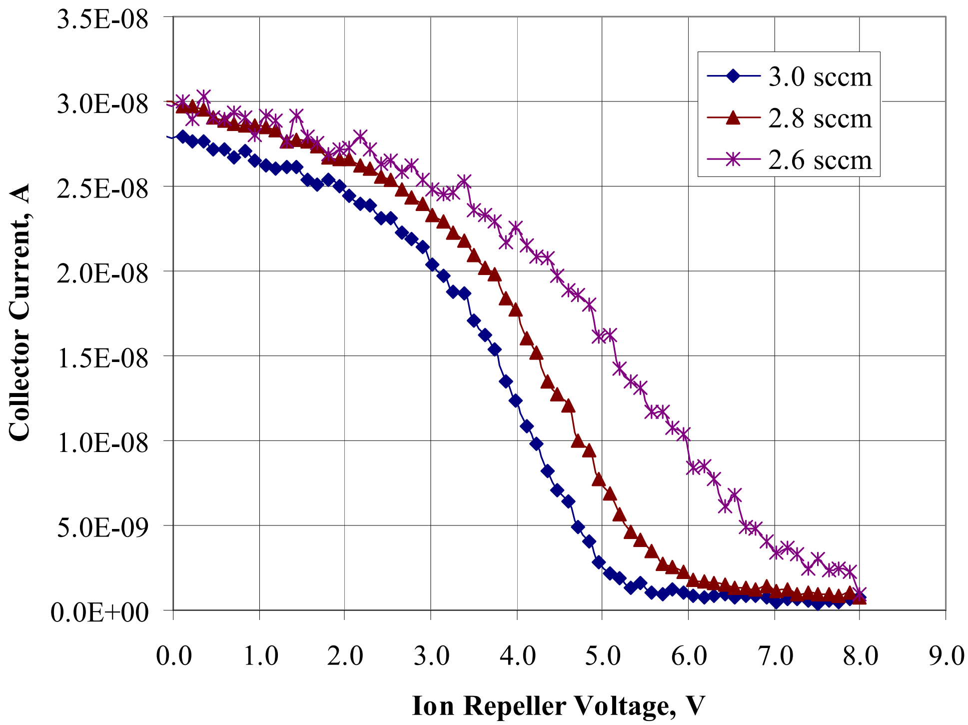

Figure 9(b).—Variation in RPA4 profiles at EM1 neutralizer with decreasing flow rate under conditions of one neutralizer active with EM1 and EM5 at full power.

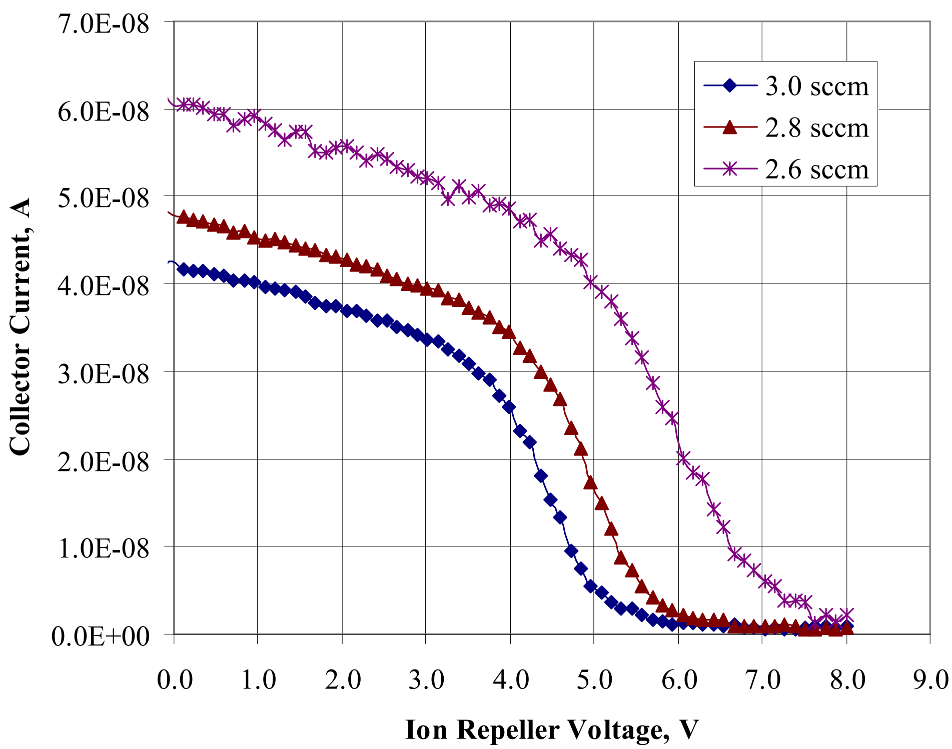

Figure 9(c).—Variation in RPA3 profiles acquired between EM1 and EM4 as EM 1's neutralizer flow rate is varied under conditions of one neutralizer active with EM1 and EM5 at full power.

1. EM1, EM4, and EM5 Operating at Full Power With Three Neutralizers

It was observed that the sensitivity of the neutralizer peak-to-peak voltage diagnostic tended to decrease with the number of thruster operating as well as the power level of thrusters operating. Under the condition where three thrusters were operating, the changes in the keeper peak-to-peak oscillation parameter with decreasing flow rate was moderately muted. The keeper peak-to-peak oscillation voltage change for three thrusters operating at full power less than ~0.5 V! Presumably this relative insensitivity is due to the increase in background plasma density which may increase electrical conductivity locally, thereby stabilizing the discharge (ballast effect). The background plasma density was observed to increase by a factor of 2.5 in going from two thrusters operating at full power to three thrusters operating at full power (ref. 20). The background plasma density can be expected to reduce the sensitivity of the Langmuir probe diagnostic as well, particularly for those probes located remote to the neutralizer being characterized. In this case, the increased background plasma density, a facility effect may actually affect the operation and thus the true flow margin of the neutralizer. In this regard, as background plasma density increases, the utility of probes located remote to the neutralizer is reduced. Probes manifesting the highest degree of sensitivity would be those closest to the neutralizer. This was observed in the EM1 neutralizer data presented in figure 10. Plotted in figure 10 is the peak-to-peak voltage oscillation at the keeper and the electron temperature acquired at three Langmuir probes: (1) Between EM1 and EM4 (LP6), (2) At the diagnostics thruster (LP1), and (3) At the EM 1 neutralizer (neutralizer under test), LP4. As can be seen here, probes remote to the EM1 neutralizer showed very little variation over the flow rate range. The keeper oscillation voltage increases slightly around 5 sccm. The electron temperature acquired from Langmuir probe closest to the neutralizer under test grew rapidly with decreasing flow rate. No data was acquired between 3 and 6 sccm but what is obvious is the exponential increase in electron temperature below 3 sccm. In this regard, the data indicates that the transition clearly has occurred below 3 sccm.

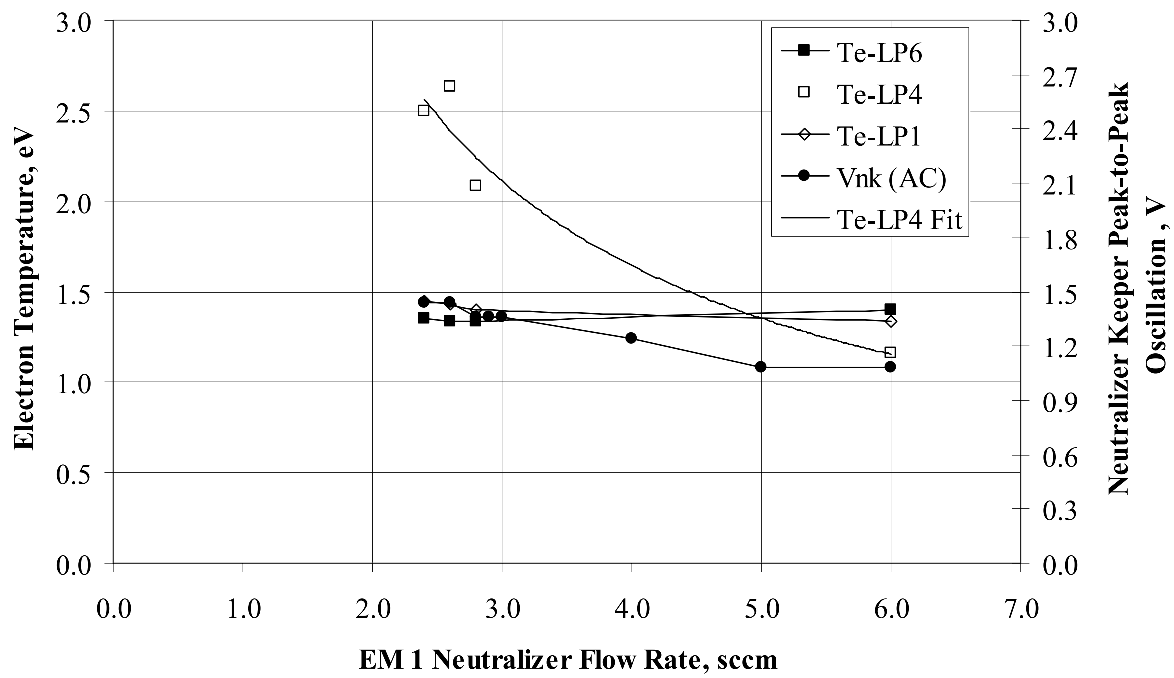

Figure 10.—Variation in electron temperature and keeper peak-to-peak voltage oscillation amplitude with neutralizer flow rate with three thrusters active at full power. Note sensitivity of probe LP4.

D. Three Thrusters With One or Three Neutralizers

As mentioned earlier, the presence of the fixed flow rate neutralizers mutes the changes in the plasma at the exit plane caused by reductions in neutralizer flow rate at EM1. This finding supports the notion that the electron distribution that neutralizes the ion beam is a consequence of supposition of qualities of the electrons populations from the various neutralizers. Of the three thruster configurations, the average electron temperature would be more or less an average of the three thrusters and therefore would be centered near the nominal values associated with the neutralizers at EM4 and EM5. Additionally, the background CEX plasma density, which increases with total array thruster power, also has the effect of suppressing plasma sensitivity due to operating mode changes at the EM1 neutralizer. This effect, of course, is facility related and is not expected to be present in space.

2. EM1, EM4, and EM5 Operating at Low Power With One Neutralizer

Three thrusters operating a low power with a single neutralizer was also investigated. Each of the active thrusters was operated at the 1.1 kW operating condition. Only EM1's neutralizer was active. The variation in neutralizer keeper peak-to-peak voltage oscillations as well as changes to plasma conditions near the neutralizer and at the exit plane of the array was documented to ascertain the magnitude of the transition spot-to-plume mode flow rate. The fact that a single cathode had to support three beams suggests that neutralizing current flow across EM1 exceeded the current necessary to neutralize the beam. In this case, likely the plume at EM1 was over-neutralized, satisfying neither current nor density neutrality. It is also worth pointing out at the "nominal" condition established for this configuration (see table I), the accelerator grid currents at the two thrusters whose neutralizers were shut down was over 25 percent lower than that measured at EM1. This disparity may indicate a nontrivial contribution of ion flux to the grids due to the operation of the neutralizer alone. The plasma conditions at the active neutralizer may be such that density in the vicinity of EM1 may be higher to support neutralization of the two additional engines.

Figure 11(a) depicts the variations in the neutralizer operating condition with flow rate. EM1 neutralizer probe (LP4) I-V characteristics were noisy and difficult to interpret over this flow rate range and thruster power level. Langmuir probe data from the LP6, located between EM1 and EM4, is presented instead. At very low flow rate conditions, the I-V characteristic even for this probe became noisy at the lower flow rates. The noise ,however, was not of sufficient magnitude to preclude interpretation and analysis of the characteristic. As can be seen in the figure, both the keeper peak-to-peak oscillation voltage as well as the electron temperature were very sensitive to changes in the neutralizer flow rate. Again, the plasma conditions remote to the neutralizer appear to be more sensitive to changes at the neutralizer when there is only one neutralizer active. Both diagnostics indicated a transition (at the knee) from spot to plume mode for flow rates below 3.5 sccm.

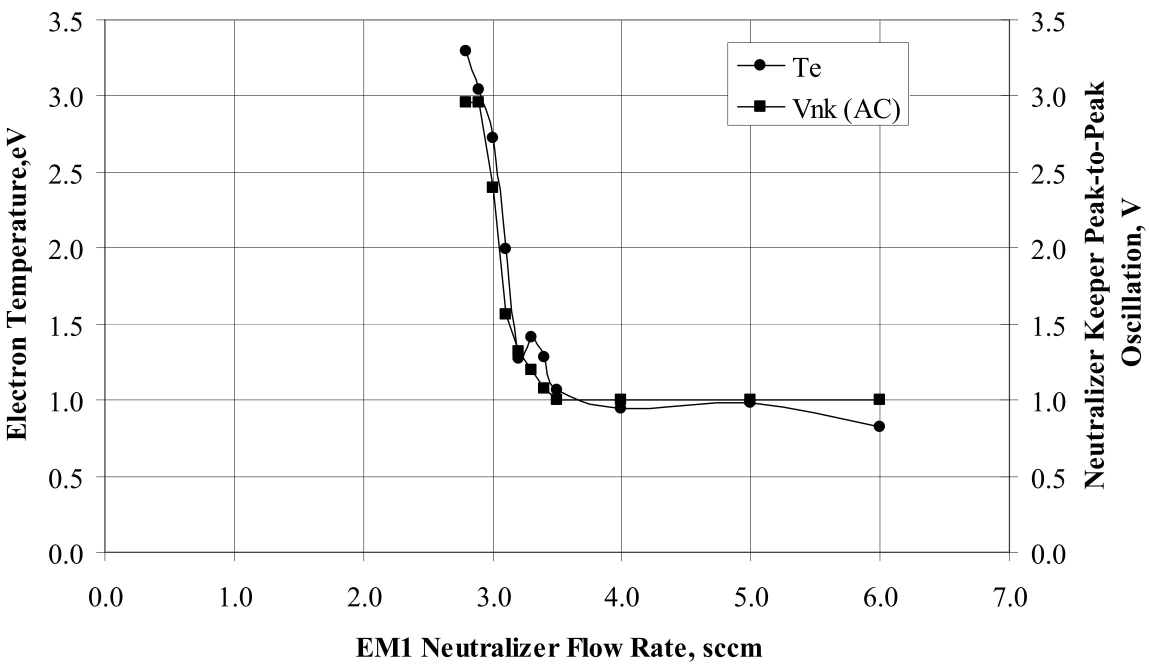

Figure 11(a).— Electron temperature as measured with LP6 and neutralizer keeper peak-to-peak voltage variations with flow rate changes during. Three thrusters active at low power. Single neutralizer operation.

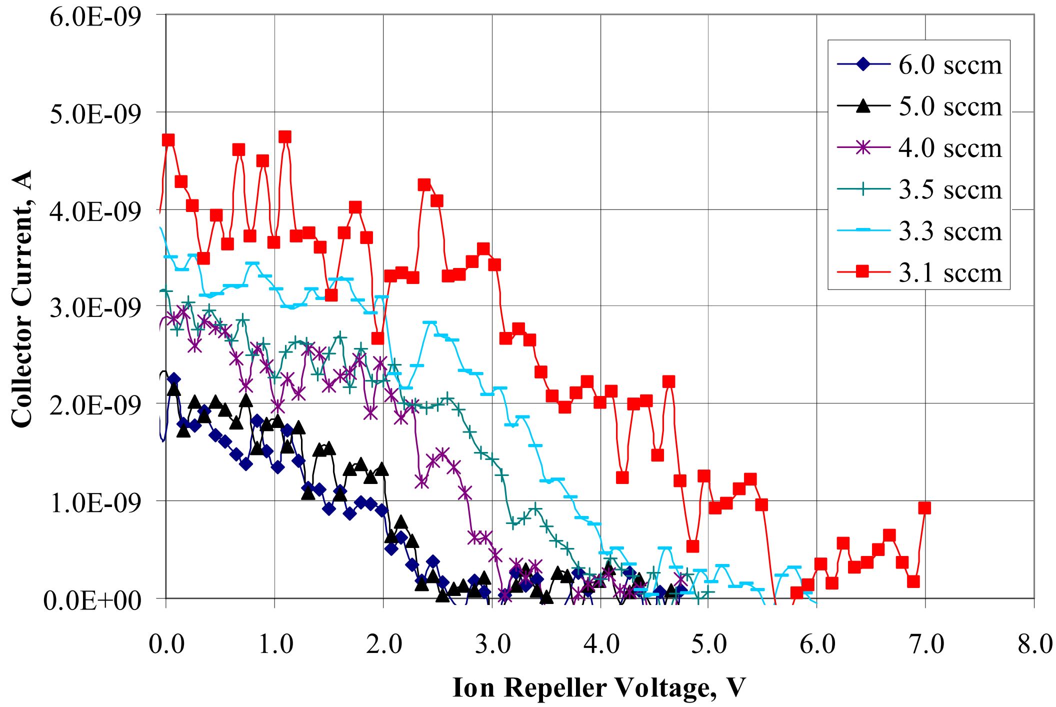

Figure 11(b).—Variation in RPA4 profiles acquired as EM 1's neutralizer flow rate is varied under conditions of one neutralizer active with EM1, EM4, and EM5 at low power.

Figure 11(b) illustrates the variations in the RPA characteristics as a function of EM1 neutralizer flow rate. These data were acquired at the EM1 neutralizer RPA, RPA4. In this respect, the measurement is local in nature. The RPA signals, though somewhat noisy, were interpretable at this probe location for this operating condition presumably due to the higher ion flux associated with three thrusters operating at albeit low power. Three main points may be taken from this figure: (1) There is a definite shift in ion energy toward higher values with decreasing neutralizer flow rate, (2) The current signal at RPA4 apparently increases with decreasing flow rate and (3) The RPA signal becomes noisier with decreasing flow rate. The increase or spread in ion energy to higher values at the neutralizer suggests a modification to the local plasma potential distribution. The larger currents at reduced flow rates are likely due to additional, locally produced ions arising from plume ionization at the neutralizer and possibly more organized ion flow associated with the increased plasma potential. RPA4 data suggests a distinct jump in energy from 5 to 4 sccm, with another significant jump occurring between 3.3 and 3.1 sccm. These jumps in ion energy suggest operating mode jumps. As can be seen from the figure, below 5 sccm, the energy shifts to higher values suggesting that continuous movement into the plume mode. The shift occurs earlier (at higher flows) than that which is expected based on electron temperature or peak-to-peak voltage oscillation changes. This data suggests that perhaps the tail of the electron energy distribution is changing early on and the plume plasma potential just downstream of the array is responding to this. After all, the electron temperature calculation is based on the assumption that the distribution is Maxwellian. Deviations, in the distribution tail in particular, from a Maxwellian profile would not be reflected in the electron temperature calculations. Distribution function tail effects may play an important role in neutralizer operation as neutralizer internal pressure is reduced with decreasing flow rate.

Ion energy data was also acquired from a probe located between the EM1 and EM4. RPA3 is located remote to the neutralizer plasma. The variations in RPA3 profiles with EM1 neutralizer flow rate is illustrated in figure 11(c). Again, the fact that the ion energy measured even at this location varies in concert with neutralizer flow rate strengthens the claim that processes occurring at the neutralizer are not local, rather they directly impact array plasma properties. This is particularly the case when a single neutralizer is being used to neutralize multiple beams. Here, the electron distribution and thus the plasma properties everywhere in the near field are influenced by the neutralizer plasma. The shift in energy to more energetic mean energies is a consequence of plasma potentials adjusting in the plume, presumably in response to the beam's attempt to establish a potential well of sufficient depth to confine the electrons. The necessary depth must increase with electron temperature which increases moderately as

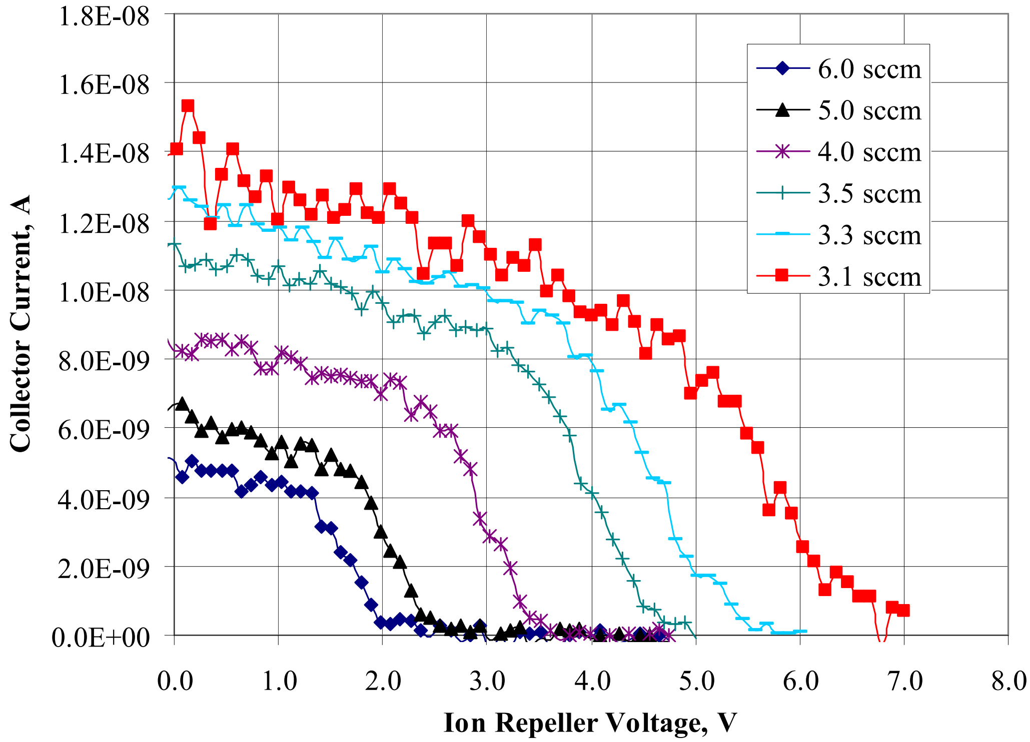

Figure 11(c).—Variation in RPA3 profiles acquired as EM 1's neutralizer flow rate is varied under conditions of one neutralizer active with EM1, EM4, and EM 5 at low power.

the neutralizer moves into the plume mode. In figure 11(c), the knee of the RPA3 I-V characteristic shifts nearly 4 V as flow varies from 3 to 6 sccm. The current magnitude also increases with reducing flow rate suggesting either increased plasma production, perhaps driven by plume ionization or more organized ion flow due to increases in the plasma potential. Increases in plasma density occurring as the neutralizer moves into the plume mode were observed during the High Power Electric Propulsion (HiPEP) test (ref. 6). In this present case however, probe data suggests that the increases are likely due to the increase in the plasma potential with decreasing flow which gives rise to more organized flow. RPA4 profiles also tended to get noisier at the lowest flow rates investigated. These profiles also indicate that below 5 sccm, a continuous shift in ion energy occurred suggesting progression toward the plume mode as neutralizer flow rate is reduced.

IV. Conclusions

The response of the neutralizer and array plasma to flow rate changes was assessed by monitoring the neutralizer keeper peak-to-peak voltage oscillation amplitude and the electrostatic probe I-V characteristics. These measured parameters were used to ascertain the transition flow rate from spot to plume mode operation, thereby determining the flow rate margin of the neutralizer. The peak-to-peak voltage approach has been used in the past. Recent tests, however, indicate that this may not be the most sensitive parameter for determining the flow rate region of transition (refs. 5 and 6). Indeed, this data as well as that of past investigations appear to indicate that the sensitivity of a given diagnostics is largely dependent of thruster configuration, making some diagnostics under certain circumstances better suited than others. In this work, peak-to-peak keeper voltage, electron temperature, and ion energy at the array were investigated as a function of neutralizer flow rate. It was found that the Langmuir probe and RPA measurements were most sensitive to changes in neutralizer flow rate when there was only one neutralizer operating, independent of the number of ion sources active. This finding suggests that under these conditions, modification to the beam plasma by the neutralizer is global, with the near field beam properties reflecting changes at the neutralizer. The probe most sensitive to neutralizer changes when multiple neutralizers were operating was that probe co-located with the neutralizer under test. In this regard, the probe is sampling locally the changes in operating condition of the neutralizer. The more remotely located probes exhibited reduced sensitivity. This is likely due to the fact that the electron population and the response, the plasmas potential profile, under these conditions, are due to the supposition of plasma electrons from multiple neutralizers. Consistent with observations, this would have the effect of muting the influence of the neutralizer under test on the plasma at locations remote to the neutralizer. These findings also suggest that the magnitude of the background plasma density likely affects operation of the neutralizer itself and therefore also neutralizer margin. Observed in this work are relatively dramatic shifts in the average ion energy during neutralizer characterization. These findings suggest modifications to the plasma potential profile in the plume near field. Again, this finding indicates the non-local influence of neutralizer operating condition on particle flow fields.

Finally, it should be pointed out that reductions in neutralizer flow rate margin were not observed when the array went from two neutralizers active to one neutralizer active for a two thruster configuration operating either at low power or at full power. On the contrary, at least in the low power case, the flow margin actually improved. This effect was also observed when a single thruster was operated at low power with a remote neutralizer. Apparently operating at the higher emission current (double) keeps the neutralizer in the spot mode over a broader flow rate range. Finally, it should be pointed out that the electron temperature tended to be highest at the lowest total power level suggesting the presence of a greater proportion of hot untrapped electrons.

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13. ABSTRACT ***(Maximum 200 words)***

Neutralizers in a multi-thruster array configuration were characterized using conventional diagnostics such as peak-to-peak keeper oscillation amplitude as well as unconventional methods which featured the application of electrostatic probes. The response of the array local plasma environment to neutralizer flow rate changes were documented using Langmuir probes and retarding potential analyzers. Such characterization is necessary for system efficiency and stability optimization. Because the local plasma environment was measured in conjunction with the neutralizer characterization, particle fluxes at the array and thus array lifetime impacts associated with neutralizer operating mode could also be investigated. Neutralizer operating condition was documented for a number of multithruster array configurations ranging from three-engines, three-neutralizers to a single engine, one-neutralizer all as a function of neutralizer flow rate.

14. SUBJECT TERMS

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