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Performance Capabilities of the 12-Centimeter Xenon Ion Thruster

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PERFORMANCE CAPABILITIES OF THE 12-CENTIMETER XENON ION THRUSTER

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ABSTRACT

The 8- and 12-cm mercury ion thruster systems were developed primarily to provide N-S station keeping of satellites with masses up to about 1800 to 3600 kg respectively. The on-orbit propulsion requirements of recently proposed Large Space Systems (LSS) are beyond the thrust capabilities of the baseline 8- and 12-cm thruster systems. This paper presents a characterization of the performance capabilities of the 12-cm Xenon ion thruster to enable an evaluation of its application to LSS auxiliary propulsion requirements. With minor thruster modifications and simplifications the thrust was increased to 64 mN, a factor of six over the baseline 12-cm mercury thruster performance. The thruster was operated over a range of specific impulse of about 2000 to 4000 seconds and at total efficiencies up to 68.0 percent. The operating levels reached in this study were found to be close to the operating limits of the thruster design in terms of perveance, grid breakdown voltage and thruster component temperatures such as those of the magnets and cathode baffle.

INTRODUCTION

Ion thrusters have been designed to provide both primary and auxiliary propulsion (refs. 1 to 3). The majority of NASA's technology development in the past decade has been with the 8- and 30-cm size thrusters using mercury as the propellant. Only recently the 12-cm thruster has received considerable attention. To meet the projected applications for primary and auxiliary propulsion, and to balance system requirements, the design point nominal thrusts for the 8-, 12-, and 30-cm thrusters were selected to be 5, 10 and 130 mN respectively. Mercury was selected as the propellant for the electron-bombardment thrusters because of its performance capabilities. Because of the number of possible applications for ion thrusters has expanded to include a more comprehensive mix of spacecraft masses, configurations, and orbits, and because the majority of these applications occur in the earth's biosphere, two changes in the technology development of ion thrusters is taking place: (1) the thrust capabilities are being increased and, (2) mercury is being replaced by inert gasses as the propellant.

On-orbit auxiliary propulsion requirements are expected to be in excess of the capabilities provided by the 8- and 12-cm mercury thrusters operating at their design thrust levels. The requirements stem from the masses, configurations, and orbits anticipated for future large spacecraft, such as space-based radar, large communications satellites, and large space systems. The increased requirements, which include east-west stationkeeping, can be met by increasing the thrust of the 8- and 12-cm thrusters, and by employing the 30-cm thruster for auxiliary propulsion. The 8- and 30-cm thrusters have been studied at higher thrust conditions (refs. 4 to 6). The work reported herein, was undertaken to characterize the 12-cm thruster using Xenon as a propellant and operating at higher thrust conditions. The data will complement existing data for scaling purposes. Xenon as a propellant, while suffering but a small penalty in performance with respect to mercury, is more desirable from an environmental and operational standpoint. Environmentally, it will not contaminate the earth's biosphere; nor is it expected to contaminate the spacecraft. Operationally, it allows simplification of the thruster construction, operation, and power processing. The propellant vaporizers and possibly the cathode heaters are unnecessary. Also the feed line high voltage isolator can be simplified and on-off transients minimized. All these thruster simplifications result in commensarate simplifications of the power processor. In addition, operation with Xenon is expected to facilitate turn-on because "preheat" will not be necessary. For these reasons Xenon and other inert gas thruster systems have received considerable attention recently (refs. 7 to 10). The work reported herein was undertaken with Xenon as the propellant.

APPARATUS AND PROCEDURE

Thruster and Feed System

The 12-cm thruster used in this study has been described in reference 11. It has dished-in grids and a small hole accelerator grid. The thruster design evolved from a program referred to as the Modularized Ion Thruster System and was originally intented for use with mercury as the propellant (ref. 11). The design was based upon the 8-cm Engineering Model Thruster (EMT) with the discharge chamber optimized for operation at a beam current of 144 mA and a thrust level of 10 mN. The thruster consisted of an 8-cm thruster Cathode-Isolator-Vaporizer (CIV), a 12-cm diameter discharge chamber and ion optics. The number of magnets was increased from 8 to 16. The main hollow cathode orifice for this test was enlarged to 0.75 mm in diameter from the 0.25 mm diameter orifice of the 8-cm thruster. The original baffle and cathode pole piece was replaced with an updated 8-cm EMT design. The revised assembly had a thicker pole piece to eliminate magnetic field saturation. Baffles made of iron and molybdenum were tested. A schematic of the thruster is shown in figure 1.

The hole sizes of the screen and accelerator grids in the two-grid ion optics were 1.91 and 1.04 mm respectively. The hole sizes in each grid were all uniform.

In the 12-cm EMT design, as in the 8-cm, all the propellant flow passes into the discharge chamber through the main discharge cathode. To increase the thruster performance and flexibility of operation, a second propellant feed system was added. This consisted of a stainless steel tube plenum installed on the backplate of the thruster. The propellant flow through the plenum into the discharge chamber was controlled independently of the main discharge cathode flow.

Gas flow rates were measured with mass flow rate transducers. Flow rate calibrations for Xenon were obtained using conversion factors supplied by the transducer vendor. The propellant flow rates were manually controlled by high precision needle valves.

Because operation with Xenon does not require a vaporizer, the propellant feed system was modified to eliminate the mercury vaporizer and isolator. High voltage isolation was achieved with the installation of a 20-cm high-quality rubber tube in the propellant line.

The ground screen was wrapped with small-mesh wire screen to significantly reduce the frequency of high voltage breakdowns (ref. 12).

Six Iron-Constantan thermocouples were installed on the thruster at various locations. Isolation transformers were used for thermocouples attached to thruster components at high voltage.

Power Supplies and Facility

The power processor consisted of laboratory power supplies, with the discharge and screen grid supply capabilities of 10.0 and 2.0 amp, respectively. The total accelerating voltage was limited to 3000 volts with 2000 and 1000 volts on the screen and accelerator supplies respectively.

The tests were performed in a 1.5 x 6.1 meter vacuum facility with water cooled diffusion pump traps and no cryogenic cooling in the baffles. The facility with the thruster operating had a pressure (corrected for Xenon) of about 1.3×10^{-3} Pa (1×10^{-5} torr).

The correction for gas ingested into the thruster from the facility is considered negligible (~6 mA at a pressure of 1×10^{-3} Pa) and, therefore, has been neglected in the data presented herein.

Thruster Operation

The modified 12-cm thruster is operated with the dual propellant feed systems just as the 30-cm thruster. The one control loop adjusts the valve in the main cathode propellant line to provide the proper flow rate for obtaining a desired discharge voltage. The beam current, on the other hand, is controlled by a valve in the main propellant line and a proper choice of discharge current. In this study all tests were conducted with an open loop, that is, the propellant flow rates were adjusted manually. Higher beam current levels were achieved by increasing both the discharge current and the propellant flow rates. As higher beam currents were obtained, the screen and accelerator voltages were increased as necessary to prevent ion impingement on the accelerator grid.

RESULTS AND DISCUSSION

The results of tests conducted to evaluate the extended performance capability of the 12-cm Xenon ion thruster are presented here. Performance of the thruster with single and double propellant feed systems is compared. The performance limits of the thruster are defined in terms of the current carrying capacity of the grids or perveance, component temperatures, beam current, and life time considerations.

Thruster Performance

Figure 2 shows the beam current of the 12-cm Xenon thruster, with a single propellant feed system, as a function of discharge propellant mass flow rate at various discharge current values. The beam current is seen in general to increase with the discharge current and the propellant flow rate, except that increasing the mass flow rate beyond an optimal value results in decreasing the beam current. Operation in this region is usually referred to as the "low mode". Unlike operation with mercury as a propellant, two beam current peaks are observed at a discharge current of 2.0 A. The first is characterized by relatively high ion production costs and high mass utilization whereas the second peak has lower ion production costs but a lower mass utilization. Increasing the discharge current to 3.0 A from 2.5 A did not result in increasing the beam current. The leveling off of the beam current at this discharge current level is associated with a decrease in the discharge voltage. At higher discharge current and power levels, higher beam currents were attained, but at higher energy cost per beam ion (see fig. 6). The measured mass utilizations of greater than 100 percent are due to multiply charged ions.

Figure 3 shows the beam current as a function of discharge power at various total discharge propellant flow rates for the dual propellant feed system configuration. For each total discharge propellant flow rate, the data are plotted for a constant ratio of cathode to total flow rate. The discontinuity of beam current with increasing discharge power seen between 140 and 160 watts for the two lowest total mass flow rates seem to correspond to the low mode operation shown in figures 2 and 3. At total flow rates > 540 mA and an optimal cathode-to-main flow rate ratios, the transition is not observed.

Figure 4 compares the maximum beam current as a function of discharge power for the single and dual propellant feed systems. The curves are obtained from data similar to that plotted in figures 2 and 3, with the maximum beam current at a given discharge power level determined from varying both the discharge current and the cathode-to-main flow ratio. Table I lists the other thruster parameters for the data that defines the maximum beam current values.

It is evident from figure 4 that the dual feed system considerably improves the 12-cm thruster performance at the higher discharge power levels by reducing the beam ion production cost. A beam current of 1.0 A with the two propellant feed system was obtained at a cost per beam ion of 255 watts/beam A. This value of beam current corresponds to a beam current density of 8.9 mA/cm^2 and represents a seven fold increase over the baseline beam current of a 12-cm thruster. Similar current densities (8.4 mA/cm^2) have been obtained by Rawlin (ref. 10) with a 30-cm J-Series thruster with mercury and argon as propellants. As expected, the ion production costs as well as the mass utilization of the 30-cm thruster are somewhat better than those measured with the conventional 12-cm thruster. Substantially improved performance has been achieved in ion thrusters utilizing a newly applied ring cusp plasma containment configuration, as demonstrated by Sovey (ref. 13).

The propellant efficiencies quoted in table I include the fixed neutralizer flow rate of 45 mA of Xenon. No attempt was made to optimize the neutralizer performance, which would have resulted in improved mass utilizations.

The thruster performance data presented herein has not been corrected for the presence of doubly charged Xenon ions. Data on the production of doubly charged ions in a 12-cm thruster is not presently available. However, Sovey (ref. 13) has measured the doubly charged ion content in the ring cusp 30-cm thruster over a wide range of discharge voltages and with various propellants. For Xe, he obtained centerline ratios of doubly to singly charged ions as high as 1:5. Sovey concluded that for a thrust loss of less than 5 percent and acceptable grid lifetimes, Xenon thrusters must be operated at a discharge voltage of 35 volts or less.

Figure 5 indicates that for discharge voltages ≤ 35 volts, a 12-cm Xenon thruster must be operated at a total discharge propellant flow rates of about 330 mA or higher. This figure shows the minimum discharge voltages measured as a function of total propellant mass flow rate for various cathode to main flow rate ratios. The minimum discharge voltages plotted were obtained at elevated cathode flow rates resulting in lower than optimum mass utilization values.

Typical beam ion production energy costs are plotted in figure 6 as a function of total discharge propellant utilization efficiency. From the beam current values given next to each data point, it may be seen that for a given discharge current the maximum beam current is obtained near the minimum ion production cost. Because the minimum beam ion energy cost corresponds with the minimum discharge voltage, generally it is desirable as well to operate the thruster near the minimum value of the ion production curve for optimum life time.

Figure 7 shows the perveance characteristics of the dished in 12-cm grids. The measured perveance slope of 1.82 agrees well with the values of 1.8 to 2.0 measured for 8- and 30-cm thruster grids (refs. 4 and 6). The data indicates that the minimum required total voltage for a beam current of one ampere is about 2500 volts. Because voltages of about 3000 volts begin to cause electrical breakdowns between the grids, a beam current of one ampere is close to the limit for the present two-grid optics configuration.

To operate the thruster over a wide range of specific impulse, it is essential to operate over a large range of R (ratio of screen to total voltage). Figure 8 shows the accelerator impingement current as a function of R at an arbitrary total voltage of 2000 volts. The data indicates that a range of R between 0.3 and 0.8 is obtainable over a wide range of beam current with the present ion optics.

Figure 9 shows the thrust to power ratio as a function of specific impulse at a beam current of 610 mA. The data was obtained by varying the R ratio at a fixed total voltage of 2000 volts, with the discharge power and total mass utilization constant. The thrust-to-power ratios between 32.0 to 42.0 mN/kW were measured over a specific impulse range of 2000 to 4000 sec. This is comparable with 30-cm J series inert gas thruster performance (ref. 10), but somewhat less than 8-cm mercury thruster performance (ref. 4). Optimization of neutralizer performance in the 12-cm thruster would somewhat increase the thrust to power ratio for a given specific impulse over the full plotted range of figure 9.

The thrust and total thruster efficiency as a function of thruster input power are shown in figure 10. The data was determined at the maximum beam current conditions, as defined previously. The thrust to power ratio is seen to be constant at 32.2 mN/kW over the entire power range to 1.9 kW under the test conditions. The measured total efficiency of 55 to 70 percent is also relatively constant. The 60 mN thrust measured at 1.85 kW of input power represents a six fold increase over the baseline 12-cm mercury thruster thrust level. This thrust level was achieved at close to the thermal limits of the present thruster design. This is discussed in more detail in the next section.

Thruster Component Temperature Measurements

Figure 11 shows the measured temperatures of the thruster backplate, screen grid and ground screen as a function of discharge power. The thruster components most readily degraded by excessive temperatures are the magnets. The ALNICO V magnets begin to experience reversible field losses at about 450° C. The magnets operate close to the temperature of the backplate. As figure 13 indicates, the thruster backplate and screen grid reach temperatures of 400° C at about 200 watts discharge power. In the present tests, a beam current of 1 amp required a discharge power level of about 200 watts. For extended thruster operation at these beam current levels, the thruster electrical efficiency must be improved so that the discharge power can be lowered at a given beam current. It is believed that beam ion production costs of 200 to 220 W/beam A can be achieved in this thruster by rather simple optimization of the discharge chamber physical and magnetic design.

Masek (ref. 14) has derived an equation for the maximum beam current from a thruster based on thermal limitations as

$$(J_B)_{max} = 1.67\times10^{-2}\ D^2 \quad \text{(amps)} \tag{1}$$

where D is the diameter (cm) of the thruster. The constant was derived from a thermal model and temperature mapping of a 30-cm mercury thruster assuming ion production cost of 185 W/beam A and a maximum ion optics temperature of 700° C. If the increased ion production costs of a 12-cm thruster are taken into account and the maximum temperature is reduced to 450° C the equation for the maximum beam current becomes:

$$(J_B)_{max} = \frac{1.85}{(\text{W/beam A})}\ D^2 \quad \text{(amps)} \tag{2}$$

Table II lists the equation (2) calculated and the measured beam current limits of the 8-, 12- and 30-cm ion thrusters. The calculated values are normalized with respect to the 30-cm thruster and are based on beam ion production costs measured at near-maximum beam current conditions. It is noted that the agreement between the calculated and measured maximum beam current is within about 15 percent for the 12-cm thruster. However, the discrepancy becomes larger for the smaller 8-cm thruster. Table II also gives equation (2) calculated beam current limits for the 8- and 12 cm-thrusters based on improved beam ion production costs, which should be readily achievable.

The only thruster component that suffered severe effects during the high power testing was the cathode baffle. The original baffle made of tantalum experienced no damage. However, the replacement iron baffles overheated and came close to melting. The exact reason for the overheating of the baffle has not been determined. There was no evidence that any of the thruster magnets overheated during the testing.

CONCLUSIONS

The performance capabilities of the 12-cm Xenon ion thruster were characterized in this study. It was found that the addition of a second propellant feed system improved thruster performance and versatility. Beam currents up to 1.0 amp were obtained. This value corresponds to a thrust level of about 60 mN, a factor of six greater than in the baseline operation of the 12-cm mercury thruster. Discharge voltages of less than 35 volts, needed for lifetime considerations, required propellant mass flow rates of 330 mN or greater. The thruster was operated over a range of specific impulse of 2000 to 4000 sec. Total thruster efficiencies up to 70 percent were obtained. The total propellant utilization at the maximum beam current, for a given discharge power, ranged between 70 and 90 percent. The utilization efficiencies would have been higher with optimized neutralizer operation. The ion production costs under maximum beam conditions ranged from 210 to 250 W/beam A.

The operating levels of the 12-cm Xenon thruster reached in this study are close to the operating limits of the present thruster design in terms of perveance, grid breakdown voltage, and certain thruster component temperatures. The total voltage required for 1.0 amp beam operation was about 2500 volts. The measured temperatures of the discharge chamber components reached 400° C at discharge power levels of 200 watts. These temperatures approach the thermal limits (~450° C) of the thruster magnets at power required for operation at 1A beam current.

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TABLE I. - THRUSTER PARAMETERS AT OR NEAR MAXIMUM BEAM CURRENT CONDITIONS
FIXED ELECTRICAL LOSSES: 10 W; NEUTRALIZER FLOW RATE: 45 mA.

Beam voltage, V	Beam current, mA	Discharge voltage, V	Discharge power per beam amp., W/amp	Measured total propellant efficiency[a]	Thruster input power, W	Thrust,[b] (mN)	Specific impulse (sec)	Thruster efficiency	Discharge current A	Thruster electrical efficiency
1600	198	50.5	235	0.70	373	12.4	3270	0.54	1.0	0.85
	254	45.7	244	.79	479	16.0	3700	.60	1.5	.85
	284	37.3	234	.79	530	17.8	3700	.61	2.0	.86
	357	31.8	200	.70	653	22.5	3270	.55	2.5	.87
1400	442	31.7	220	.79	705	26.0	3450	.59	3.5	.83
1400	550	41.7	225	.90	903	32.3	3930	.69	3.5	.85
1800	652	33.0	220	.74	1328	43.4	3670	.59	5.0	.88
	743	34.4	266	.83	1535	49.5	4110	.65	6.5	.87
	738	32.0	230	.72	1498	49.2	3570	.58	6.0	.89
	853	34.2	265	.84	1762	56.8	4170	.66	7.5	.87
1620	1013	33.9	250	.86	1877	63.9	4040	.68	8.5	.87

[a]Uncorrected for doubly charged ions.
[b]Fixed thrust loss of 5% assumed due to Xe^{++} beam content and beam divergence

TABLE II. - THERMALLY-LIMITED THRUSTER PERFORMANCE

Thruster		Assumed limiting temperature, °C	Measured beam ion cost, W/beam A	Beam current limit, A		Assumed improved beam ion cost, W/beam A	Calculated beam current limit, A
Diam. (cm)	Propellant			Calculated	Measured		
30	Hg	450	185	9.0	----	---	----
12	Xe	450	306	.87	1.0	250	1.1
8	Hg	450	395	.3	.4[b]	260	.45

[b]Extrapolated value.

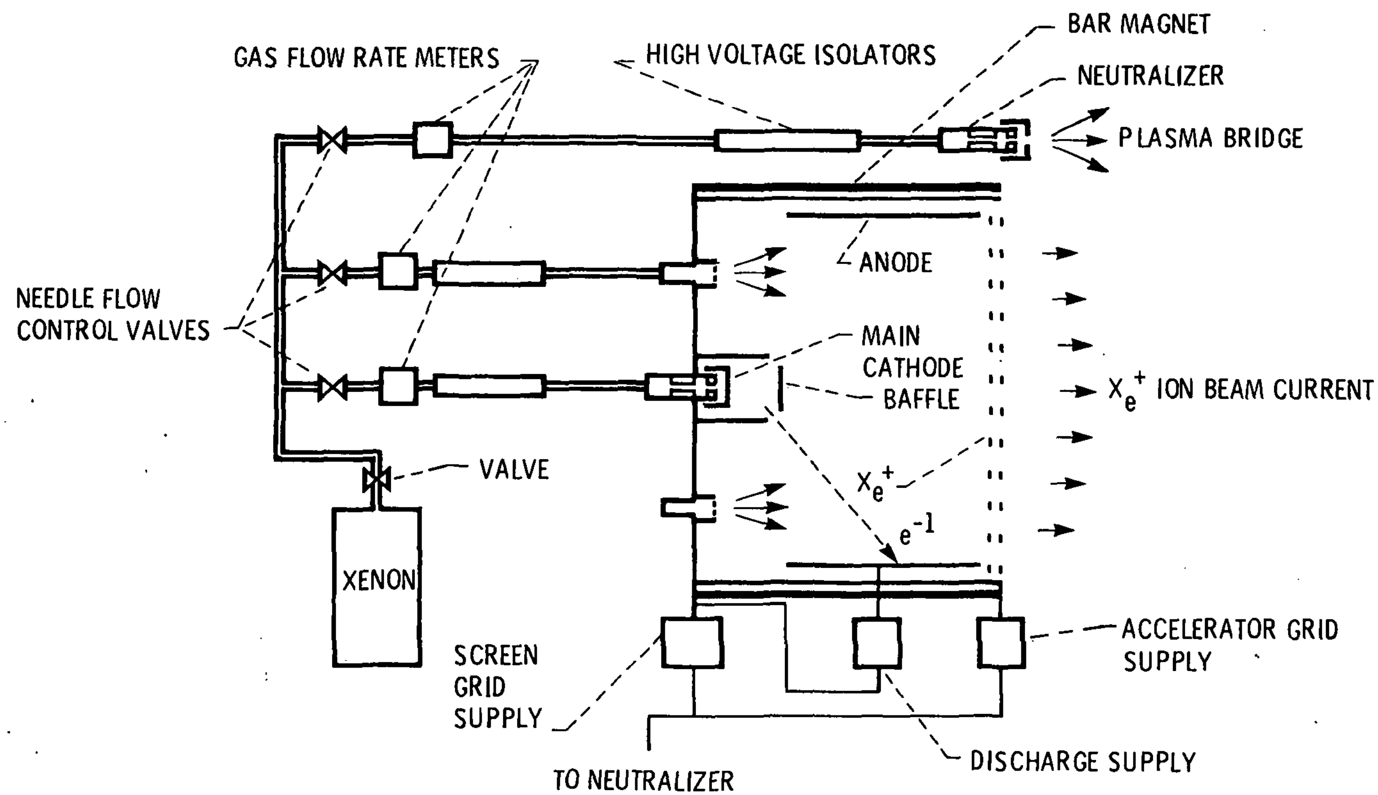

Figure 1. - Xenon ion thruster schematic.

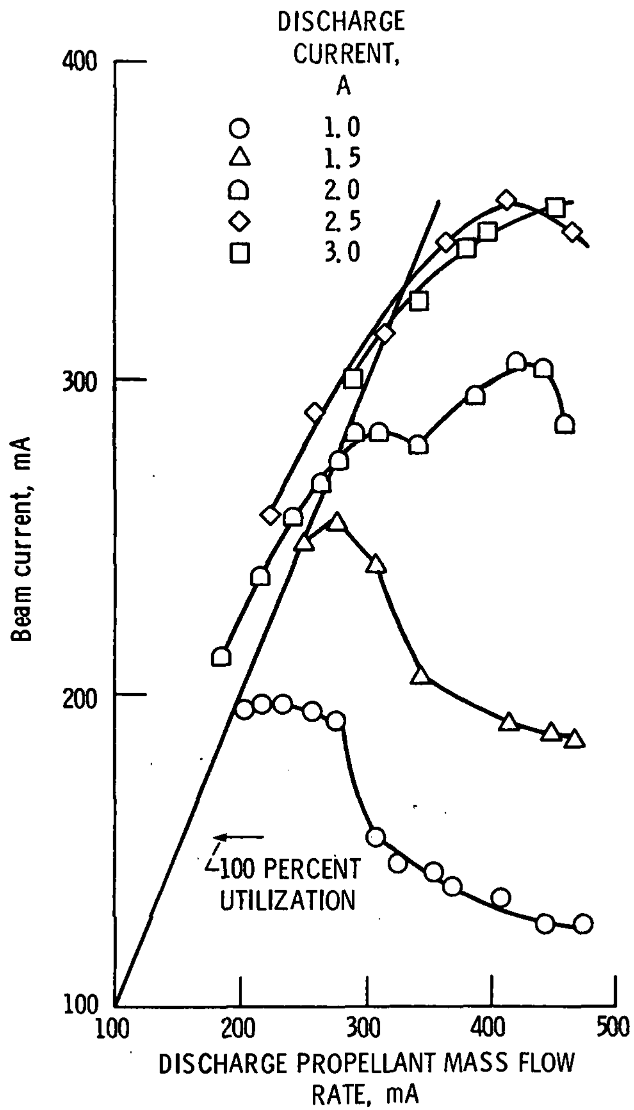

Figure 2. - Beam current as function of propellant mass flow rate at various discharge currents. (Single propellant feed system.)

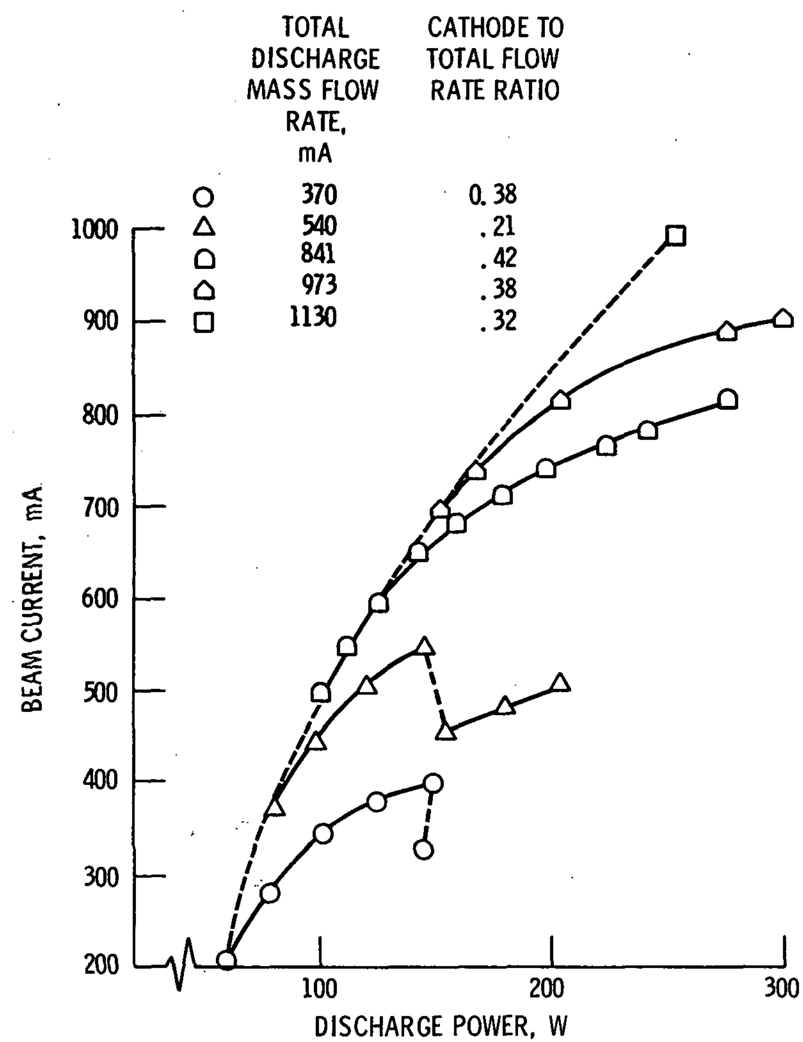

Figure 3. - Beam current as function of discharge power at various cathode to main flow ratios.

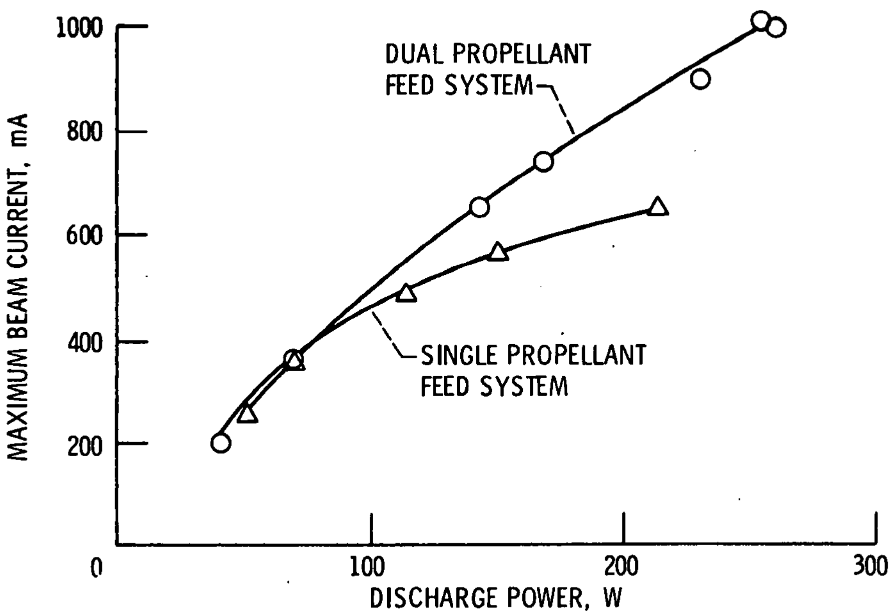

Figure 4. - Maximum beam current as function of discharge power.

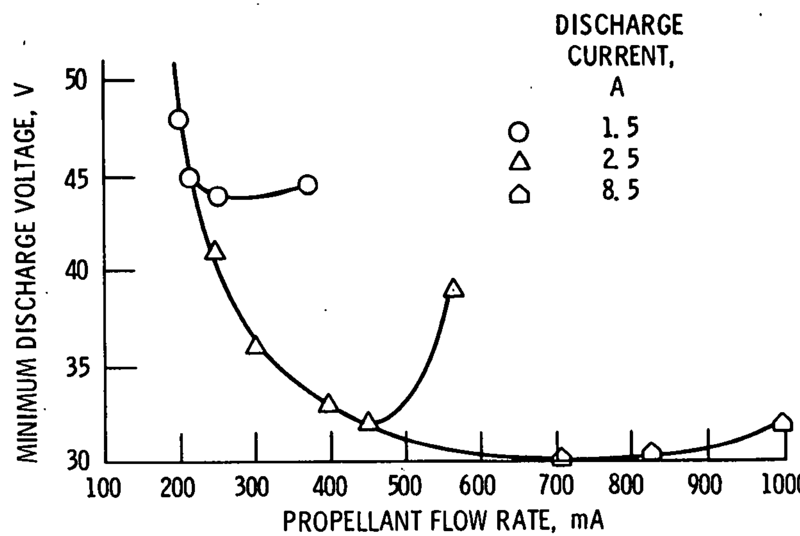

Figure 5. - Minimum discharge voltages as function of propellant flow rate, with dual propellant feed system.

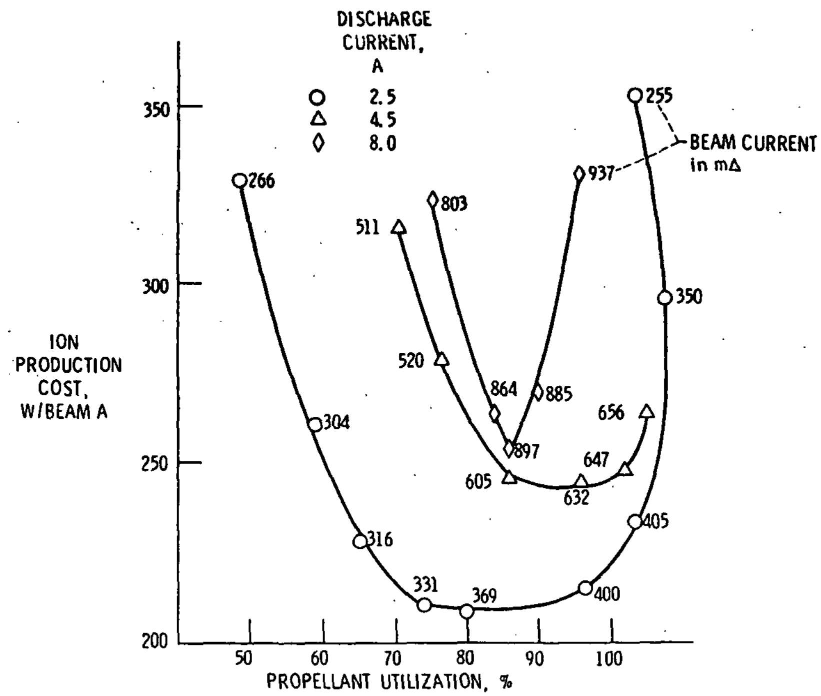

Figure 6. - Beam ion production cost as a function of discharge propellant utilization. Dual propellant feed system.

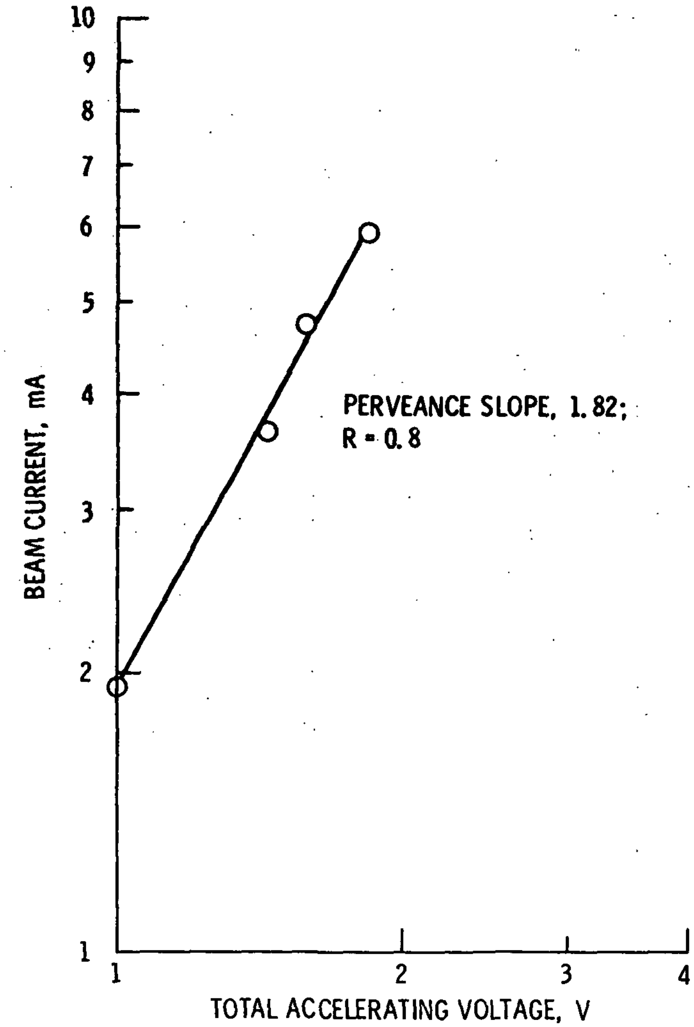

Figure 7. - Perveance of 12-cm xenon thruster with dished-in two-grid ion optics.

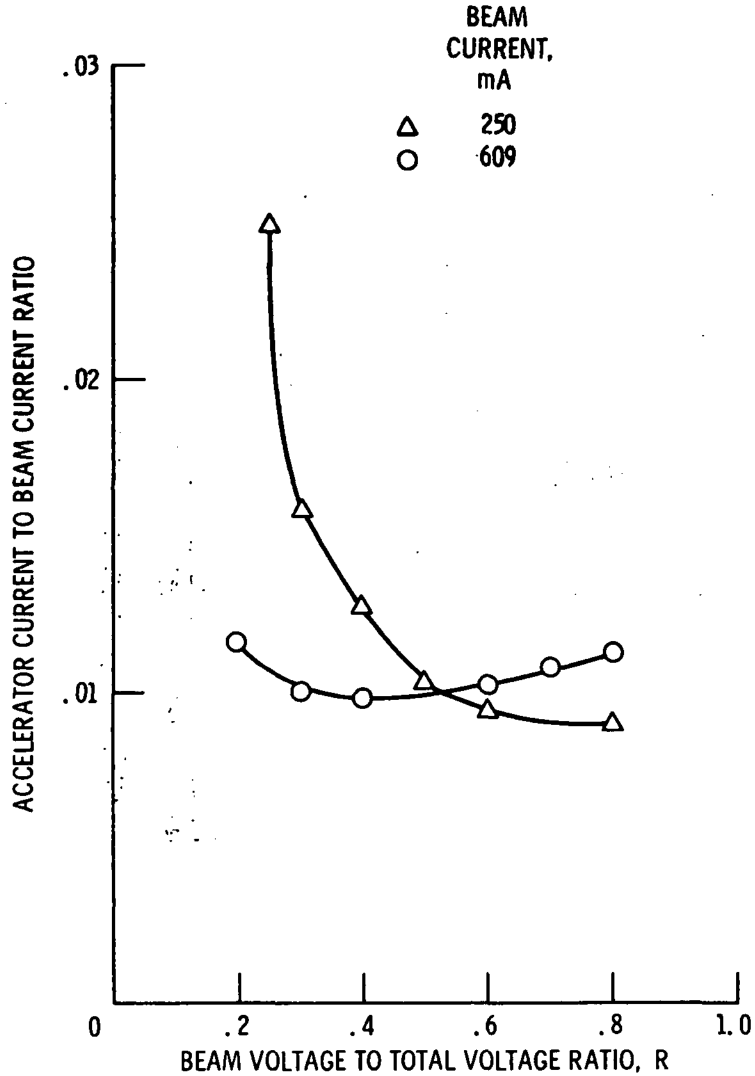

Figure 8. - Accelerator impingement current as function of beam voltage to total voltage ratio R. Total voltage, V_T, 2000 V.

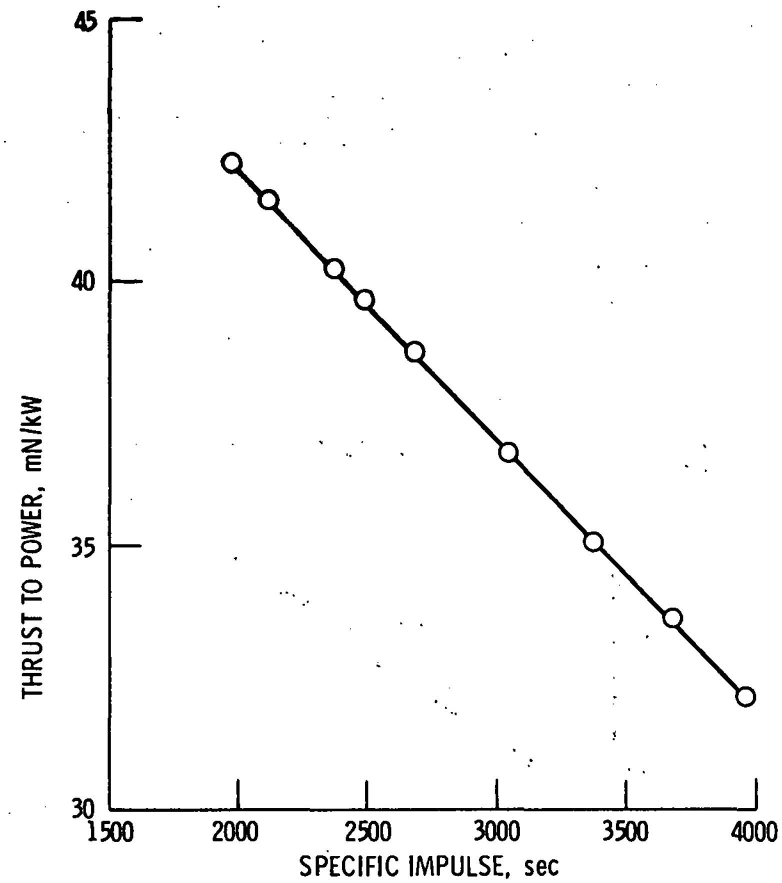

Figure 9. - Thrust to power ratio as function of specific impulse. Beam current, 610 mA; total voltage, 2000 V.

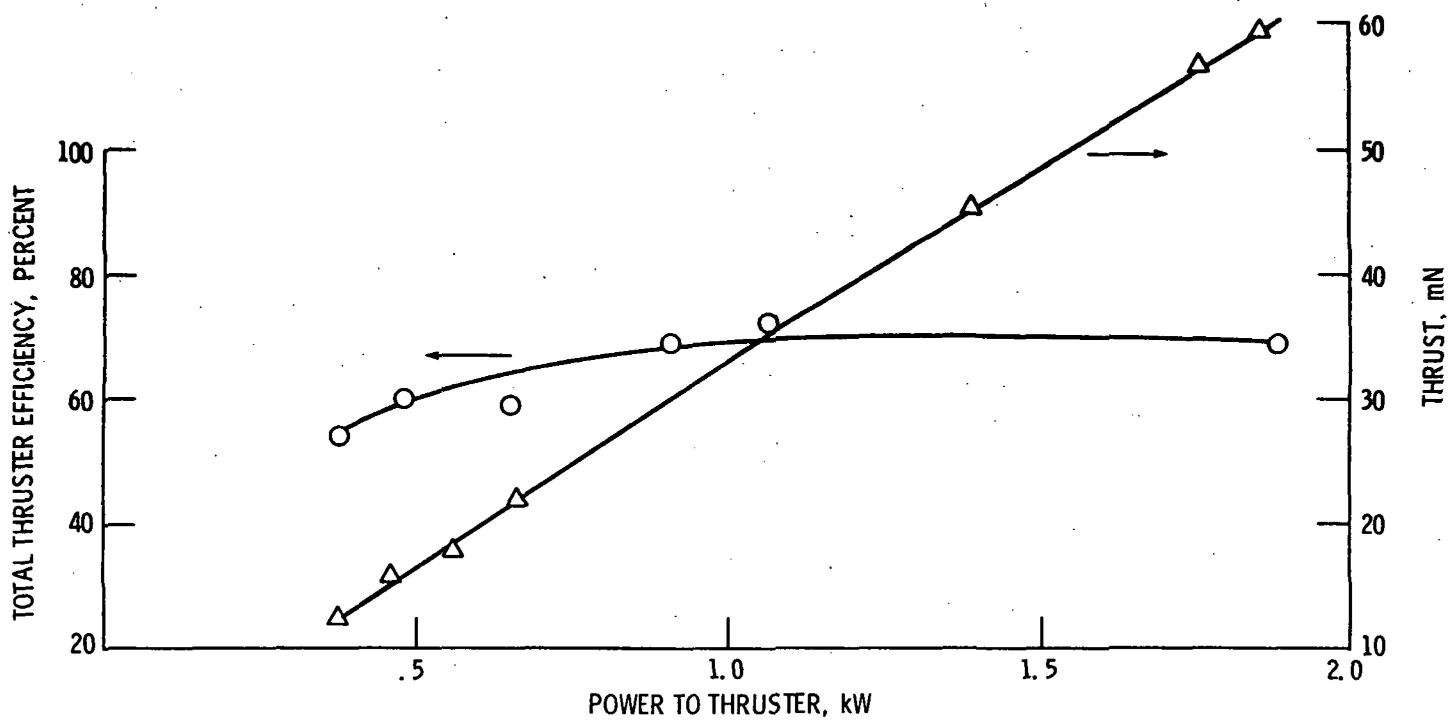

Figure 10. - Total thruster efficiency and thrust at maximum beam current conditions as function of thruster input power. Beam voltage to total voltage ratio, R, 0.8.

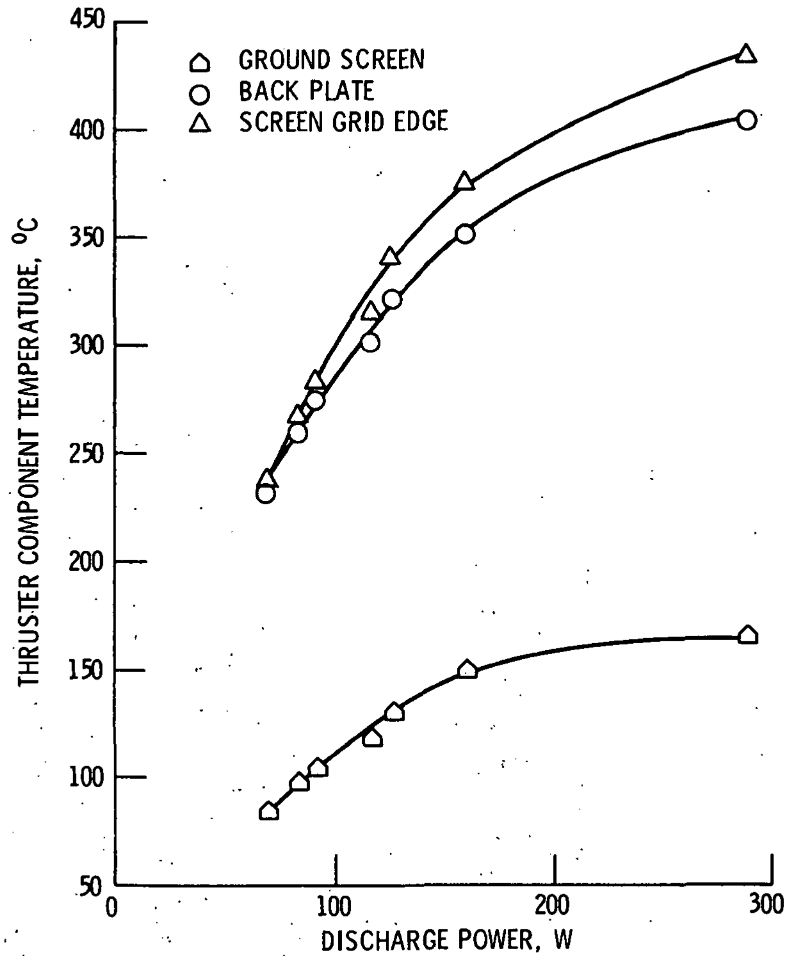

Figure 11. - Thruster component temperatures as function of discharge power.

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16. Abstract

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