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Abstract

The characteristics of power processors strongly impact the overall performance and cost of electric propulsion systems. A program was initiated to evaluate simplifications of the thruster-power processor interface requirements. The power processor requirements are mission dependent with major differences arising for those missions which require a nearly constant thruster operating point (typical of geocentric and some inbound planetary missions) and those requiring operation over a large range of input power (such as outbound planetary missions). This paper describes the results of tests which have indicated that as many as seven of the twelve power supplies may be eliminated from the present Functional Model Power Processor used with 30-cm diameter Hg ion thrusters.

Introduction

The characteristics of power processors strongly impact the overall performance and cost of electric propulsions systems.(1) The 30-cm diameter Hg ion thruster, proposed for solar electric propulsion, has evolved to a state of technology readiness.(2,3) Functional model power processors (FMPP) have been designed,(4) fabricated,(5) and are presently being endurance tested with thrusters.(6)

The major purpose of the power processor is to condition the unregulated solar array power into the various regulated voltages and currents needed to satisfy the thruster operating requirements. In addition, the power processor provides telemetry signal conditioning for power processor input, operating, and status parameters and thruster operating and status parameters. As shown in figure 1, the present FMPP has 12 regulated power supply outputs which provide the power required by the thruster to perform its four basic functions of: propellant flow control; ion production; ion acceleration; and beam neutralization. Figure 2 shows the thruster power processor interconnection diagram. The isolator power supply heats the propellant high-voltage isolators and feedlines, prior to thruster operation, to avoid Hg condensation. The Hg propellant is controlled by the three propellant vaporizer power supplies through feedback control loops. The main, cathode, and neutralizer vaporizers are controlled by the thruster beam current, discharge voltage, and neutralizer keeper voltage, respectively. Bombarding electrons, required for ion production, are provided by a hollow cathode which is heated (cathode tip power supply) during startup to initiate and maintain a Hg plasma discharge between the cathode and keeper electrode (cathode keeper power supply). The discharge power supply accelerates the electrons from the cathode to an anode. In transit, they bombard and ionize some of the Hg atoms from the main vaporizer to create a plasma in the discharge chamber. For reasons of lifetime the magnetic baffle supply is used to maintain the cathod flow rate at a near-constant value as the thruster is operated over nearly a 4:1 range of input power. The ions are electrostatically accelerated from the discharge chamber by the screen and accelerator grid power supplies to form the ion beam, thereby producing thrust. The positive ion beam is neutralized by electrons from the hollow cathode neutralizer which also requires tip heater and keeper supplies to start and maintain the hollow cathode discharge. All but the isolator and tip heater supplies are presently used during operation. Details of the power supply designs and output characteristics may be found in reference 4.

The present 30-cm power processor was designed to meet the requirements of the thruster as they were perceived in 1972. The thruster-power processor interface requirements were specified to accommodate a very broad spectrum of solar electric propulsion missions which included significantly different thruster operating requirements. Both planetary missions (inbound, outbound, and out-of-the-ecliptic(7)), and Earth orbital missions(8) were considered. The resultent power processor design allows great flexibility in thruster operation but at the cost of power processor complexity. This is evident from the power processor characteristics listed in Table I. Table I compares the FMPP with the power processor used in the Space Electric Rocket Test (SERT) II which is still operational after nearly a decade in space.(9)

Over the past 12 years, the design of the 30-cm thruster has been continuously changing to improve the performance, lifetime, and structural properties.(2) However, the power processor requirements, specified by the thruster, have remained nearly constant.

A program has been initiated at the NASA Lewis Research Center to evaluate further 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. The goals of this program are to define reduced power processor requirements; demonstrate their feasibility with laboratory power supplies; and evaluate their impact, if any, on thruster design, performance, or lifetime. Interface requirements will be evaluated primarily for the baseline thruster. However, the requirements of advanced thrusters, such as those that use three grid ion optics,(10) will also be considered.

In addition, the information presented is of value for application to thrusters which operate at high power on alternate propellants, such as inert gases.

The thruster-power processor interface requirements depend heavily on the power profile of a particular mission. The evaluation program is, therefore, being conducted both for missions with variable solar array power (such as outbound planetary missions), and those with near-constant solar array power (typical of geocentric and some inbound mis-

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sions). The major differences between these types of missions, in regard to thruster operation, are those concerning speed of startup, power level at startup, and variation of beam power.

This paper presents the initial results of the program to reduce the thruster-power processor interface requirements. The application of these results to future power processor designs may enhance the overall thrust subsystem characteristics.

Apparatus

Thruster

A 30-cm diameter laboratory thruster, functionally equivalent to the baseline Engineering Model J-series thruster,[3] 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. Two other minor differences were the use of various diameter physical baffles at the end of the cathode pole piece and a neutralizer cathode heater with cold and hot resistances different than those of the baseline thruster.

Power Supplies

Except as noted in the text, 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

Some of the results presented herein have been suggested and/or implemented by others and are so referenced. Also, application of some results are mission-dependent and are offered to show the ranges of thruster flexibility to different control schemes. This section will be divided into "demonstrated results" and a discussion of "projections" with each group sub-divided into three topics: Multi-purpose power supplies; Power supply output characteristics; and Control of thruster parameters.

Demonstrated Results

Multipurpose power supplies. - The baseline FMPP has 12 power outputs. Of those, the isolator heater supply (25 W maximum output) presently would be used only if mission requirements demanded operation of the 30-cm thruster at values of beam current less than about 0.7 ampere.[2] For normal startup, the discharge supply (700 W maximum) is used to provide the isolator heater power (up to 120 W) through the use of a relay. When the thruster isolators have been heated to temperatures high enough to avoid Hg condensation, the relay is opened allowing the discharge supply to provide its normal function.

Reference 11 demonstrated the feasibility of using the discharge supply to rapidly heat the thruster. There the discharge supply was used to heat the cathode tip, the isolator heaters, and an additional plenum heater.

Extending these examples, the discharge supply was used to provide the functions of heating the cathode tip and isolators, as well as starting the cathode keeper discharge. The electrical schematic is shown in figure 3. Baseline thruster hardware was used, therefore, the isolators, which are connected in parallel, shared the normal 4.3 ampere cathode tip heater current and received less than 40 watts of power. Because this is about one-third the normal value, the preheat time was doubled to about 70 minutes. At the end of preheat, the main vaporizer temperature had reached a steady-state value corresponding to a Hg flow rate of 700 mA while the cathode flow rate was negligible. Normal cathode vaporizer power was then applied. As the cathode flow rate increased, vacuum relays S1 and S2 which replaced the cathode tip and isolator heater power supplies were cycled until the cathode discharge was established. Opening S2 disconnected the isolators from the discharge positive output while S1 switched the discharge negative lead from the cathode tip heater to cathode common. This allowed the open circuit discharge voltage to appear at the cathode keeper and anode electrodes. The magnitude of this voltage will be discussed later. The cathode keeper discharge always initiated at vaporizer temperatures corresponding to cathode flow rates between 60 and 100 mA equivalent. Within 10 seconds the cathode discharge coupled to the anode and normal discharge parameters were obtained. This procedure was repeated several times, starting with a cold or warm thruster and with and without the main field and magnetic baffle electromagnets energized. No differences were noted. Using this procedure eliminated the present internal power processor function of sensing the discharge current and reducing the cathode tip heater current to zero (to avoid overheating the cathode insert).

The high voltages could now be applied as usual to extract the ion beam. Relay S3, which replaced the cathode keeper supply, was opened 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. Operation with no keeper current has also been examined by the author, with identical results, using another 30-cm thruster and the three-inverter bread-board power processor, which is similar to the FMPP, described in reference 12. It appears, therefore, that the keeper discharge, which is required for starting, may be eliminated once the main discharge has been established. On several thruster starts, switch S3 was opened prior to the application of high voltage with no observed affect on performance or stability.

Based on the results of the thruster starting tests, it has been demonstrated that three of the twelve power supplies presently contained in the FMPP may be replaced with an additional relay and minor isolator heater termination changes without impacting thruster operation over the baseline standard operating envelope. The added relay could also be actuated by the thruster controller according to the present startup algorithm.[2]

Power supply characteristics. - The present open-circuit output voltage requirements for the cathode keeper, neutralizer keeper, and discharge supplies of the FMPP are 1000, 1000, and 60 volts, respectively. Those of the keeper supplies have been reduced to about 350 volts on several power processors presently used to test 30-cm thrusters.[13] In addition, starting tests have been conducted with 8- and 30-cm diameter thruster cathodes and neutralizers, some of which have been tested for more than 25,000 hours, with maximum keeper voltages of less than 60 volts.[14] Based on the results of those tests, the open-circuit voltages, applied to both keepers and anode, were limited to 60 volts for all of the tests reported in the previous section. There were no observed differences in cathode starting between the high and low keeper voltage cases. This is attributed to the long-life easy starting characteristics of hollow cathodes with impregnated inserts. The major impacts of the reduction of the open-circuit voltages are to ease some of the high-voltage isolation problems of the power processor design, and to eliminate the high-voltage section of the keeper supply.

Control of thruster parameters. - Presently, normal operation of the baseline thruster is accomplished by controlling the Hg propellant flow rates (vaporizer supply output power) via feedback control loops which compare thruster output parameters (beam current, discharge voltage, and neutralizer keeper voltage) to reference signals. Also, the two keeper supplies, the magnetic baffle supply, and the main discharge are operated in the current limited mode while the beam and accelerator supplies are voltage limited. The magnetic baffle is used to set the cathode flow rate to desired values over the thruster input power range.[15,16]

This section discusses alternate methods of controlling the thruster which may allow mission planners and power processor designers to perform tradeoff studies and improve the overall thrust system properties. Because a large number of thruster control functions have been required solely for the purpose of power throttling this section will be divided into two parts: one for a constant thruster operating point; and the other for variable thruster input power.

Constant thruster operating point. - Efficient operation of a thruster and power processor is much less complicated for a near-constant operating condition than for a thruster with the widely varying operating parameters presently required of the baseline thruster. The SERT II power processor was essentially designed to operate at a fixed input power; although operation at lower levels of thrust was possible.[17] Two immediate benefits of single point operation are the need for only one thruster vaporizer power supply to control the main and cathode flow rates and no need for a magnetic baffle and its associated power supply. A single vaporizer (with split flows) may be used, as on SERT II, or two vaporizers may be powered from one supply. In either case, the physical baffle diameter is chosen to obtain the desired ratio of main to cathode flow rates.[18]

The experimental thruster was started several times and operated for more than 100 hours with the main and cathode vaporizers in series and controlled via the beam current. For this test the physical baffle diameter was increased to 6.3 cm, from the baseline value of 5.6 cm, to allow efficient operation at full thruster input power with no magnetic baffle current. The ratio of main to cathode flow rates was set by adjusting a fixed resistor placed across the main vaporizer heater. The steady-state power dissipated in this resistor was about 2 watts. There were no measurable differences in thruster performance or stability between this mode of operation and that of the baseline thruster.

Thus, if a near-constant operating point is allowed, from mission considerations, the magnetic baffle and the cathode vaporizer supplies may also be eliminated. The resulting seven power supplies and their functions are listed in Table II. Projected applications of these philosophies to the neutralizer assembly are presented later.

Variable thrust level conditions. - Starting with the seven power supplies listed in Table II, the operating conditions of the thruster were varied from those at full power following the beam and discharge set points of the standard throttling profile.[2]

In these tests a magnetic baffle supply was used with a physical baffle identical to that of the baseline thruster. The magnetic baffle current was first held constant, which is equivalent to operating with a larger physical baffle and no baffle current. As the beam current and discharge current were reduced, the power to the main and cathode vaporizer decreased (vaporizers connected in series) to follow the beam current. Thus, the cathode flow rate decreased and the discharge voltage increased rapidly. The magnetic baffle current was then lowered to reduce the discharge voltage to the desired value of 32 volts. A feedback controller was installed to vary the magnetic baffle current and hold the discharge voltage constant as the beam current was further decreased. For the baseline thruster-power processor combination, the cathode flow rate remains nearly constant as the beam current is reduced from 2.0 to 1.3 A.[19] However, when the main and cathode vaporizers were connected in series the cathode flow rate decreased from 120 eq. mA to about 70 mA as the beam current was varied from 2.0 to only 1.5 A. In order to vary the beam current over the entire throttle profile, the cathode flow at a 2.0-A beam current had to be increased to about 400 eq. mA. Two penalties of very high cathode flow rate are increased baffle erosion[20] and decreased discharge chamber propellant utilization efficiency.[18] The cathode flow rate decreased nearly linearly to about 100 eq. mA at the minimum beam current of 0.75 A. Thus, to throttle the input power over a 4:1 range, using the standard profile, required the addition of at least a magnetic baffle supply and a feedback controller. To maintain operation at low cathode flow rates would require a separate cathode vaporizer supply or a cathode vaporizer current controller.

As one alternative, the thruster was operated with no magnetic baffle current and the 6.3-cm diameter baffle. A separate cathode vaporizer supply was used to increase the cathode flow rate as the beam current was reduced. In this fashion, the standard throttling profile was followed from full power to about half power (beam current from 2.0 to 1.2 A) at normal operating conditions using only one additional power supply and feedback controller. The addition of a magnetic baffle supply would allow normal operation of thruster over the full range of the standard operating profile.

In figure 4, the shaded area shows the operating envelope of screen voltage as a function of beam current for the baseline thruster.[2] Again, starting with the seven power supplies listed in Table II, another method of power throttling was investigated. For the baseline thruster, operation at a constant beam current of 2.0 A is limited to screen voltages between 1100 and 900 volts (a power throttle of about 1.2:1) because of perveance and focussing limitations of two-grid optics. The use of three-grid optics allows operation at all values of screen voltage and beam current shown by the shaded and open areas of figure 4. Operation at a beam current of 2.0 A may be extended to screen voltages of less than 300 volts. The addition of a third grid would, therefore, permit operation of the discharge chamber at near-constant conditions while allowing nearly a 2.5:1 power throttle. The throttle range may be extended to 4:1 by reducing the beam current to 1.6 A and screen voltage to 200 volts. This would require a separate cathode vaporizer supply as discussed earlier. The use of three grid optics would also require an increase in the accelerator supply maximum output voltage of from 500 to 1100 volts.

Table III lists the power supplies used to demonstrate various methods and degrees of power throttling the baseline thruster using two-grid and three-grid ion accelerating systems.

Projections

Multipurpose power supplies. - The philosophy of multipurpose power supplies was also applied to the neutralizer. The neutralizer keeper supply (75 W maximum), which is needed for normal operation, could be used to heat the neutralizer cathode (which requires about 50 W) prior to ignition. The experimental neutralizer heater was not compatible with the neutralizer keeper supply. Therefore, this procedure was not demonstrated, although it appears straightforward. Again, a relay could be used to switch power from the keeper supply to either load.

References 2 and 6 state that the startup algorithm is one of the most critical routines because of the time-temperature sequence of the main vaporizer (which does not have a reference signal when the beam current is zero).

The use of space-flight qualified thermally actuated relays mounted on the thruster, as suggested in reference 21, are being evaluated in attempts to reduce the complexity of power processor-thruster controller requirements during thruster starting. These relays will be used to sense appropriate thruster temperatures (those which are directly related to the critical starting temperatures) to turn on vaporizer power supplies (propellant flow rates) and switch the discharge and neutralizer keeper supplies from the heater loads to the discharge electrodes. Temperatures on the thruster body over the downstream end of the anode increase rapidly with discharge current.[10] Therefore, a temperature relay at this position could also be used to automatically open the cathode keeper circuit.

Power supply characteristics. - Presently, the discharge supply of the FMPP must be capable of handling discharge currents up to 14 A at voltages up to 50 volts (700 W). Normal operation is in the current-limited mode with the discharge current set to a value proportional to the beam current reference value. The cathode propellant flow rate is varied, through a feedback control loop (which varies the plasma impedance), to obtain the desired discharge voltage. The normal steady-state discharge voltage is 32 volts, except during ignition, off normal, and low mode correction when it is 36 volts,[2,6] to minimize discharge chamber sputtering erosion.[22] Similar reasoning was used in the development of the SERT II power processor which resulted in a discharge supply which was a near-constant voltage supply (programmable to 35, 37, or 40 V). There, the discharge supply was current limited at values about 20% more than the normal operating point so that the thruster was operated on the constant voltage portion of the supply characteristic. The power to the single vaporizer was controlled by a discharge current control loop in the absence of beam current and by the beam current when the high voltages were turned on.

Variations of the discharge supply output characteristics will be investigated to evaluate possible reductions of the maximum power rating to a value nearer to the normal operating point and possible elimination of the discharge voltage-cathode flow rate control loop.

Other power supply properties which will be evaluated are load regulation requirements for output current and voltage.

Control of thruster parameters. - Because all of the Hg vaporizers are at the same potential (spacecraft common) it appears feasible to use the thruster vaporizer supply to provide power to the neutralizer vaporizer. Another adjustable shunt resistor could be used to select a near-constant neutralizer flow rate and eliminate the feedback control loop. The selected neutralizer flow rate would probably be greater than that of the present baseline thruster neutralizer (but less than double) to provide operating margin during variations in the thruster's thermal environment. A factor of two increase in neutralizer flow rate would represent a loss in thruster efficiency of about 1%.

This may be offset by the elimination of the power supply, the feedback controller and the neutralizer flow rate control problems and associated correction algorithms.[6]

Applying these projections to the demonstrated results presented in Tables II and III reduces the present need of three neutralizer power supplies to one neutralizer keeper supply. Therefore, depending on mission requirements and thruster modifications, the operation of a 30-cm diameter thruster over a 2.5:1 range in power using only five power supplies appears straightforward. One possible electrical arrangement of these five power supplies is shown in figure 5.

Conclusions

The characteristics of power processors strongly impact the overall performance and cost of electric propulsion systems. The present functional model power processor incorporates 12 power supply outputs to provide operational power for the 30-cm Hg ion thruster. A program was initiated to evaluate simplifications of the thruster-power processor interface requirements. The power processor requirements are mission dependent with major differences arising for those missions which require a constant operating point and those requiring operation over a large range of input power. Depending on the mission requirements and thruster modifications, test results indicate that as many as seven low-level power supplies may be eliminated by extending the multipurpose power supply philosophy presently used for the isolator heaters-discharge power supply. In addition, reduction of propellant flow rate control loops requirements have been indicated. The use of advanced technology three-grid ion optics allows extension of the power throttle range while using only five power supplies by operating at constant discharge chamber conditions.

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TABLE I. - POWER PROCESSOR CHARACTERISTICS

	Functional model power processor (refs. 2 and 5)	SERT II power processor (ref. 24)
Power supply outputs	12	9
Parts count	4000	~1100 (ref. 25)
Mass, kg	37.5	14.5
Volume, cm^2	80,518	19,438
Cost of PP relative to thruster	~3 (ref. 23)	~10 (ref. 25)
Input power range, kW	3.15 to 0.88	~1.0 to ~0.35
Efficiency variation over power range	0.88 to 0.74	0.875

TABLE II. - POWER SUPPLIES REQUIRED FOR DEMONSTRATED SINGLE POINT THRUSTER OPERATION

Power supply	Function(s)
1. Vaporizer	Control propellant flow rates to desired operating point
2. Discharge	1. Heat thruster to avoid Hg condensation and prepare cathode for operation 2. Start and maintain discharge for ion production
3. Screen and 4. Acceleration	Focus and accelerate ions out of thruster
5. Neutralizer keeper	Start and maintain discharge for ion beam neutralization
6. Neutralizer cathode	Heat neutralizer to avoid Hg condensation and prepare cathode for operation
7. Neutralizer vaporizer	Control neutralizer propellant flow rate

TABLE III. - POWER SUPPLY REQUIREMENTS DEMONSTRATED FOR VARIABLE THRUSTER INPUT POWER

Power supply	Two-grid optics power variation			Three-grid optics power variation	
	1.2:1	2:1	4:1	2.5:1	4:1
1. Vaporizer	✓	✓	✓	✓	✓
2. Discharge	✓	✓	✓	✓	✓
3. Screen	✓	✓	✓	✓	✓
4. Accelerator	✓	✓	✓	✓	✓
5. Neutralizer keeper	✓	✓	✓	✓	✓
6. Neutralizer cathode	✓	✓	✓	✓	✓
7. Neutralizer vaporizer	✓	✓	✓	✓	✓
8. Cathode vaporizer		✓	✓		✓
9. Magnetic baffle			✓		

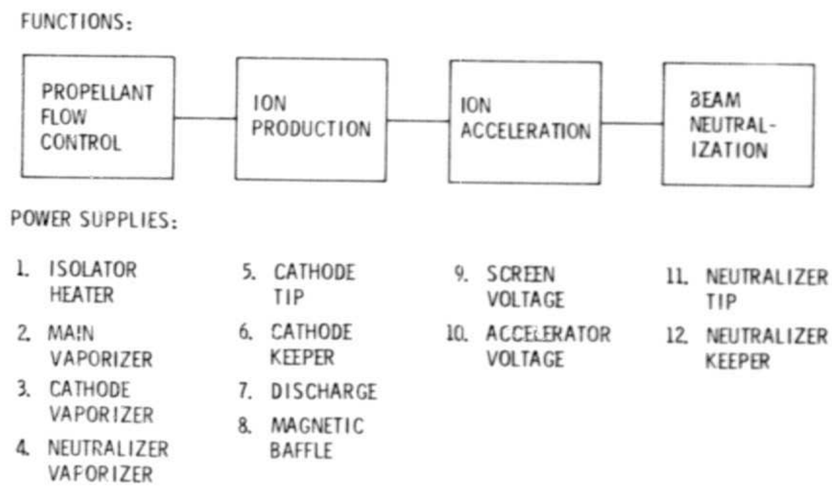

Figure 1. - 30 cm ion thruster functions and power supplies.

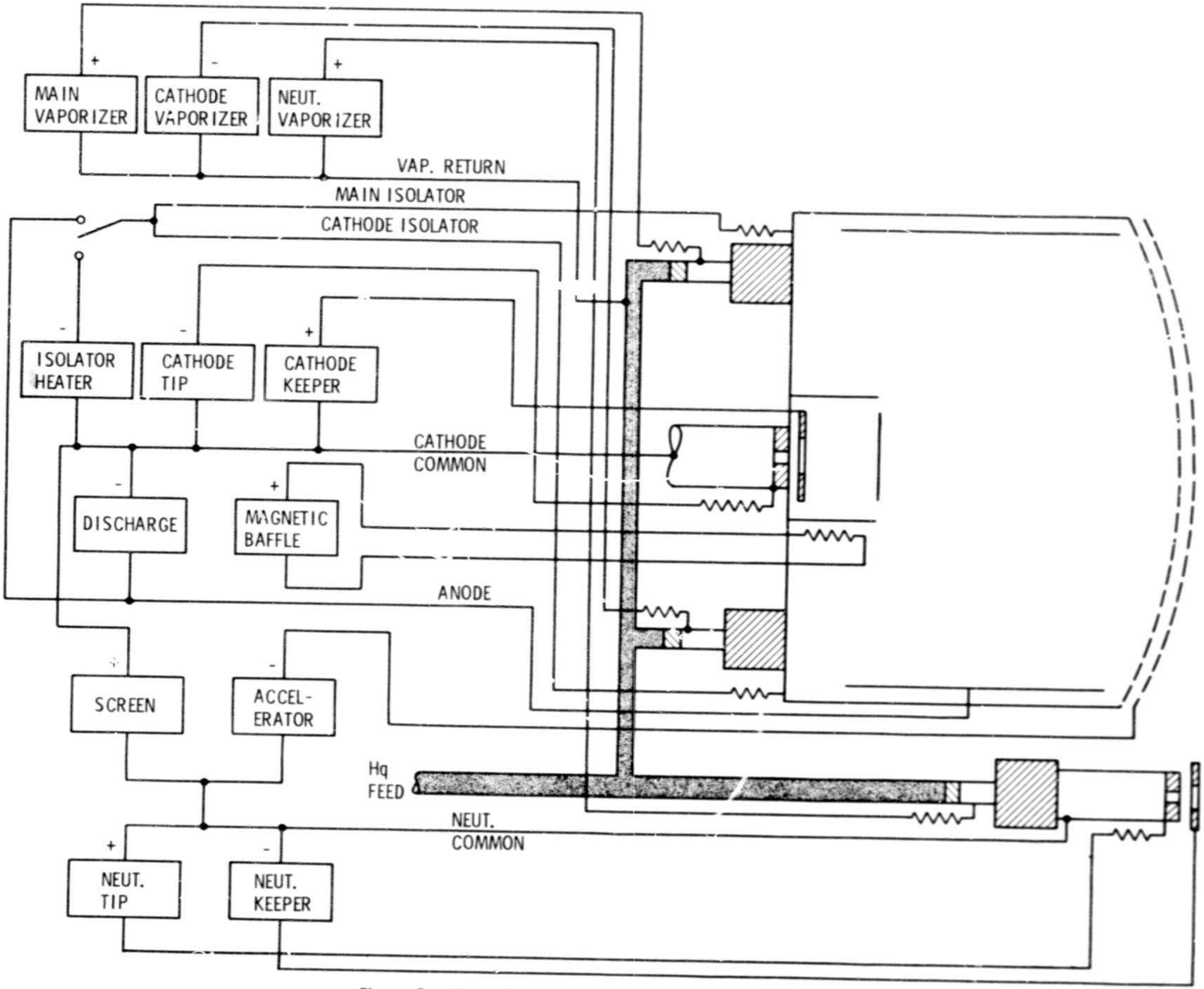

Figure 2. - 30 cm thruster - FMPP interconnection diagram.

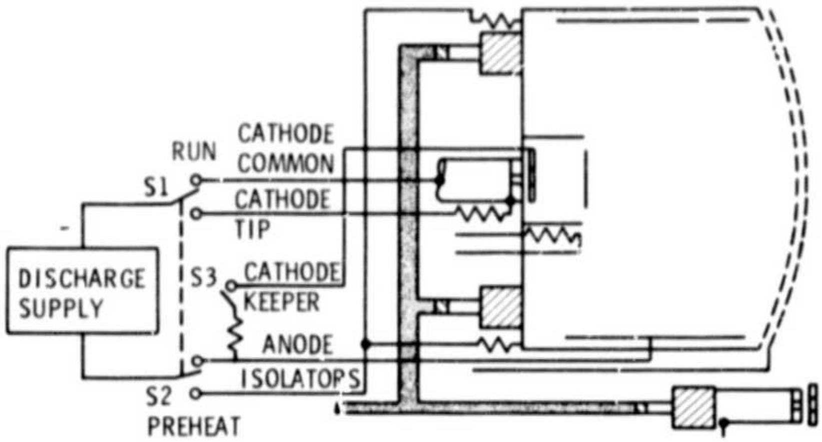

Figure 3. - Electrical schematic for demonstrated multipurpose power supply tests using the discharge supply.

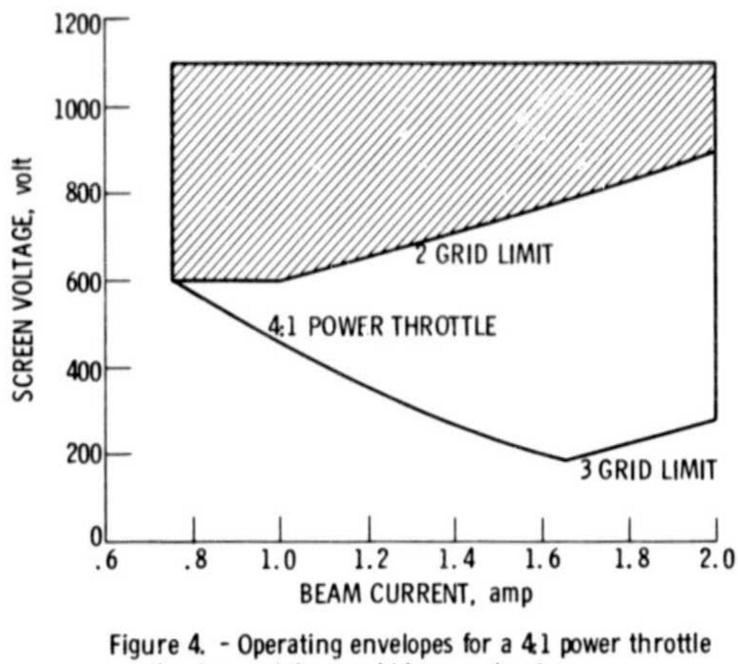

Figure 4. - Operating envelopes for a 4:1 power throttle using two and three grid ion accelerators.

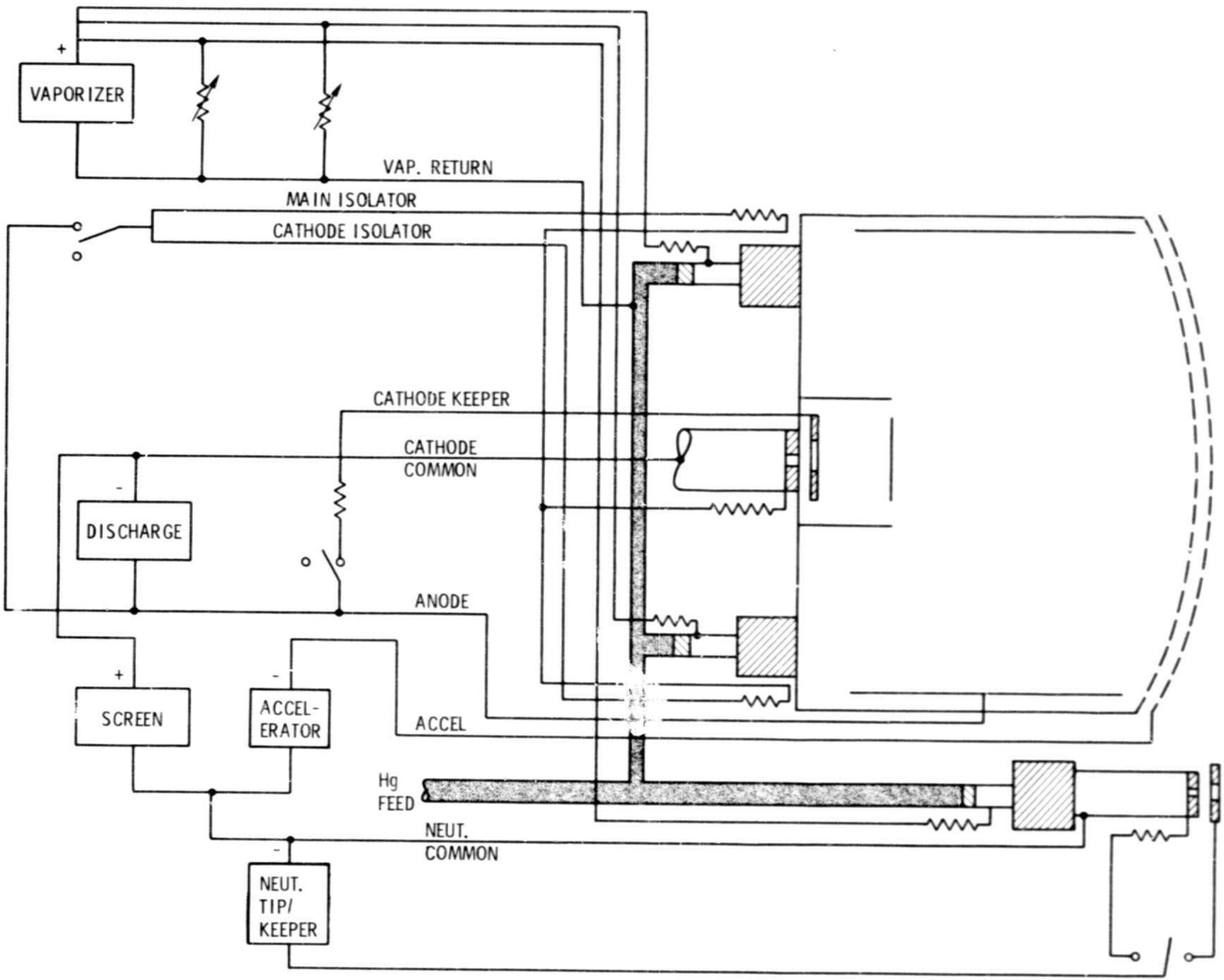

Figure 5. - Projected schematic for thruster and five power supply power processor.