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# Extended Operating Range of the 30-cm Ion Thruster with Simplified Power Processor Requirements

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# EXTENDED OPERATING RANGE OF THE 30-cm ION THRUSTER WITH SIMPLIFIED POWER PROCESSOR REQUIREMENTS

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## Abstract

The characteristics of power processors, which are defined by thruster and spacecraft requirements, strongly impact the overall performance and cost of electric propulsion systems. This paper presents the results of tests and analyses conducted to evaluate simplified power processing. A two grid 30-cm diameter mercury ion thruster was operated, with only six power supplies, over the baseline J-series thruster power throttle range with negligible impact on thruster performance. An analysis of the Functional Model Power Processor showed that the component mass and parts count could be reduced considerably and the electrical efficiency increased slightly by only replacing power supplies with relays. The input power, output thrust, and specific impulse of the thruster were then extended, still using six supplies, from 2660 watts, 0.13 newtons, and 2980 seconds (maximum baseline values) to 9130 watts, 0.37 newtons, and 3820 seconds, respectively. Increases in thrust and power density will enable reductions in the number of thrusters and power processors required for most missions. Preliminary assessments of the impact of thruster operation at increased thrust and power density on the discharge characteristics, performance, and lifetime of the thruster were also made.

## Introduction

The 30-cm diameter mercury (Hg) ion thruster, proposed for solar electric propulsion, has evolved to a state of technology readiness.[1,2] Functional model power processors (FMPP) have been built[3,4] and are presently being endurance tested with baseline J-series, thrusters.[5] The major purpose of the FMPP is to condition the unregulated solar array power into the various regulated voltages and currents needed to satisfy the thruster operating requirements. The FMPP was designed to meet the requirements of 30 cm thrusters as they were perceived in 1972. Those requirements were specified to accommodate a very broad spectrum of solar electric propulsion missions which included planetary[6] and Earth orbital[7] missions. The resultant FMPP allows great flexibility in thruster operation but at the cost of power processor complexity. As shown in Fig. 1, the FMPP has 12 power supply outputs which provide the power required by the thruster.

Reference 8 presented initial results of a program to evaluate reductions of the thruster-power processor interface requirements and thereby reduce the mass and cost, and increase the efficiency and reliability of proposed thrust subsystems. This paper presents the results of further tests and analyses conducted to evaluate the impact of power processor simplifications on thruster performance and FMPP properties over baseline conditions.

The payload capability of any solar electric propulsion mission is enhanced when the propulsion system mass is reduced without compromising operational lifetime. One way of reducing the propulsion system mass is to reduce the number of thrusters and power processors by increasing the thrust and power per thruster-power processor combination. This paper also presents the results of tests in which the thruster was operated, with six power supplies, and characterized over an extended range of thrust and input power.

## Apparatus

### Thruster

A 30-cm diameter laboratory thruster, functionally equivalent to the baseline Engineering Model J-series thruster,[2] was used for the tests presented herein. One major difference was the use of electromagnets, rather than permanent magnets, to provide the magnetic field in the discharge chamber. Except as noted, the magnetic field was held fixed at a configuration fully equivalent to that of the J-series thruster. With the exception of a few tests, which are specified in the text, the magnetic baffle coil and mounting tube were eliminated. Non-magnetic physical baffles of various diameters were mounted from the downstream end of the cathode pole-piece.

### Power Supplies

All of the data were obtained from 60 hertz, laboratory power supplies. The screen and accelerator high-voltage supplies were of a high-capacity, three-phase, full-wave bridge rectifier design. The discharge, magnetic baffle, electromagnets, main and neutralizer keeper supplies were single-phase, full-wave, rectified sources. The resistive heaters were powered with six alternating current supplies. Because the electromagnetic field is usually provided by permanent magnets, the two magnet supplies were not counted in power supply tallies.

### Facility

The tests were conducted in a 0.9-m diameter bell jar of the 7.6-m diameter by 21.4-m long vacuum tank at Lewis Research Center. The facility pressure was about $5 \pm 3 \times 10^{-6}$ torr for all tests.

## Results and Discussion

A 30 cm diameter Hg ion thruster was tested with a reduced number of power supplies over an extended range of thrust and input power. The results of those tests are presented below and are separated into two sections. The first describes thruster operation over the baseline range of input power (0.7-2.7 kW) with a reduced number of power supplies for single point and variable input power operation. A preliminary assessment of the impact of reducing the number of power supplies in the FMPP is made. The second section describes the results of thruster operation when the input power range was extended upward to more than 9.1 kW. The thruster-power supply interface characteristics of subassemblies such as the cathode pole piece, discharge chamber, ion optics, and neutralizer are also described.

## Baseline Operating Range

Reduced number of power supplies. Figure 1 shows the interconnection diagram for the baseline 30-cm thruster and FMPP. Twelve power supplies provide the necessary voltage and currents to provide propellant flow control, ion production, ion acceleration, and beam neutralization. For single point steady-state thruster operation (constant propellant flow rates) only the five power supplies shown in Fig. 2 are required.[8] The heater and cathode keeper power supplies are required only during startup. Vacuum relays were used, as shown in Fig. 2, to allow the startup functions of those four supplies to be provided by the five steady state supplies. In addition, the magnetic baffle coil and power supply were eliminated and the three Hg vaporizers were operated in parallel from one supply. Fixed adjustable resistors, in series with the vaporizers (Fig. 2) were used to obtain the necessary currents to the vaporizers. To start the thruster, vacuum relays S1 through S4 were closed (Fig. 2) to provide power to the appropriate resistive isolator and cathode heaters. After sufficient "preheat" time had elapsed, the vaporizer power was applied. When the propellant flow rates from the cathode and neutralizer vaporizes were about 100 and 50 equivalent milliamperes, respectively, switches S1, S2, and S4 were actuated. This applied the open circuit discharge voltage to the cathode keeper and anode and the open circuit neutralizer keeper voltage to the neutralizer keeper electrode. The cathode keeper discharge was established almost immediately and would couple to the anode within 10 seconds. The neutralizer discharge was usually established within 10 seconds of switch actuation.

The high voltages could now be applied as usual to extract the ion beam. Relay S3, which replaced the cathode keeper supply, could be opened before or after beam extraction, with no differences in thruster performance noted at any operating point over the throttle range or during the high-voltage recycle sequence. Additional information on thruster "start up" with a similar configuration may be found in Ref. 8. The use of double-ended isolator or cathode heaters would permit the elimination of S1 or S2.

For single point operation the experimental thruster was started with the three vaporizers connected in parallel as shown in Fig. 2. The vaporizer supply output power was controlled via a feedback loop from the beam current. The variable resistors were adjusted to vary the cathode flow rate in order to set the discharge voltage and also to adjust the neutralizer flow rate to about 40 eq. ma. The thruster could then be shut down, restarted without adjusting the resistors, and be controlled at the original beam current and discharge voltage. This procedure was demonstrated, for single point operation, at several values of beam current from 0.75 to 2.0 A. If desired for lifetime considerations, small variations in the discharge voltage (<1 V) could be corrected by adjusting the discharge current (<1 A).

As explained in Ref. 8, the range of efficient and stable operation is limited when the cathode and main Hg flow rates are not independently controlled. It is desirable to operate thrusters of this design at near constant cathode and neutralizer propellant flow rates. Large variations of beam current require large variations in main flow rate and thus, separate control of the main vaporizer. Therefore, a sixth power supply will be necessary when mission considerations require large variations of beam current.

As an alternative method of power throttling, Ref. 8 showed that the use of three-grid ion optics would allow about a 3.7:1 variation of beam power at a constant beam current of 2.0 amp. This approach would only require the five supplies shown in Fig. 2.

The experimental thruster has been operated at fixed conditions with only five power suplies and over the baseline power throttle range with six power supplies.

Impact on power processor properties. An analysis was made of the impact of reducing the number of power supplies (and associated components) in the FMPP to that shown in Fig. 2. Parameters of the FMPP which were compared were component mass, parts count, and electrical efficiency. Table I lists the values of these parameters for FMPP and the percentage change for the five and six supply power processors. For single point operation the anticipated reduction in mass and parts count are 14 and 37 percent, respectively, while the electrical efficiency was estimated to increase by 1.6 percent. The need for a separate main vaporizer to allow beam current variation, would slightly negate some of these improvements. Use of a new circuit design, such as that described in Ref. 10, for the vaporizer and neutralizer keeper power supplies would permit total reductions of component mass and parts count of 20 and 50 percent, respectively, from that of the present FMPP. In addition, the large reduction in the number of parts would be expected to permit a reduction in the required structure.

Impact on thruster and power processor performance. The performance of the experimental thruster, operated with a tantalum non-magnetic baffle, was compared with that of the baseline J-series thruster. Decreasing the baffle diameter from 5.6 to 5.1 cm, to allow nominal thruster operating parameters at the maximum power point of the J-series power throttle profile, was the only attempt at optimizing the thruster performance.

As the thruster was power throttled downward from the 2 to 1 amp beam current points, at a constant discharge voltage of 32 V, the cathode flow rate remained nearly constant. J-series thrusters normally operate over this range with a nearly constant magnetic baffle current and cathode flow rate. Operation of the J-series thruster at lower values of beam current results in discharge instabilities unless the magnetic baffle current increased to raise the discharge impedance and thereby cause an increase the cathode flow rate. Operation of the experimental thruster at values of beam current less than 1 ampere was attained by lowering the discharge voltage set point from 32 to 30 volts and raising the discharge current to maintain values of discharge power per beam ampere equal to those of the J-series throttle profile. Table II shows that over the baseline power throttle profile, the measured propellant utilization efficiency was between 2 and 2.8 percent lower than that of present J-series thrusters. However, optical spectrometer measurements indicated a 14 percent reduction in the ratio of doubly to singly charged ions, which suggest that the corrected propellant utilization efficiency was only about 1 percent lower than that of the J-series thruster. Over the throttle range, the electrical efficiency of the thruster varied from 0.2 to 1.3 percent greater than that of the J-series thruster because there were no power losses for the cathode keeper or magnetic baffle. When thruster efficiency variations are combined with expected power processor efficiency gains (Table I) the total efficiency of the thruster and power processor is increased slightly (<1 percent) over that of the J-series thruster and the present FMPP.

## Extended Operating Range

Power supply requirements. The experimental thruster was operated with six power supplies over a range of thruster input power which was varied from 0.7 to 9.1 kW. The beam current was varied from 0.75 to 5.0 amp. With respect to the FMPP, the discharge current capability was increased from 14 to about 50 amperes. The beam voltage and current capabilities were increased from 1100 volts to 2.1 amp to 1600 volts at 5.2 amp. The accelerator grid voltage capability was also increased from 500 to 1000 volts. The supply used for operating the three vaporizers in parallel had a current capability of 5 amperes. The neutralizer keeper current capability was increased from 3.0 to 4.3 amp to heat the neutralizer cathode. The main vaporizer supply was unchanged.

Impact on thruster performance. The experimental thruster was operated with values of input power up to 9133 watts as the beam current was increased to 5 amp. The total accelerating voltage was increased only as needed to satisfy the perveance requirements. The net-to-total accelerating voltage ratio was held nearly constant (0.75±0.03) to minimize the beam divergence of the two-grid optics. Adjustment of the beam voltage in this manner led to near minimum values of specific impulse and near maximum values of the thrust to power ratio. Figures 3 and 4 present the thrust and thruster efficiency as functions of input power and specific impulse, respectively. Tables II and III list the values of thruster parameters used to calculate the thruster performances shown in Figs. 3 and 4. For comparison, typical data for the baseline J-series thruster are also presented. For values of input power up to 2660 watts the output thrust of both thrusters are seen (Fig. 3) to be nearly equal. From 2660 to 9130 watts of input power the output thrust increased less than linearly from 0.13 to 0.37 N. The thrust-to-power ratio decreased with increasing input power because the beam voltage had to be increased (to satisfy the perveance relationship) as the beam current was increased. The thruster efficiencies (Fig. 4) of both thrusters were nearly the same for values of specific impulse up to about 3000 sec. As the beam current and input power of the experimental thruster were increased the thruster efficiency increased with the specific impulse but at a slower rate. This occurred because the thrust loss factor decrease more than offset the power and propellant efficiency increases. It should be noted that this thruster was only optimized for operation at lower power so that some gains in efficiency, especially the propellant utilization efficiency, would be expected with minor effort.

During thruster operation over the 13:1 power throttle range of Figs. 3 and 4, the neutralizer vaporizer temperature varied less than 20° C as the beam current was reduced from 5 to 0.75 amp. All three vaporizers received thermal input from their respective heaters as well as radiation and conduction from the thruster discharge chamber. As the thruster was throttled down in beam and discharge power the radiated and conducted contributions decreased. In fact, the main vaporizer heater power remained nearly constant and the power to the cathode and neutralizer vaporizers had to be increased as the beam current was decreased. This behavior is also typical of J-series thrusters.

Thruster subassembly characteristics. Several properties of four thruster subassemblies and their sensitivities to propellant flow rates are discussed below.

Cathode pole piece: The cathode pole piece assembly consists of: the hollow cathode; the cathode keeper electrode; the 7.6 cm diameter by 2.5 cm long magnetic cylinder which shapes the upstream end of the main discharge magnetic field; and the baffle which physically and electrically separates the cathode discharge from the main discharge. The degree of separation depends on the baffle diameter and essentially determines the cathode propellant flow rate at any given thruster operating point. When a magnetic baffle is used to provide a variable magnetic field in the baffle-pole piece opening independent control of the cathode flow rate is achieved.[11,12] Normal values of cathode flow rate in J-series thrusters are between 80 and 100 eq. ma. Values less than 60 eq. ma lead to discharge instability while values greater than 100 eq. ma can lead to bistable operation.[13] In addition, Ref. 12 has shown that the propellant utilization efficiency decreases about 2 percent for every 100 eq. ma above the normal range.

Figure 5 shows the variations in cathode flow rate obtained when the experimental thruster was operated without a magnetic baffle over a range of beam current from 0.75 to 5.0 amp at values of discharge voltage of 28, 30, and 32 volts. All of the experimental thruster data of Figs. 3 and 4 and Tables II and III were obtained at points shown in Fig. 5. In general, at a given value of discharge voltage, there was little variation in cathode flow rate as the beam current was decreased from about 5.0 to 2.5 amp. However, there was considerable variation in cathode flow rate as the beam current was decreased from 2.5 amp. The physical baffle diameter was selected to give normal cathode flow rates at a discharge voltage of 32 volts over most of the baseline power throttle range. A decrease in baffle diameter would be expected to permit thruster operation at values of beam current above 2 amp, discharge voltage of 28 volts, and near constant normal values of cathode flow rate. This optimization technique should lead to propellant utilization efficiency increases of about 4 percent. However, it would probably preclude operation at lower values of beam current at discharge voltages of 28 volts or more.

The experimental thruster was operated with a 5.1 cm diameter two-piece baffle for 874 hours at an average beam current of about 2.4 amp (0.75 to 5 amp), discharge voltages between 28 and 32 volts, and an average cathode flow rate of about 250 eq. ma. Wear rates of the upstream and downstream pieces of the baffle, calculated from measured weight losses and thickness measurements were 2600 and 7 angstroms per hour, respectively. References 14 and 15 show that the erosion rate of the downstream side of the baffle decreases as the discharge voltage is decreased, which is consistent with the low erosion rate measured here. They also indicate that the erosion rate of the upstream side of the baffle is relatively insensitive to discharge voltage. However, the high erosion rate measured here was unexpected and was apparently the result of a nonlinear combination of increased beam current, discharge current, and cathode flow rate.

Operation of 30 cm thrusters at a beam current of 5 amp, low discharge voltage, and values of discharge power per beam ampere of about 200 requires cathode emission currents of about 40 amp. A J-series design cathode (0.75 mm diameter orifice) was operated for 950 hours at emission currents up to 42 amp (20 amp average) with no measurable erosion or change in orifice dimensions. Reference 16 presents the results of tests in which three cathodes with different orifice diameters (1±0.25 mm) were tested for 500 hours at 40 amp emission current. Mantenieks[17] has tested a 1.9 mm diameter orifice cathode at a 40 amp emission current for more than 5000 hours with no measurable erosion. Based on these results there does not appear to be any problem in designing and fabricating long life high current cathodes.

The cathode to keeper electrode discharge was always initiated with keeper potentials of 40 volts or less for nearly 100 thruster starts. When the circuit of Fig. 2 was used, the discharge supply open circuit voltage of 40 volts was applied to the keeper. The ballast resistor limited the keeper current to values of about 1 ampere. When the low work function surface of the cathode was properly conditioned, ignition always occurred with only 40 V applied to the keeper electrode, at cathode flow rates of 80±20 eq. ma. For some tests a separate keeper supply was used. It was found, as expected, that the keeper voltage required for ignition decreased with increasing cathode flow rate: The cathode discharge coupled to the anode (40 V open circuit voltage) when the cathode flow rate reached about 120±20 eq. ma. The main flow rate for these tests was constant at about 350 eq. ma., which is representative of the value at the end of preheat with no main vaporizer power applied. At higher values of main flow rate ignition and coupling occurred at nearly the same ti[illegible].

Thus, it has been shown th[illegible] the thruster may be operated efficiently at values of beam current from 2.5 to 5 ampere without the need for a variable magnetic baffle. This occurs because the cathode flow rate required remains nearly constant. The value of cathode flow note required for a given value of discharge voltage may be determined by the selection of size of the physical baffle. The keeper voltage required for reliable initiation of the cathode-keeper discharge does not need to be higher than the open circuit voltage of the discharge supply thereby eliminating the need for a cathode keeper supply. There do not appear to be any lifetime or operational problems with cathodes required to provide the emission current necessary for operation at high beam current. But, an unexpectedly high erosion rate of the upstream side of the physical baffle was experienced when the thruster was operated at values of cathode flow rate, emission current, and beam current greater than those of the baseline thruster. Determination of the cause and elimination of this erosion is required for long life operation at high values of beam current.

Discharge chamber: The primary purpose of the discharge power supply is to provide power to the discharge plasma. Thruster requirements include the need for operation at 32 volts or less (greater values of discharge voltage cause larger fractions of multiply charged ions which lead to increases in discharge chamber component erosion[9,18]) and the ability to handle an anode current about 8 times the beam current. The voltage/current characteristics of the main discharge are strong functions of the magnetic fields in the cathode pole piece-baffle aperature and main discharge chamber as well as the cathode and main propellant flow rates. Figure 6 shows the discharge voltage-current relationships for the experimental thruster operated with and without the magnetic baffle. With the magnetic baffle the thruster was operated at constant cathode and main propellant flow rates for four values of magnetic baffle current (equivalent to four different fixed baffle diameters). Propellant utilization efficiencies of 0.8 or more occur on the portion of each curve to the right of the minimum discharge voltage. The minimum discharge voltage increases with increasing magnetic baffle current as does the plasma impedance. For any value of magnetic baffle current, the plasma impedance decreases with increasing discharge current. For comparison, Fig. 6 also shows the discharge characteristic for the same thruster operated without a magnetic baffle. With a physical baffle diameter of 5.7 cm, the cathode flow rate at the nominal operating point was 208 eq. ma. In the normal efficient region of thruster operation, the trends of the discharge volt-amp characteristics are similar with and without the use of the magnetic baffle.

Figure 7 shows the discharge voltage and beam current as functions of the discharge current for the experimental thruster operated with propellant flow rates required for a nominal beam current of 3 amp. The shapes of the curves are typical of those for other values of beam current. The current, energizing the main magnetic field, was varied for two ratios of cathode to main propellant flow rates. As before, efficient thruster operation occurs to the right of the minimum discharge voltage. From Fig. 7(a), the plasma impedance decreases from about 2 to 1 ohms, with increasing discharge current or decreasing magnet current. In the region of efficient operation, and for the same magnet current, the discharge voltage is lower and less sensitive to discharge current variations when the cathode flow rate is high. In all cases the apparent discharge chamber performance improves with increasing magnet current, primarily due to an increase in the discharge voltage. But, increases in the discharge voltage reduces thruster lifetime as mentioned earlier. Trends of reduced discharge component erosion with decreasing discharge voltage, even at increasing beam current, were indicated spectroscopically and were nearly identical to those reported in Ref. 9. However, as in Ref. 9, the minimum discharge voltage attainable, which gave stable efficient thruster operation, was about 26 volts. Compared to the maximum screen grid erosion rate of the J-series thruster operated at a beam current of 2.0 amp,[9] the spectroscopic results indicate about a factor of two increase for a thruster operated at a beam current of 5 amp and a discharge voltage of 28 volts. This implies a screen grid lifetime of about 15 000 hours.

An attempt to operate efficiently at lower values of discharge voltage by flowing all of the propellant through the cathode, as done in Ref. 19, was unsuccessful. It appears that long life, efficient operation of a 30 cm diameter Hg thruster at high values of beam current will require modification of the discharge chamber. The most likely areas of redesign are the shape and strength of the main magnetic field. Current progress in these areas are described in Refs. 16, 20, 21, and 22.

Ion optics: All of the data presented herein were obtained with a set of two-grid optics of the J-series thruster design. The minimum total accelerating voltage, $V_{TM}$, for a given beam current, $J_B$, may be calculated from the following empirical perveance relationship for close-spaced (~0.5 mm) 30 cm diameter dished grids:

$$J_B \approx 1.4\times10^{-6}\, V^2_{TM}$$

where the beam current is in amperes and the minimum total voltage is in volts.

Normal operation, away from the minimum voltage limit, requires approximately an additional 200 volts. With close spaced optics, the maximum total voltage is limited by electrical breakdown to about 2500 volts. The normal range of the net-to-total accelerating voltage ratio for two-grid optics is 0.6 to 0.8. Values lower than 0.6 cause severe beam defocusing and accelerator grid ion impingement while values greater than about 0.8 allow external electrons to backstream into the discharge chamber.

Thruster operation at the maximum ratio of output thrust to input power implies operation at the minimum possible beam voltage and maximum beam current. Thus, the baseline thruster is power throttled near the perveance limit. In the present FMPP operation, the screen grid voltage is linearly reduced with the beam current and the accelerator grid voltage is regulated to a constant 300 volts. If it were advantageous to the power processor design, both voltages could be reduced during power throttling as long as the perveance, focusing, and backstreaming limits were satisfied. Furthermore, the use of three-grid optics, which extend the range of the net-to-total voltage ratio down to about 0.2, may allow sufficient power throttling at a constant beam current. This would simplify the discharge requirement but require separate regulation of the screen and accelerator grid voltages.[8]

Neutralizer: A 60 hertz, full wave rectified laboratory power supply was used with a current regulator and vacuum relay, S4, for the neutralizer heater and keeper discharge functions as shown in Fig. 2. Open circuit voltages of 35 volts or less were used to initiate the neutralizer discharge. The neutralizer keeper discharge started when the neutralizer flow rate was at least 50 eq. ma. The neutralizer keeper current was then set to 2.1 amp and the flow rate controlled to give a keeper voltage of 12 to 13 volts. No data were taken without beam extraction.

The Space Electric Rocket Test II[23] (SERT II) used the neutralizer keeper voltage to adjust the neutralizer flow rate because the keeper voltage was found to be proportional to the spacecraft potential or thruster floating potential (neutralizer common with respect to facility ground). The neutralizer flow rate controls the spacecraft potential or thruster floating potential. Reference 24 indicated increased difficulty with this scheme for larger thrusters operated at higher values of beam current. For the experimental thruster, the neutralizer keeper voltage and the thruster floating potential (zener diode damped at a maximum value of 60 V) were measured as functions of neutralizer flow rate and beam current and are shown in Fig. 8. The keeper current was held fixed at 2.1 amp, the value for the J-series thruster. It can be seen that the keeper voltage became less sensitive to flow rate with increasing beam current and is, therefore, less desirable as a control parameter. However, the floating potential, which is the actual parameter of interest to be controlled, varies more gradually as the beam current is increased and, thus, appears to be more useful for control purposes, if necessary. Using neutralizer hardware, which was optimized for a beam current of 2.0 amp, and laboratory power supplies, the minimum neutralizer flow rate (defined here as the value at the knee of the flow rate-floating potential curve) increased from about 40 to 52 eq. ma as the beam current was increased from 2 to 5 amp. Near the minimum flow rate the floating potential decreased about 0.5 V per amp of beam current.

No extensive recycle data were taken but at flow rates equal to or greater than the minimum value, the neutralizer keeper discharge remained lit, without increasing the keeper current, during a high voltage recycle as required by the J-series thruster and FMPP. Recycle times with the laboratory supplies were about 5 seconds compared to 350 msec for that of the FMPP. The reliability of a successful thruster recycle increases with neutralizer flow rate and may be traded for thruster performance.

Figure 9 shows how the keeper voltage and floating potential varied with keeper current for several values of beam current and neutralizer flow rate. As mentioned earlier, the normal operating keeper current for the J-series thruster was 2.1 amp and was, therefore, the point of departure for these tests. When the beam current was 2 amp and neutralizer flow rate was 38 eq. ma., a decrease of the keeper current of only 0.1 amp would have no effect on the keeper voltage but would cause the floating potential to decrease rapidly. Increases in the keeper current would cause the keeper voltage to increase and the floating potential to decrease slightly. Increasing the flow rate to 46 and 73 eq. ma. permitted reductions in the keeper current to 1.4 and 0.75 amp, respectively, before the floating potential rapidly decreased. The keeper voltage, at these flow rates, was insensitive to variations in keeper current. But, with increasing keeper current the keeper voltage became more sensitive to variations of propellant flow rate. These trends were similar to those obtained for neutralizer operation at higher values of beam current (Fig. 9). Therefore, it appears that some trades can be made between power supply capability and neutralizer flow rate which may provide alternative approaches to neutralizer operation.

Observation of the neutralizer orifice after more than 1000 hours at values of beam current up to 5 amp revealed only a slight chamfering of the orifice which is typical of J-series hardware.

While the J-series neutralizer was capable of providing adequate neutralization of ion beams up to 5 amp, the ability to control the neutralizer flow rate via the keeper voltage decreased with increasing beam current. The neutralizer hardware and/or control philosphy will probably be changed to allow simple, efficient operation at higher values of beam current.

## Concluding Remarks

A 30 cm diameter Hg ion thruster, similar in design to the J-series thruster, was operated at fixed conditions with only five power supplies and was throttled over the baseline power range with six supplies. An analysis of the FMPP showed that the component mass and parts count would be reduced by about 14 and 35 percent, respectively, and the electrical efficiency would be increased about 1.5 percent by only replacing power supplies with relays. By introducing new circuit designs additional reductions in the component mass (6 percent) and parts (19 percent) and an increase in the electrical efficiency (0.4 percent) would be expected. The impact on thruster performance of reducing the number of power supplies was to lower the propellant utilization efficiency about 1.0 percent and raise the electrical efficiency values from 0.2 to 1.3 percent over the throttle range. The thruster-power processor system efficiency would be expected to increase slightly (4 percent) over that of the baseline system using J-series thrusters and the FMPP.

The same experimental thruster was also characterized over ranges of input power, output thrust, and specific impulse of 690 to 9130 watts, 0.037 to 0.374 newtons, and 1850 to 3820 seconds, respectively, using only six power supplies. In particular, the cathode pole piece, discharge chamber, ion optics, and neutralizer subassembly operating characteristics were documented. In summary, the thruster could be operated efficiency over a 13:1 range of input power, which included values of beam current from 5 amp to 0.75 amp, without a variable magnetic baffle. Both the cathode-keeper and the neutralizer-keeper discharges could be initiated in a normal manner with open circuit keeper voltages of 30 to 40 volts which eliminated the need for the cathode keeper supply and the high voltage section of the neutralizer keeper supply. Neither cathode showed any abnormal wear from operation at high values of beam current. Results of spectroscopic observation of the discharge chamber indicated a screen grid erosion rate, at a beam current of 5 amps, of about twice that of the J-series thruster or a lifetime of about 15 000 hours at the higher value of beam current. The only thruster component which showed evidence of limiting the lifetime of a thruster, operated at values of beam current up to 5 amp, to less than 15 000 hours was the upstream side of the physical baffle which separates the cathode from the discharge chamber.

## References


1. Maloy, J. E., Dulgeroff, C. R., and Poeschel, R. L., "Characteristics of 30 Cm Mercury Ion Thrusters," AIAA Paper 81-0715, Apr. 1981.
2. Schnelker, D. E., Collett, C. R., Kami, S., and Poeschel, R. L., "Characteristics of the NASA/Hughes J-Series 30-Cm Engineering Model Thruster," AIAA Paper 79-2077, Oct. 1979.
3. Biess, J. J. and Frye, R. J., "Electrical Prototype Power Processor for the 30 Cm Mercury Electric Propulsion Engine," AIAA Paper 78-684, Apr. 1978.
4. Sharp, G. R., Gedeon, L., Oglebay, J. C., Shaker, F. S., and Siegert, C. E., "A Mechanical, Thermal, and Electrical Packaging Design for a Prototype Power Management and Control System for the 30 Cm Mercury Ion Thruster," AIAA Paper 78-685, Apr. 1978.
5. Bechtel, R. T. and James, E. L., "Preliminary Results of the Mission Profile Life Test of a 30 Cm Hg Bombardment Thruster," AIAA Paper 79-2078, Oct. 1979.
6. Duxbury, J. H., "An Integrated Solar Electric Spacecraft for the Encke Slow Flyby Mission," AIAA Paper 73-1126, Oct. 1973.
7. Gilbert, J. and Guttman, C. H., "Evolution of the SEP Stage/SEPS/Concept," AIAA Paper 73-1122, Oct. 1973.
8. Rawlin, V. K, "Reduced Power Processor Requirements for the 30-Cm Diameter Hg Ion Thruster," AIAA Paper 79-2081, Oct. 1979.
9. Rawlin, V. K. and Hawkins, C. E., "Increased Capabilities of the 30-Cm Diameter Hg Ion Thruster," AIAA Paper No. 79-0910, May 1979.
10. Gruber, R. P., "Simplified Power Supplies for Ion Thrusters," AIAA Paper 81-0693, Apr. 1981.
11. Poeschel, R. L., "The Variable Magnetic Baffle as a Control Device for Kaufman Thrusters," AIAA Paper 72-488, Apr. 1972.
12. Rawlin, V. K., "Performance of 30-Cm Ion Thrusters with Dished Accelerator Grids," AIAA Paper 73-1053, Oct. 1973.
13. Bechtel, R. T., and Rawlin, V. K., "Performance Documentation of the Engineering Model 30-Cm Diameter Thruster," AIAA Paper 76-1033, Nov. 1976.
14. Mantenieks, M. A. and Rawlin, V. K., "Studies of Internal Sputtering in a 30-Cm Ion Thruster," AIAA Paper 75-400, Mar. 1975.
15. Mantenieks, M. A., and Rawlin, V. K., "Sputtering Phenomena of Discharge Chamber Components in a 30-Cm Diameter Hg Ion Thruster," AIAA Paper 76-988, Nov. 1976.
16. Beattie, J. R. and Kami, S., "High-Thrust and Low-Power Operation of a 30-Cm-Diameter Mercury Ion Thruster," AIAA Paper 81-0718, Apr. 1981.
17. Mantenieks, M. A., Private Communication, 1980.
18. Rawlin, V. K. and Mantenieks, M. A., "Effect of Facility Background Gases on Internal Erosion of the 30-Cm Mercury Hg Ion Thruster," AIAA Paper 78-665, Apr. 1978.
19. Mantenieks, M. A., "Performance Capabilities of the 8-Cm Hg Ion Thruster," AIAA Paper 81-0754, Apr. 1981.
20. Ramsey, W., "Magneto-Electrostatic Thruster Physical Geometry Tests," AIAA Paper 81-0753, Apr. 1981.
21. Kaufman, H. R., Robinson, R. S., and Trock, D. C., "Inert-Gas Thruster Technology," AIAA Paper 81-0721, Apr. 1981.
22. Sovey, J. S., "Performance of a Magnetic Multipole Line-Cusp Argon Ion Thruster," AIAA Paper 81-0745, Apr. 1981.
23. Kerslake, W. R., Goldman, R. G., and Nieberding, W. C., "SERT II: Mission, Thruster Performance, and In-Flight Thrust Measurements," AIAA Paper 70-1125, Aug. 1970.
24. Bechtel, R. T., "A Hollow Cathode Neutralizer for a 30-Cm Diameter Bombardment Thruster," AIAA Paper 73-1052, Oct. 1973.
25. Poeschel, R. L., "High Power and 2.5 kW Advanced Technology Ion Thruster," Hughes Research Labs., Malibu, Calif., Feb. 1977 (NASA CR-135163).

TABLE I. - POWER PROCESSOR CHARACTERISTICS

| | Component mass, kg | Parts count | Electrical efficiency, percent |
|---|---|---|---|
| Functional Model Power Processor (FMPP) | 17.2 | 4000 | 87.2 |
| Modification | Percent change due to modification | | |
| Reduced number of power supplies | -14 | -37 | +1.6 |
| Fixed point or 4:1 throttle | -13 | -31 | +1.3 |
| New circuit design[10] | -6 | -19 | +0.4 |
| Minimum total change | -19 | -50 | -1.7 |

TABLE II. - THRUSTER PERFORMANCE - BASELINE THROTTLE RANGE

| Thruster | Beam current, amp | Beam voltage, V | Accelerator voltage, V | Discharge voltage, V | Discharge losses per beam ampere, W/A | Measured propellant utilization efficiency | Thrust loss factor[a] | Thruster input power, W | Thrust, N | Specific impulse, sec | Thruster efficiency |
|---|---|---|---|---|---|---|---|---|---|---|---|
| J-Series (J-4, 6 LeRC) | 2.0 | 1100 | 317 | 32 | 192 | 0.940 | 0.955 | 2660 | 0.1292 | 2980 | 0.709 |
| | 1.6 | 940 | 313 | ↓ | 200 | .923 | .955 | 1890 | .0955 | 2705 | .670 |
| | 1.3 | 820 | 311 | ↓ | 209 | .893 | .961 | 1400 | .0729 | 2459 | .627 |
| | 1.0 | 700 | 307 | ↓ | 224 | .857 | .967 | 985 | .0522 | 2194 | .570 |
| | .75 | 600 | 300 | ↓ | 245 | .803 | .974 | 691 | .0365 | 1917 | .496 |
| Experimental thruster without magnetic baffle | 2.0 | 1105 | 297 | 32 | 192 | 0.920 | 0.960 | 2663 | .1303 | 2942 | .705 |
| | 1.4 | 860 | 297 | 32 | 206 | .880 | .964 | 1549 | .0807 | 2490 | .636 |
| | .75 | 600 | 300 | 30 | 245 | .775 | .974 | 687 | .0365 | 1850 | .482 |

[a]Estimated values from Ref. 1 and spectroscopic measurements.

TABLE III. - THRUSTER PERFORMANCE - EXTENDED THROTTLE RANGE

| Beam current, amp | Beam voltage, V | Accelerator voltage, V | Discharge voltage, V | Discharge losses per beam ampere, W/A | Measured propellant utilization efficiency | Thrust loss factor[a] | Thruster input power, W | Thrust, N | Specific impulse, sec | Thruster efficiency |
|---|---|---|---|---|---|---|---|---|---|---|
| 2.0 | 1100 | 300 | 32 | 192 | 0.920 | 0.960 | 2663 | 0.1303 | 2942 | 0.705 |
| 3.0 | 1300 | 400 | 28 | 224 | .920 | .971 | 4651 | .213 | 3207 | .728 |
| 4.0 | 1450 | 450 | 28 | 220 | .958 | .952 | 6773 | .294 | 3457 | .743 |
| 5.0 | 1570 | 600 | 28 | 232 | 1.04 | .927 | 9133 | .374 | 3823 | .767 |

[a]Estimated values from Ref. 26 and spectroscopic measurements.

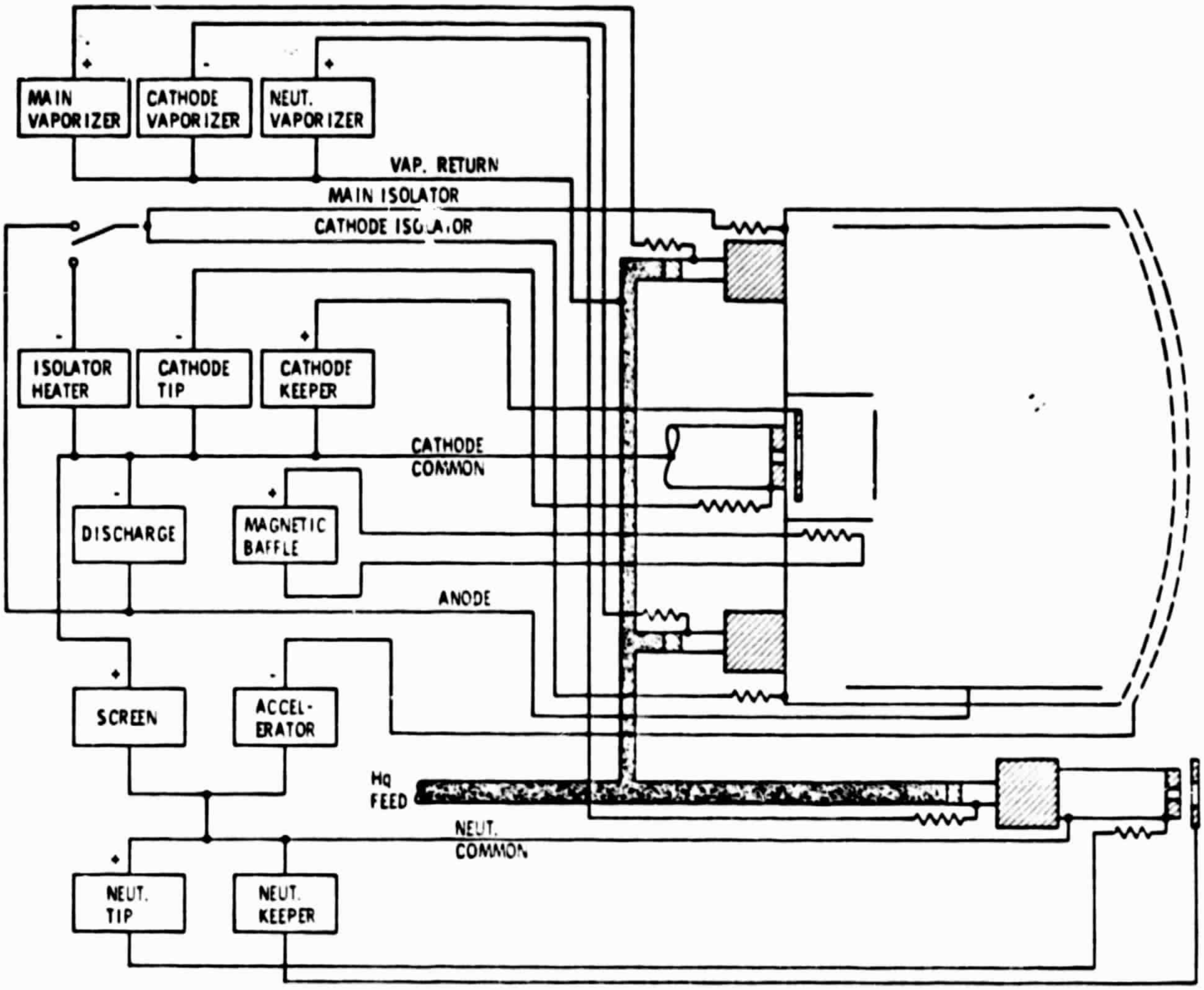



Figure 1. - 30 cm thruster - FMPP interconnection diagram.

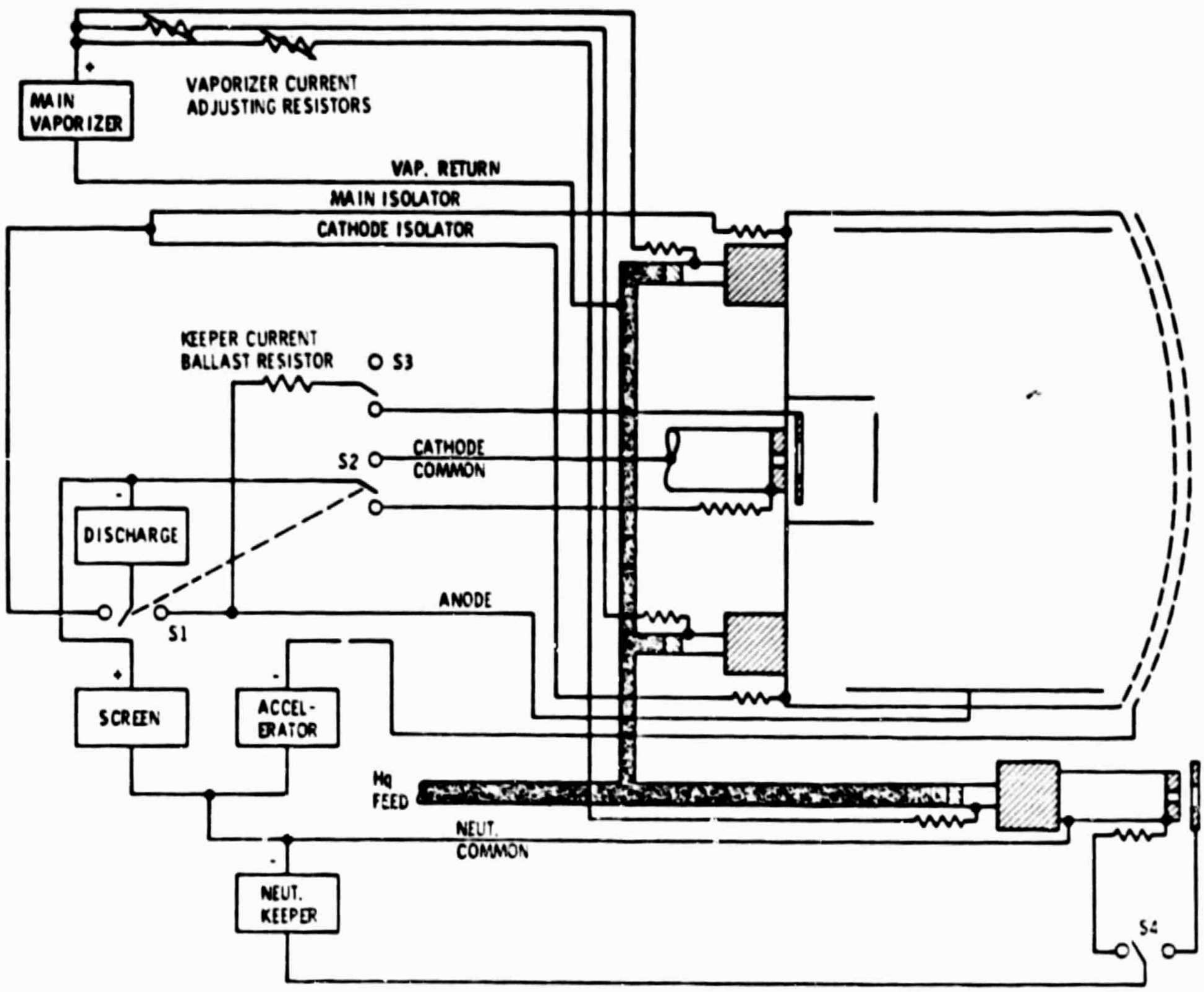



Figure 2. - 30 cm thruster - FMPP interconnection diagram.

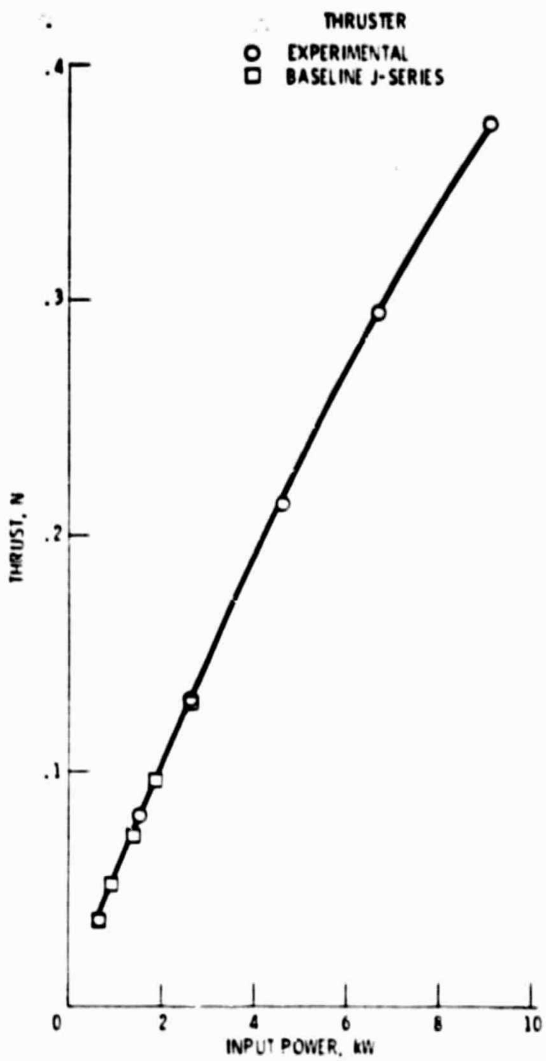



Figure 3. - Thruster thrust as a function of input power.

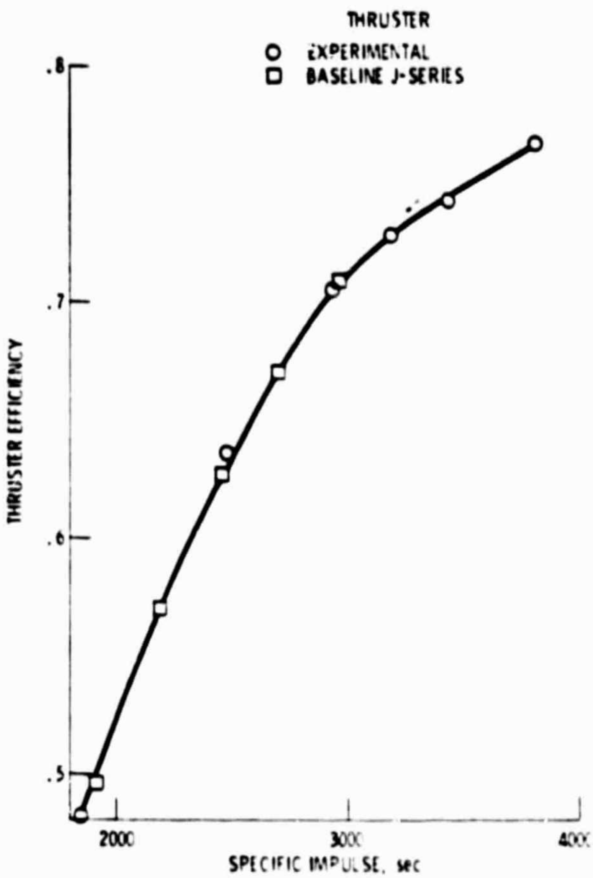
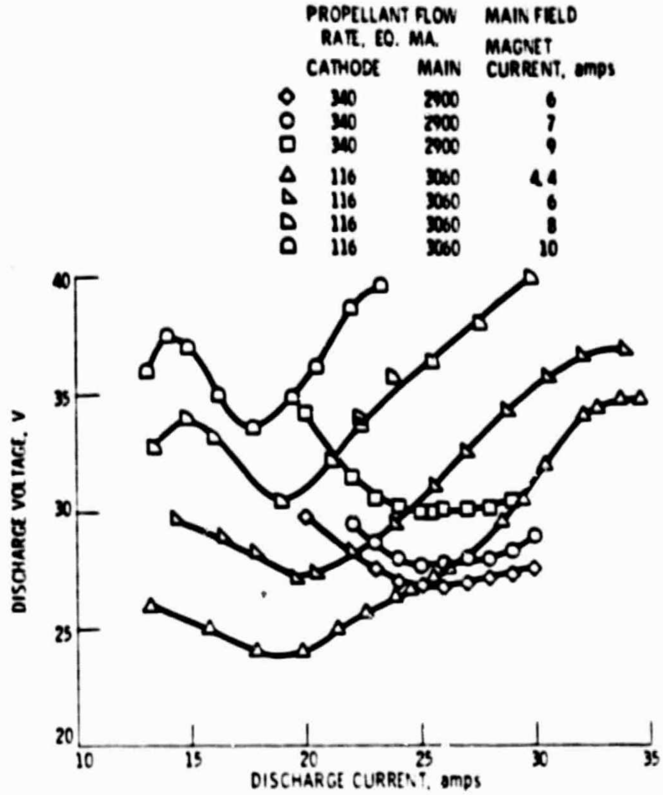



Figure 4. - Thruster efficiency as a function of specific impulse.




(a) DISCHARGE VOLTAGE.

Figure 7. - Discharge voltage and beam current as functions of discharge current and main field magnet current for two different propellant flow conditions. (Nominal beam current = 3.0, thruster without magnetic baffle.)

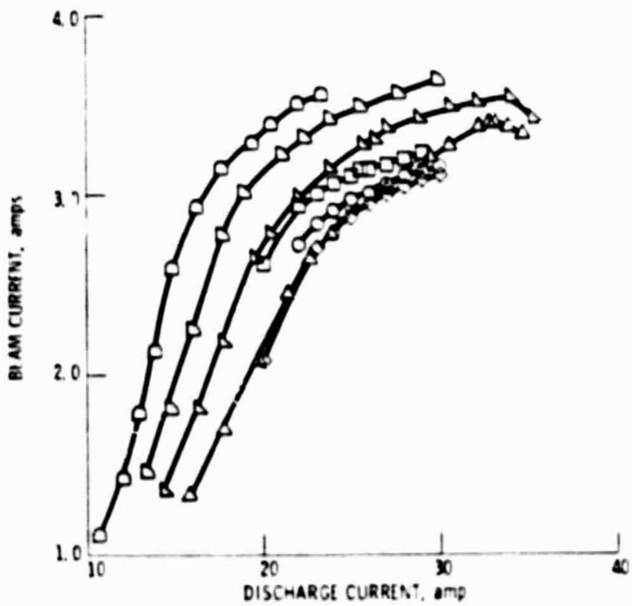



Figure 7(b). - Beam current.

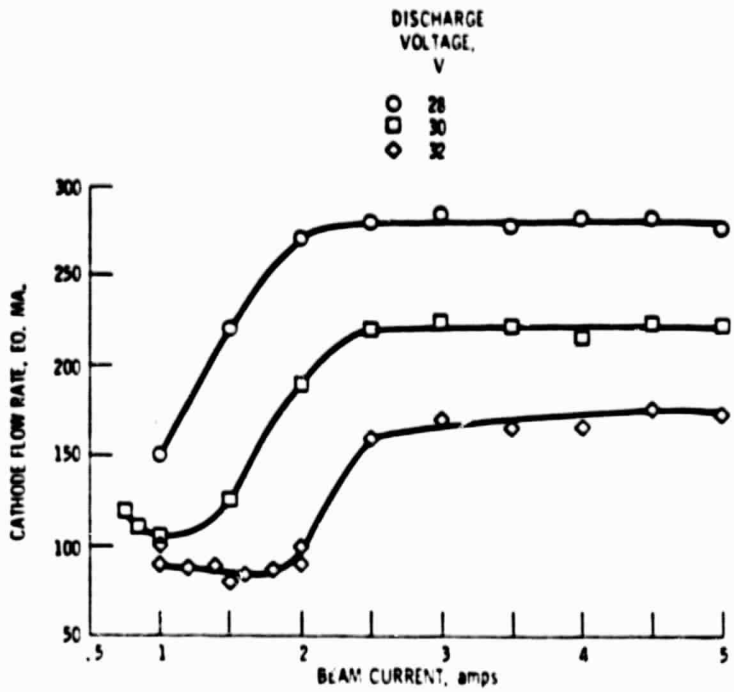



Figure 5. - Cathode flow rate as functions of beam current and discharge voltage for thruster without a magnetic baffle.

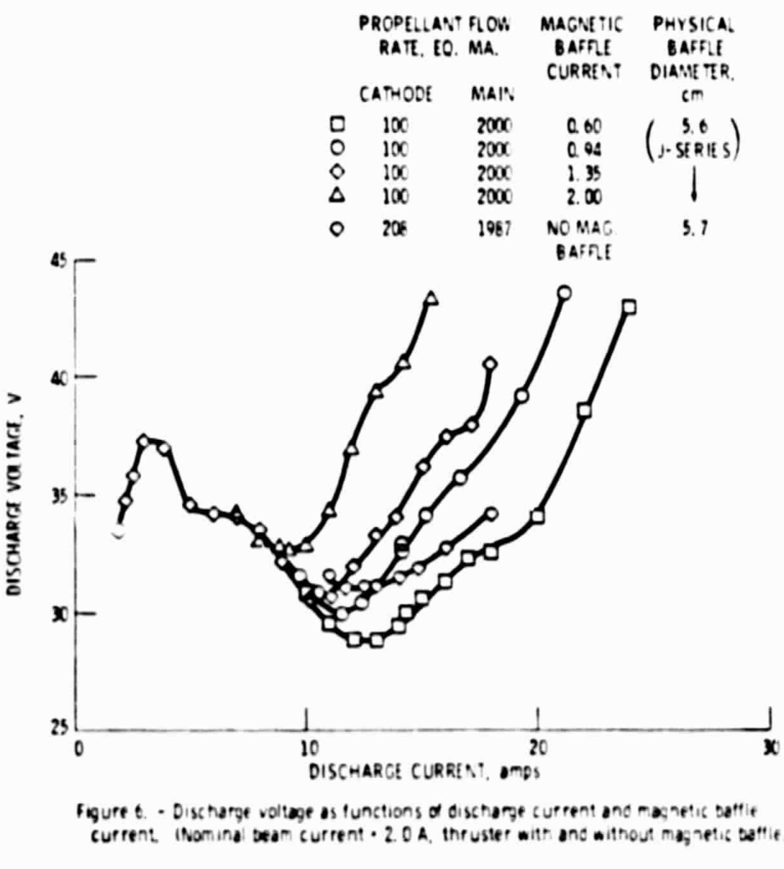



Figure 6. - Discharge voltage as functions of discharge current and magnetic baffle current. (Nominal beam current - 2.0 A, thruster with and without magnetic baffle.)

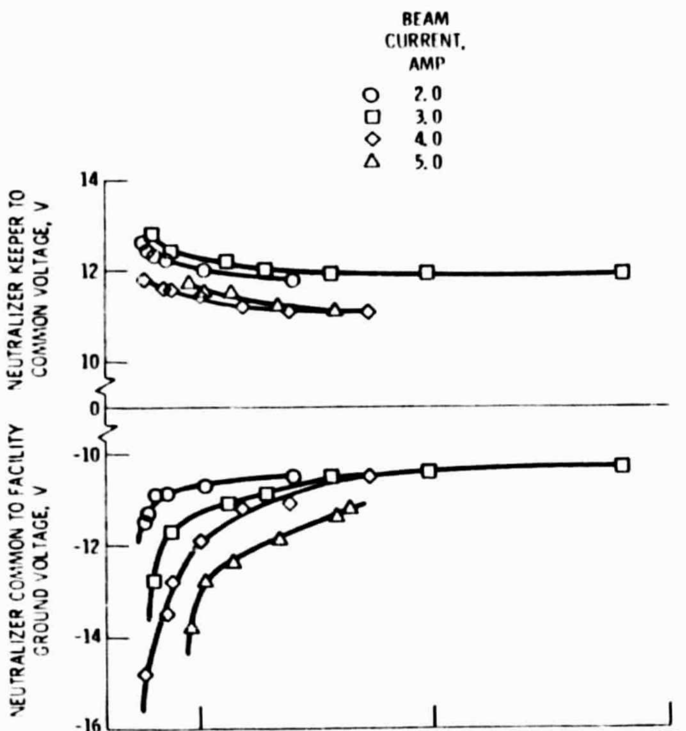



Figure 8. - Neutralizer keeper and floating potentials as functions of neutralizer propellant flow rate and beam current. (Keeper current • 2.1 A.)

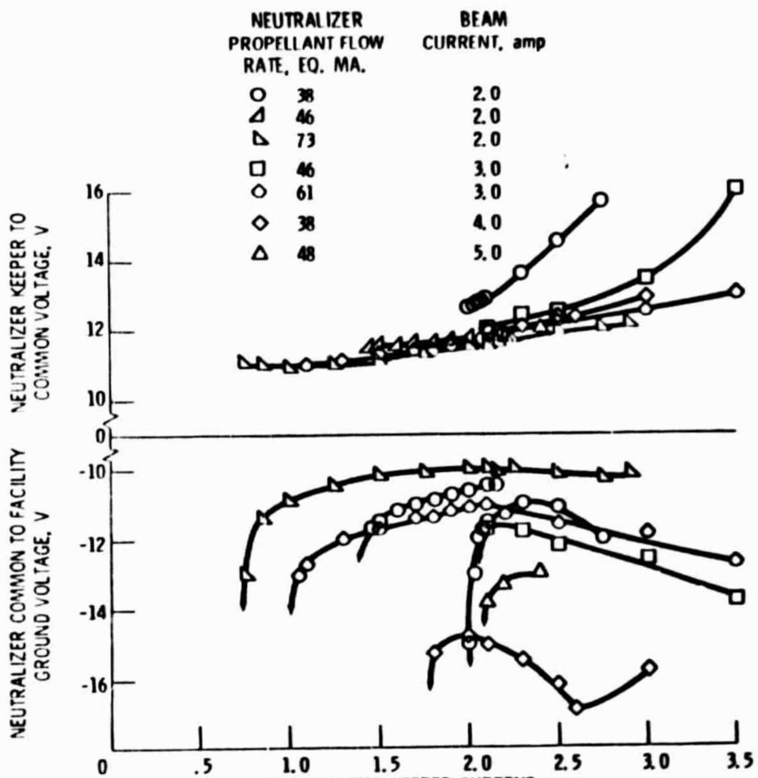



Figure 9. - Neutralizer keeper and floating potentials as functions of neutralizer keeper current, beam current, and flow rate.