Study and Optimization of 15-cm Kaufman Thruster Discharges

R. L. Poeschel,* J. W. Ward,† and W. Knauer‡
Hughes Research Laboratories, Malibu, Calif.

Parametric and diagnostic studies of the Kaufman thruster discharge have shown that the transmission of the ion extraction optics and the magnetic field shape are the parameters that most significantly affect thruster performance. A high transmission ion optical system produces unexpected beneficial changes in the discharge plasma; over-all plasma density and electron temperature are lowered and the plasma potential distribution inhibits much of the ion loss to discharge chamber electrodes. A magnetic field configuration that distributes energetic electrons across the entire extraction screen produces a uniform plasma density distribution and thereby significantly improves thruster performance. Several different magnetic configurations have been found to provide such uniformity. In all cases the discharge losses are similar, typically 190 ev/ion at 85% propellant utilization in mercury discharges with hollow cathodes and with ion optics of about 70% transmission.

Introduction

In recent years, the performance of Kaufman thrusters has been improved dramatically by parameter optimization.[1-5] Our study[6] has employed a more physically oriented approach in order to establish a relationship between the thruster parameters and the observable properties of the thruster discharge plasma. It was conducted with 15-cm-diam thruster chambers, operated with both oxide and hollow cathodes and with mercury as the propellant. As a basis for comparison, a SERT II-type thruster was tested with the same facilities as the experimental thrusters. As in earlier programs, parameters were varied to achieve optimization; however, suitable diagnostic measurements were made whenever significant performance improvements were observed. The parameters investigated were discharge, chamber length, magnetic field configuration and field strength, cathode location, ion extraction optics, and the mode of propellant injection. The principal diagnostic techniques were Langmuir probe measurements in the discharge plasma, Faraday cup probe measurements in the extracted ion beam, powdered iron magnetic field maps, and current measurements in isolated segments of discharge electrodes.

The combined parametric and diagnostic studies have led to a good understanding of the important discharge properties. As a result, specific rules can be advanced for the design of efficient thrusters. It is shown that these rules must be given in terms of physical discharge conditions rather than parametric specifications. As a consequence, thrusters of significantly different geometries can be equally efficient.

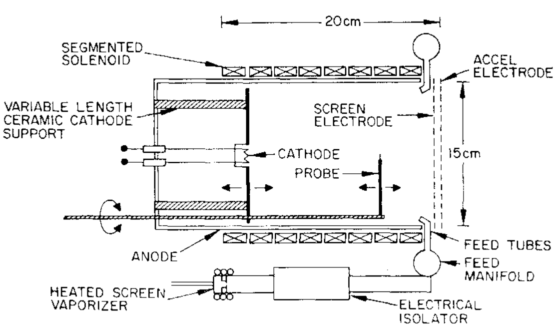

Fig. 1 The versatile experimental oxide-cathode thruster.

Presented as Paper 69-257 at the AIAA 7th Electric Propulsion Conference, Williamsburg, Va., March 3–5, 1969; submitted April 2, 1969; revision received October 15, 1969. Supported in part by NASA Lewis Research Center.

* Member of the Technical Staff. Member AIAA.
† Member of the Technical Staff. Member AIAA.
‡ Section Head. Member AIAA.

Experimental Method

The apparatus and experimental method will be described here only briefly; the details may be found in Ref. 6. Parametric and diagnostic experiments were performed with two thrusters of the type shown schematically in Fig. 1. By controlling the current in the individual solenoid segments and by inserting magnetic material between the segments, a variety of magnetic field shapes could be achieved. The discharge chamber length could be adjusted from 4 to 20 cm by varying the length of the cathode support rods. The cathode was mounted on the probe support to permit variations in cathode location. The current to each electrode was monitored and currents were recorded. Propellant injection was changed by altering the length and shape of the feed tubes. Two types of ion extraction optics were tried (Table 1).

The Langmuir probe used was cylindrical, 0.025 cm in diameter, and extending 0.152 cm from its quartz insulator. Probe data were analyzed using a technique described by

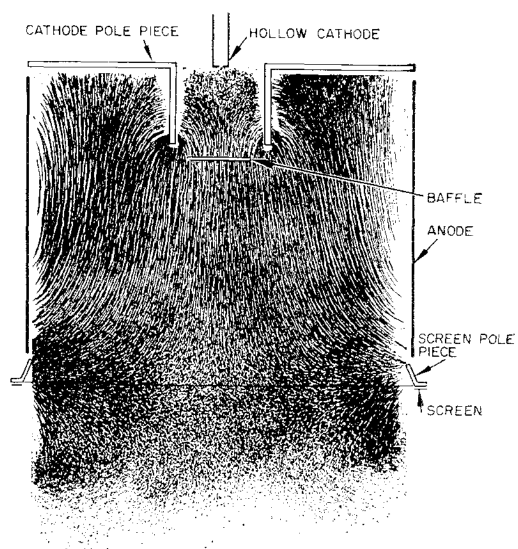

Fig. 2 Powdered-ion map of magnetic field in the discharge chamber of a SERT II permanent magnet thruster.

Table 1 Critical dimensions of ion extraction

Optic type	Number of holes	Screen: Nominal diam, cm	Screen: Thickness, cm	Screen: Hole diam, cm	Hexagonal array center-to-center hole space, cm	Accelerator: Thickness, cm	Accelerator: Hole diam, cm	Screen open area, %
A	499	15.0	0.160	0.470[a]	0.650	0.160	0.470	47.5
B	847	13.9	0.076	0.399	0.450	0.152	0.326	71.0

[a] Screen grid holes with 30° chamber to a depth of 0.160 cm on the upstream.

Strickfaden et al.,[7,8] and discussed in some detail in Ref. 6. Magnetic configurations were evaluated using powdered ion field maps of the type shown in Fig. 2 and gaussmeter measurements of the field strength. Ion beam profiles were measured with a Faraday cup probe which could be swept through the beam at several locations downstream from the accel electrode.

Experimental Findings

Performance measurements with the two different ion extraction systems led to the following unexpected finding: ion optical modifications produce more significant changes in discharge behavior than does the transition from uniform to divergent B field. This is reflected in the observed performance changes shown in Fig. 3. The transition from an ion optical system with 48% open area (type A) to one with 71% open area (type B) improved the performance of a uniform magnetic field thruster from 254 ev/ion to 178 ev/ion (90% propellant utilization). In contrast, the change from a uniform to a divergent magnetic configuration reduced the energy expenditure more modestly from 254 ev/ion to 210 ev/ion. It is interesting to note that for type A optics, the ratio of extracted ion current to screen current is approximately 1.5, corresponding to about 60% effective transmission. For type B optics, this ratio was approximately 7, corresponding to 87.5% effective transmission.

Large performance improvements associated with ion optical changes were also reported by Bechtel[2] and by Masek and Pawlik.[1] In their cases the performance improved from 570 ev/ion to 280 ev/ion (80% propellant utilization), and from 540 ev/ion to 130 ev/ion (90% propellant utilization), respectively.

Langmuir probe measurements of the discharge plasma properties shown in Fig. 4 (operating conditions are given in Table 2), indicate that the extraction system with the higher ion optical transmission reduces the over-all plasma density, inhibits radial ion loss by establishing a radial "potential well" for ions, and decreases the plasma electron temperature. These changes in the discharge plasma are attributed to a reduction in the number of ions intercepted by the extraction screen and returned to the discharge as neutrals. Fewer neutrals in the discharge chamber result in a reduction of the ion generation rate. There is a resultant decrease in the plasma density, and the plasma potential is lower in the center of the discharge. This latter property establishes a "potential well" for ion confinement because the potential ridge near the anode becomes an effective potential barrier. Finally, the plasma electron temperature decreases because the reduction in plasma density reduces the number of energy exchanging collisions between plasma and primary electrons. These modifications in the discharge plasma result in fewer ionizations and thus in less energy loss per extracted ion. Efficient ion extraction was found to depend not only on the grid design, but also (as might

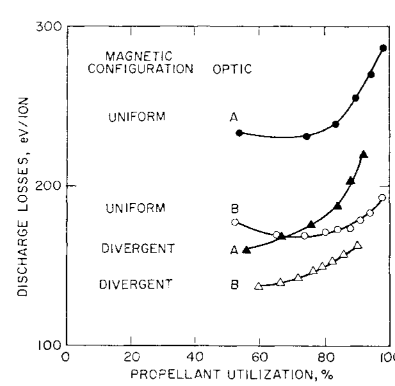

Fig. 3 Effects of uniform and divergent magnetic configurations with extraction optics A (48% transparency) and optics B (71% transparency) on performance.

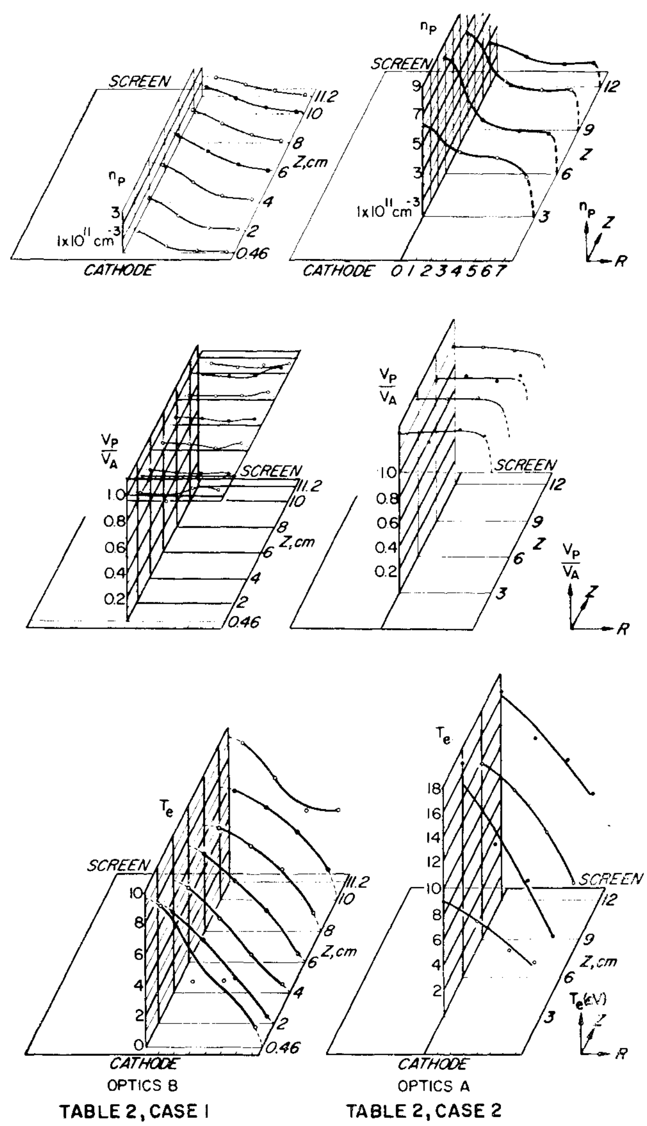

Fig. 4 Distributions of plasma density n_P, normalized plasma potential V_P/V_A, and Maxwellian plasma electron temperature in an oxide cathode thruster with a uniform magnetic configuration, with optics A and B. Operating conditions are given in Table 2.

Table 2 Operating conditions for Figs. 4, 6, and 8

Case	1	2	3	4
Magnetic configuration	Uniform	Uniform	Divergent	
Optics	B	A	A	
Discharge voltage, v	40.4	40.2	41.2	37
Discharge current, amp	1.03	1.15	1.03	1.7
Ion beam current, ma	268	203	240	238
Drain current, ma	1.3	0.9	0.8	0.9
Equivalent neutral current, ma	330	265	265	...
Propellant utilization, %	81	76	77	82
Discharge loss, ev/ion	155	228	208	264
Hollow cathode, ma	...	...	...	40
Neutral flow (total), ma	...	...	...	290

be expected) on the mechanical stability of the mounting system.

Magnetic Field Configuration

Four magnetic field configurations (Fig. 5) were examined. The results shown in Fig. 3 verify the now well-known fact that divergent magnetic configurations give improved thruster performance. The reason for this improvement can be seen from the discharge plasma properties shown in Fig. 6. In the thruster chamber operated with a divergent configuration, the plasma density is less "peaked" in the center of the chamber, and the plasma electron temperature is on the average lower than in the discharge operated with a uniform magnetic configuration. These observations are relatively easy to interpret. The trajectories of the primary electrons are spread over a larger volume of the discharge chamber by the divergent field lines; thus the plasma generation volume "spreads out," and a more uniform plasma density is produced. Because the plasma density is radially more uniformly distributed, a lower over-all plasma density is required to achieve high propellant utilization. A lower over-all plasma density results in fewer Coulomb collisions and consequently in less transfer of energy between primary electrons and plasma electrons. Thus, the energy of the primaries is better utilized for ionization and the discharge losses are reduced. Several configurations with field line patterns of the type shown in Fig. 5b gave similar results; however, if the field lines were made to diverge so much that cathode electrons could intercept the anode on a single transit, thruster performance would begin to deteriorate. A good example of a satisfactory divergent configuration can be seen in Fig. 2. The radial and cusped magnetic configurations shown in Fig. 5c and d were also tested and yielded thruster performance essentially equivalent to that of the divergent configuration. Confinement similar to that in the cusped geometry also has been demonstrated recently by Moore et al.[9] in a configuration labeled magnetoelectrostatic thruster. The radial configuration displays some rather interesting and unique properties, and is discussed in detail in another paper.[10]

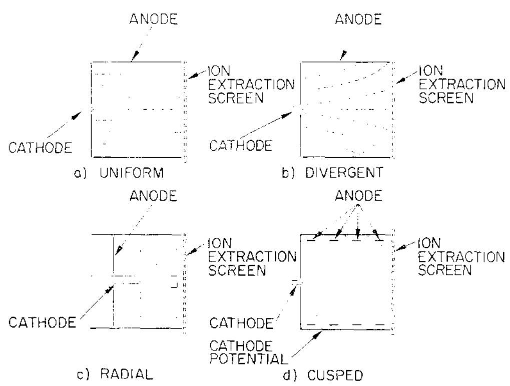

Fig. 5 Sketches of magnetic field line configurations investigated.

Cathode Location and Type

An oxide cathode thruster was operated with a magnetic configuration of the type shown in Fig. 5a, and with the cathode located at a number of axial and off-axis positions. The lowest discharge losses resulted with the cathode lo-

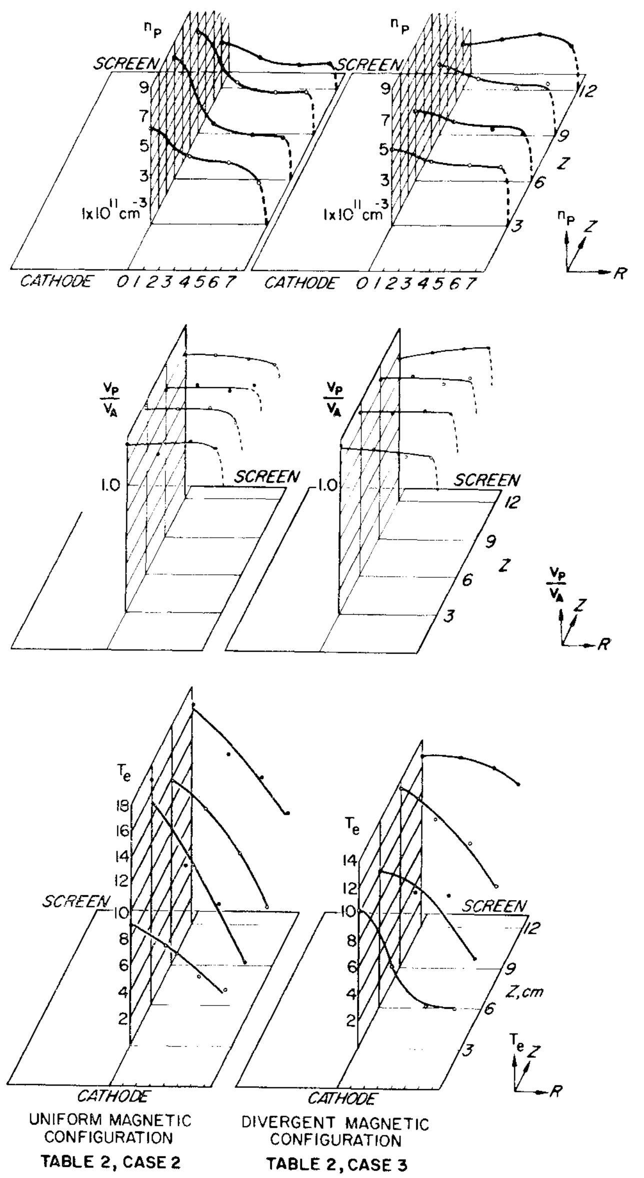

Fig. 6 Distributions in uniform and divergent magnetic configurations with optics A. Operating conditions given in Table 2.

cated on the discharge axis at the upstream boundary of the chamber. This is not too difficult to understand since the magnetic field is axially symmetric, and the cathode best utilizes whatever slight divergence exists in the magnetic field lines when it is located in the upstream discharge chamber boundary.

Integration of a hollow cathode in a thruster requires a parametric effort of the type performed by Bechtel et al.[2] The results obtained by Bechtel et al. were utilized in this study, and only a limited number of parametric variations were performed. The major effort was devoted to probing and understanding the hollow cathode region.

Langmuir probe measurements in the discharge chamber of a SERT II-type thruster (electrode and magnetic configuration shown in Fig. 2) and a similar configuration obtained with the experimental thruster revealed that two distinct plasma regions exist; these are the main discharge chamber plasma and a plasma generated by the hollow cathode within the confines of the cathode pole piece. This latter plasma, which we call the hollow cathode plasma, has properties similar to those found when the hollow cathode is operated in a diode configuration in the spot mode. As can be seen in both Figs. 7 and 8, the plasma potential within this cathode region is nearly level at about 13 to 14 v, the plasma electron temperature is of the order of 1 to 2 ev, and the plasma density rises steeply to nearly 2×10^{11} cm^{-3} on the axis. It is also apparent that the plasma potential rises within the open area between the baffle and the cathode pole piece to the plasma potential of the main discharge volume (approximately anode voltage), where the plasma parameters are little different from those found in the oxide cathode thruster. Thus it can be said that the true electron source in these thrusters is the hollow cathode plasma, and the true discharge voltage is really the difference between anode potential and the hollow cathode plasma potential (since the electron temperature of the hollow cathode plasma electrons is only about 1 to 2 ev). Consequently, the discharge losses associated with hollow cathode thrusters tend to be somewhat higher than for oxide cathode thrusters, partly because the primary electrons are not as energetic (Langmuir probe measurements indicate primary electrons constitute 5% to 10% of the electron density and have an energy equivalent to the discharge voltage) and partly because a portion of the discharge power is really cathode power. The ratio of voltage to current (discharge impedance) was found to be controllable by adjusting the "effective aperture" between the baffle and cathode pole piece. This effective aperture depends upon the physical dimensions of the opening, the magnetic field in the opening, and/or the neutral propellant flow through the hollow cathode. Because ions generated within the hollow cathode plasma have energies of $\leq$13 to 14 ev when they strike the hollow cathode face, the hollow cathode lifetime is limited only by the bombardment

Table 3 **Discharge losses of several optimized thrusters operated at 85% propellant utilization**

Thrusters with oxide cathodes	
JPL[a] 20-cm-diam thruster[1]	130 ev/ion
HRL[b] 15-cm-diam divergent B thruster	158 ev/ion
HRL 15-cm-diam cusped B thruster	182 ev/ion
Thrusters with hollow cathodes	
HRL 15-cm-diam radial *B* thruster[10]	180 ev/ion
NASA 15-cm-diam experimental thruster[3]	183 ev/ion
JPL 20-cm-diam thruster[1]	225 ev/ion

[a] Jet Propulsion Lab.
[b] Hughes Research Lab.

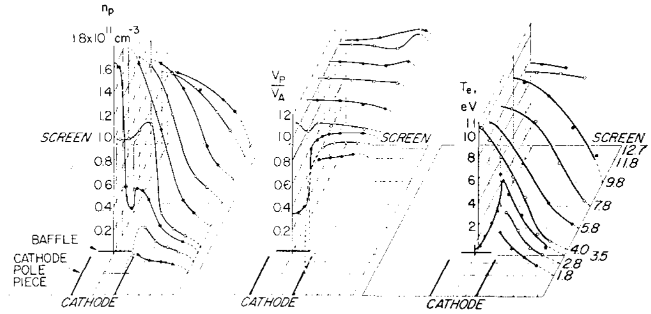

Fig. 7 Probe data for SERT II thruster.

of ions generated in the main discharge volume. This sputter damage could be minimized by appropriate geometric shielding.

Discharge Chamber Length

The discharge chamber length is important in obtaining a plasma of sufficient density and volume to minimize the probability that a neutral atom can traverse the discharge chamber and be lost without being ionized. If the magnetic configuration is uniform (Fig. 6a), the physical length of the chamber is important; in any other case, however, the length of the magnetic confinement region is decisive. This can be concluded from Fig. 8a, which shows that the plasma is confined essentially to the inside of the conical region defined by the diverging magnetic field lines.

Propellant Injection

As long as the neutral propellant atoms are injected into the discharge chamber so that they become well distributed over the discharge volume, the method of propellant injection is of secondary importance. However, if the propellant is injected directly into the energetic electron stream, plasma generation becomes highly localized and the resultant "peaked" plasma density distribution leads to poor performance.

Performance of Well-Tuned Thrusters

Table 3 compares the discharge losses for several well-tuned thrusters, operated at 85% propellant utilization with both oxide and hollow cathodes. The "state-of-the-art" discharge losses amount to 130–182 ev/ion for oxide cathode operation and 180–225 ev/ion for hollow cathode operation. The additional discharge loss observed in hollow cathode operated thrusters (amounting to 20–90 ev/ion) is consumed in the hollow cathode plasma and may be considered a form of cathode heater power.

Conclusions

This study has examined the characteristics of several types of thruster discharge chambers that provide efficient

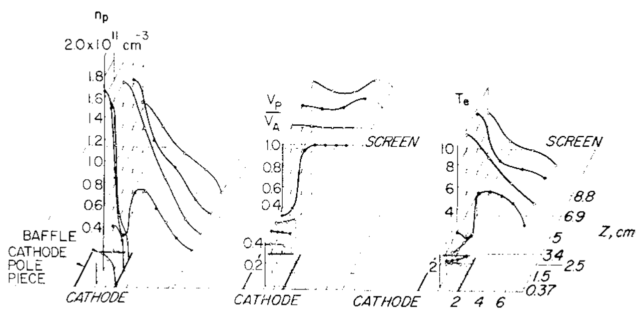

Fig. 8 Distributions for hollow-cathode operated experimental thruster (Table 2, case 4).

thruster performance. These discharge chambers are found to have in common the following physical properties:

1) The plasma density is relatively uniform across the extraction screen and there are no exaggerated local maxima or "peaks" in the spatial density distribution.

2) The plasma potential is essentially constant over the discharge chamber, generally above anode potential, and displays a slight gradient toward the screen electrode. In addition, there is a slight rise in potential near the anode.

3) The plasma electrons have a more or less Maxwellian energy distribution with a temperature on the order of 7 ev. Primary electrons have energies which are an appreciable fraction of the anode voltage and constitute 5 to 10% of the electron density.

These physical properties can be translated into the following configurational requirements for good performance:

a) The magnetic field shape must be arranged so that primary electrons are distributed across the discharge diameter. This results in a plasma with relatively uniform density and electron temperature distributions. A plasma of this type serves as an effective barrier across the screen electrode against the escape of the neutral propellant gas.

b) The anode and all electrodes at cathode potential must be arranged with respect to the magnetic field so that a Penning discharge type confinement results. In particular, those field lines which guide primary electrons must not intercept or come too close to the anode. As a result, all primaries remain trapped long enough to expend their kinetic energy in ionizing, exciting, and energy sharing collisions.

c) With a hollow cathode, the outflow of electrons into the discharge region must be limited by geometrical obstructions and magnetic fields to prevent excessive electron flow rates through the discharge. The discharge voltage can then be raised to a level where the ionization efficiency is high.

d) A high ion-optical transmission must be used. With a transmission on the order of 70%, the discharge adopts a particularly favorable potential distribution which confines ions radially. This significantly improves discharge performance.

It appears (Table 3) that thruster chambers built in accordance with these general rules exhibit similarly good performance.

References

[1] Masek, T. D. and Pawlik, E. V., "Thruster System Technology for Solar Electric Propulsion," AIAA Paper 68-541, Cleveland, Ohio, 1968.

[2] Bechtel, R. T., "Discharge Optimization of the SERT II Thruster," AIAA Paper 67-668, Colorado Springs, Colo., 1967.

[3] Bechtel, R. T., Csiky, G. A., and Byers, D. C., "Performance of a 15 cm Diameter, Hollow-Cathode Kaufman Thruster," AIAA Paper 68-88, New York, 1968.

[4] Reader, P. D., "Investigation of a 10 cm Diameter Electron Bombardment Ion Rocket," TN-D1163, 1962, NASA.

[5] Reader, P. D., "Experimental Effects of Propellant Introduction Mode on Electron-Bombardment Ion Rocket Performance," TN-D2587, 1965, NASA.

[6] Knauer, W. et al., "Discharge Chamber Studies for Mercury Bombardment Ion Thrusters," CR-72440, Sept. 1968, NASA.

[7] Strickfaden, W. B. and Geiler, K. L., "Probe Measurements of the Discharge in an Operating Electron Bombardment Engine," *AIAA Journal*, Vol. 1, No. 8, Aug. 1963, pp. 1815–1823.

[8] Masek, T. D. and Kerrisk, D. J., "Plasma Characteristics for Mercury and Cesium Bombardment Ion Engines," *JPL Space Programs Summary No. 37-32*, Vol. IV, Jet Propulsion Labs., Pasadena, Calif., 1966.

[9] Moore, R. D., "Magnetoelectrostatically Contained Plasma Ion Thruster," AIAA Paper 69-260, Williamsburg, Va., 1969.

[10] Knauer, W., Poeschel, R. L., and Ward, J. W., "The Radial Field Kaufman Thruster," AIAA Paper 69-259, Williamsburg, Va., 1969.