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Abstract

Two engineering model 30-cm ion thrusters have been assembled, calibrated, and qualification tested. This paper discusses the thruster design, performance, and power system. Test results include documentation of thrust losses due to doubly charged mercury ions and beam divergence by both direct thrust measurements and beam probes. Diagnostic vibration tests have led to improved designs of the thruster backplate structure, feed system, and harness. Thruster durability is being demonstrated over a thrust range of 97 to 113 mN at a specific impulse of about 2900 seconds. As of August 15, 1974, the thruster has successfully operated for over 4000 hours.

E-8087

Introduction

The 30-cm diameter mercury ion thruster is a primary propulsion candidate for deep space and geosynchronous missions (1-3). Typically a thruster would consume 2.75 kW of electrical power; produce 135 mN of thrust at a specific impulse of approximately 3000 sec and would be required to operate in excess of 300 days. An Engineering Model Thruster (EMT) tailored to meet these needs has been developed by NASA both through in-house efforts at the Lewis Research Center and under contract at the Hughes Research Laboratories. The cooperative efforts of these two programs have produced a spectrum of unique technological advances to bring the thruster to its current high level of performance (4-19).

This paper defines the structural and operational characteristics of the EMT and discusses in detail the changes which have been made to improve on the performance of the two precursor models (4). The data and references are presented in a manner which should be useful to systems designers and mission planners who are primarily interested in the state of the art as well as those who may be more concerned with specific design criteria or operational limits of the various components. Results of the first 4000 hours of a continuous ongoing life test of a thruster and its associated flight prototype power conditioning are also summarized.

Thruster Design Goals

The EMT (Engineering Model Thruster) performance goals are a thrust level of 135 mN at 3000 seconds specific impulse with thruster nominal electrical power input of 2750 watts. Thrust throttling over a four to one range of input power is required for some applications. The thruster structure has been designed to be compatible with both the projected launch loads of either the Titan III E-Centaur or the Thor Delta vehicles as well as the constraints imposed by the gimbal mounts which control the relative thruster-solar array orientation during the mission (4). The thermal design requirements are dependent upon both spacecraft configuration and mission profile where solar intensities may vary by a factor of ten (1).

Two precursor Engineering Model Thrusters were fabricated by Hughes Research Laboratories in response to the above design specifications. The first EMT, #701, is undergoing endurance testing while the second, #702, has been designated for structural qualification tests. Figures 1(a), 1(b) and 1(c) are photographs of the 700 series EMT.

EMT Subassemblies

The structural-thermal design aspects and performance characteristics of EMT 701 and 702 have been described in some detail in reference 4. Briefly, the thruster is composed of five subassemblies: ion optics, neutralizer, cathode-isolator-vaporizer (C-IV), main isolator-vaporizer (MIV) and outer housing. Because some of the subassemblies contain nearly identical components, the thruster will be described on both a subassembly and component basis.

Outer Housing

The outer housing assembly includes the basic structural elements, magnetic circuit, anode and ground screen. The basic thruster structure is constructed of titanium and consists of two annular rings connected by twelve ring supports (figure 1(b)). The stiff annular ring structure serves to support the ion optics, gimbal pads, thruster shell, backplate, pole pieces and ground screen. The gimbal pad is connected to the ring structure with six insulators. The aluminum rear braces (figure 1(b)) stiffen the backplate and conduct heat away from the cathode assembly. The high and low voltage harness (figure 1(c)) exit the thruster at ±30 degrees relative to the gimbal axis. The three propellant lines join to a common manifold which is mounted to the rear shield. The ground screen includes a titanium mask, punched aluminum cover and rear shield. EMT-701 overall mass is 7.3 kg.

Ion Optical System

It was determined that flat ion optics such as those used on early 30-cm thrusters were not stable under thermal-mechanical loading and did not meet demanding long life requirements because of grid sputter erosion (8, 19). Dished ion optics have been developed (5, 6) which meet

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thrust and specific impulse performance requirements and also satisfy attendant structural, thermal and reliability considerations. The ion optical hole array in the molybdenum grids is produced by chemical milling. The grids are first coated with photoresist, photographically imprinted with the desired pattern and then hydroformed to a 2.16 cm dish depth. The holes are then chemically etched. Screen and accelerator grid hole diameters are 0.191 cm and 0.152 cm respectively. The accelerator holes are located on 0.22 cm centers in a hexagonal array. In order to compensate for the grid curvature and make each hole beam-let paraxial, the center to center spacing of the screen grid hole array is reduced by 0.4 percent relative to the accelerator hole array. The grid interelectrode spacing is approximately 0.060 cm.

The ion extraction capability and operating envelope of this set of optics is shown in figure 2. A two ampere beam has been extracted with a total accelerating voltage of less than 1200 v although normal design total accelerating voltage is 1600 v. Typical screen and accelerator voltages at full thrust are about 1100 v and -500 v respectively. Endurance tests (greater than 1000 hours) of these optics have shown negligible accelerator grid wear due to the combined effects of low accelerator grid voltage and impingement current. The ion optics hole array compensation process yields nearly paraxial beamlets such that the thrust loss due to beam divergence is less than 1.5 percent.

Discharge Chamber

Significant gains in discharge chamber performance have been made by the incorporation of high perveance dished ion optics described in the previous section. Starting with the HRL 400 series thruster (7, 8) as a baseline, the discharge chamber losses were decreased by approximately 70 ev/ion (at a propellant utilization of 0.93) when flat ion optics were replaced by an EMT dished configurations (7). Further performance gains were made by increasing the main magnetic field strength and increasing the baffle to screen pole piece distance (7). Figure 3 shows the EMT magnetic circuit which resulted from the optimization studies. Also shown is a $7\frac{1}{2}$ turn magnetic baffle which controls the magnetic field in the region of hollow cathode electron injection (16, 17). Magnetic baffle control permits the operator (or control system) to select the amount of mercury vapor to be introduced through the hollow cathode so as to optimize discharge chamber performance and stability over the required throttling range. Figure 4 is a display of typical EMT discharge chamber performance (uncorrected for double ionization) over a 4:1 throttling range.

Doubly charged mercury ions (Hg^{++}) lead to a thrust-to-power loss relative to singly charged mercury ions. Further, a low Hg^{++} density is desirable to reduce discharge chamber sputtering since the sputter yield of metallic atoms is nearly exponential with mercury ion energy in the range 20-80 ev. Reference 9 has documented the ion beam doubly charged ion content for a thruster with an EMT discharge chamber configuration. The associated thrust factor necessary to correct the electrical metered thrust value varies from 0.96 at 2 A beam current to approximately 0.99 at 0.5 A (table I). The electrical metered thrust value assumes all singly-charged beam ions.

Main Cathode

The main cathode assembly (figure 5) is composed of the hollow cathode, cathode heater and insert (8, 11, 12). The thoriated tungsten cathode tip geometry is shown in figure 5. The cathode heater is made of the following elements: A plasma sprayed tungsten layer on top of the 0.63 cm diameter tantalum tube, a layer of plasma sprayed alumina, 8 turns of 0.025 cm diameter tungsten-26 percent rhenium wire and a layer of flame sprayed alumina. The insert is 0.10 cm x 0.13 cm x 0.001 cm tantalum foil coated with a barium/strontium oxide emissive mix. The insert is mounted on tantalum wire, rolled and located in the cathode tube 0.6 cm from the upstream face of the cathode tip. The insert has been positioned in this relatively cool location to reduce cathode performance changes with time and prolong lifetime (11). Also shown in figure 5 is a tantalum foil radiation shield required to reduce heater radiation losses during the thruster preheat sequence. The radiation flange provides a large surface area for temperature control when the cathode is locally self heated by the discharge. Nominal temperatures for the cathode in the preheat and run conditions are shown in table II.

Neutralizer

A careful effort has been devoted to the definition of neutralizer position, cathode geometry and control characteristics. The EMT neutralizer is located 9 cm axially and 9 cm radially from the last row of accelerator grid holes (figure 1). At this position, results of reference 13 indicate negligible direct ion beam interception and accelerator grid wear due to neutralizer ion sputtering. The neutralizer cathode diameter, heater and insert (figure 6) are identical to the main cathode configuration. The neutralizer cathode orifice dimensions are 0.38 mm diameter by 1.22 mm long and were determined as a result of the optimization program described in reference 13. Neutralizer tip and insert temperatures during preheat and at a 2 A beam current set point are shown in table II. Closed loop control of the neutralizer vaporizer via an error signal from the neutralizer keeper voltage has been demonstrated over the required t[illegible]ling range. Neutralizer flow rates less than 40 equivalent ma of mercury and thruster floating voltages less than 20 v are held with a neutralizer reference voltage of approximately [illegible]5 v and keeper currents from 1.3 to 1.7 A.

Propellant Isolators

Propellant isolators are required to decouple the thruster high voltage from the feed system. The main and cathode propellant isolators (figure 1(b)) are required to stand off approximately 1100 v at mercury pressures ranging up to tens of torr. The isolators contain a series of seven alumina spacers and metal screens which divide the total voltage so that the Paschen breakdown voltage is not exceeded at any point along the tube. This basic configuration has been employed by Hughes Research Laboratories since 1968 (8). Early endurance tests (19) have indicated unacceptable leakage currents caused by exterior surface contamination due to deposition of metals or metal oxides (14). A number of procedural and design changes were used to eliminate isolator surface contamination on the EMT. These included: relocation of the cathode isolator opposite the main isolator (figure 1(b)) to allow operation of the assembly at lower temperature (200-300° C); nickel plating all metallic parts of the isolator assembly to prevent oxidation; mechanical attachment of the isolator shields to eliminate possible contamination from spot welding; elimination of the line of sight view of isolator heater with isolator body; and bead blasting the alumina body with high purity alumina. The EMT isolator flange temperatures now range from 260-210° C over a 4:1 throttling range (4). Endurance test results of the EMT-701 isolator indicate leakage currents less than 0.1 uA after more than 4000 hours of test.

Figure 6 shows the neutralizer propellant isolator which allows for a common mercury storage and feed system. This isolator requires voltage isolation of less than 60 v.

Vaporizers

The cathode and neutralizer vaporizers are designed to operate in a temperature range of 290-320° C. The main vaporizer operates in the same temperature range for beam current set points from 1.5 to 2.0 A. The dimensions, densities and typical flow rates of the various vaporizers are shown in table III.

Porous tungsten is selected based on nitrogen flow calibration data (15). The circular disks are then electron beam welded into a vaporizer housing after which final flow calibration and liquid mercury intrusion tests are performed. The vaporizer pore size is such the liquid mercury intrusion pressure exceeds 80 N/cm^2 (120 PSIA) at room temperature. All vaporizer and isolator heaters are coaxial swaged assemblies having nichrome conductor, magnesium oxide insulator and inconel sheath. The nichrome heater wire is 0.25 mm diameter which increases to a 0.50 mm diameter before exiting the heater coil. Heaters are attached to the vaporizer assembly with a nickel braze (8).

EMT Test

Design verification tests of the two precursor EMT's are underway. Minor modifications to the thruster structure have resulted from diagnostic vibration tests. Thruster harness and feed system layout has been improved to provide a well defined system interface. These modifications are being incorporated into an EMT 800 series.

EMT-701 Calibration

Performance calibration of EMT-701 over a 4:1 throttling range is shown in table I. These data were taken with 0.5 percent compensated ion optics. These optics were later replaced with a 0.4 percent compensated set to reduce accel impingement and to reduce the alignment precision required during assembly. The change in the thrust factor due to beam divergence is less than one percent. The overall thruster efficiency varies from 0.716 to 0.486 and effective specific impulse from 2911 to 1990 seconds over the range of throttling. For these data, no attempt was made to optimize magnetic baffle or neutralizer keeper set points. This implies performance gains may still be possible, particularly in the lower throttle range. A significant amount of effort remains in the area of detailed performance mapping and control characteristic documentation.

Direct Thrust Measurements

The EMT thrust (table I) is calculated from the metered values of beam current and voltage. The calculated values are corrected by doubly changed ion and beam divergence thrust factors. The thrust factors are experimentally evaluated as described in references 9 and 10. In order to verify these measurements members of the LeRC Electric Propulsion Branch staff have directly measured the thrust of an EMT prototype. A calibrated EMT prototype along with its propellant storage and feed system was placed on a 3 wire pendulum thrust stand, figure 7. Power was supplied to the thruster via conductors from the moving stand which was dipped into insulated mercury filled pots. Pendulum displacement was monitored by a laser interferometer.

Thrust measurements were taken using an EMT prototype with 0.35 percent compensated ion optics whose dish depth was approximately 2.2 cm. The beam current was varied between 0.5 and 2.5 A, net accelerating voltage between 700 and 1500 v and discharge voltage between 33 and 45 v. Preliminary results indicate that at normal operating conditions and 1100 v net accelerating voltage, 37 v discharge voltage and a 2 A ion beam current the measured thrust was 130.6 $\pm$0.6 mN. This represents a 5 percent thrust loss relative to the ideal thrust calculated from metered values. The EMT prototype and EMT-701 thrust values determined by thrust stand measurements and beam diagnostics respectively compare to within one percent.

EMT-702 Vibration Test

A diagnostic vibration test was carried out on the 702 EMT. Sinusoidal, random and shock test parameters are shown in table IV. The first three test segments were conducted for three orthogonal orientations of the EMT. The fourth test segment called for high level sinusoidal vibration tests at 18 g's.

Observations during the three axis 9 g sinusoidal test indicated cracks in the neutralizer cover, a broken MIV tantalum feed line and a misalined neutralizer keeper. Dominant frequencies measured in the thrust axis direction were 160 and 240 hertz.

A broken CIV feed line occurred during the random vibration tests. The 30 g shock tests were conducted without incident. The final test was an 18 g sine test along the thrust axis. This test resulted in fractures of the rear braces (figure 1(b)) at the four peripheral mounting stations. The unsupported backplate then severely deflected in the thrust direction causing damage to other components.

EMT-800 Series Design

Redesign efforts include stiffening of the backplate support structure, a neutralizer assembly modification, and a new layout of the liquid mercury feed system and electrical harnessing. The next generation thruster EMT-800 series which includes these modifications differs from the 700 series only in structural design. The thrusters will present identical loads to a power processor.

The elements of the design modification center primarily around the thruster backplate structure (figure 8). Four hollow titanium beams (1.27 cm x 1.9 cm) serve to stiffen the backplate and support the cathode, isolator and plenum assemblies. Stainless steel feed lines exit the main and cathode vaporizer housings parallel to the backplate and manifold at two stations to insure short feed line runs. Liquid propellant lines are supported by double shadow shielded insulators. Provision for a temperature sensor is made on one surface of the exit manifold. This sensor is necessary to detect a frozen mercury feed system. The aluminum rear shield (figure 1(c)) will now have four dip brazed caps at the periphery to allow sufficient separation to the rear braces. The rear shield may be easily removed without disturbing feed system or harness. The harness routing is shown in figure 8. The terminals provide ease of interfacing with power processing systems. The harness exits through a fiberglass impregnated nylon cable clamp.

The neutralizer assembly requires a stiffer mounting bracket, minor changes in the perforated cover and a less cantilevered keeper assembly.

The 700 series ion optics mount (4) contained twelve screen grid mounting brackets which were attached to a tubular stainless steel ring. This ring was then mounted to the titanium annular ring. Ion optics alinement was complicated by distortion of the stainless steel ring and machining of the twelve mounting brackets. In the 800 series this has been changed to a titanium mounting structure (figure 9), which mounts directly to the annular ring. The screen grid (without a molybdenum stiffening ring) will mount directly to the titanium optics mount. The titanium optics assembly has been successfully vibration tested at vibration levels commensurate with the amplification factors experienced in the previous vibration test of EMT-702. Calibration on a thruster before and after vibration test indicate reproducible performance.

EMT-702 will be refurbished to include all structural modifications and then subjected to the complete test sequence of calibration, sinusoidal vibration, inspection, random vibration, shock, calibration and final inspection.

Endurance Testing

EMT-701 Endurance Test

The endurance test of EMT-701 is being carried out by Hughes Aircraft Company (HAC) in a vertical 5.6 m long by 2.7 m diameter vacuum facility equipped with a 2.4 m diameter frozen mercury target (19). The purpose of this test is to determine the potential lifetime of the EMT, to evaluate long term control stability and also ascertain life-limiting phenomina not observable in short term tests.

The test was initiated February 22, 1974 at a beam current set point of 1.5 A. During the course of the test, the beam current has been raised from 1.5 to 1.76 A. The 1.76 A beam current level is considered near the maximum reliable allowable power output of that particular power processor test console consistent with thermal constraints. There have been no significant unexpected variations in the principal thruster electrical parameters during the first 4000 hours except for the neutralizer keeper voltage ($\pm$1 v) and thus system floating voltage. This situation was corrected at the 1240 hour point in the test by incorporation of a line regulator for the D.C. bias supplies which provide power to the neutralizer controller. A frozen neutralizer mercury line caused thruster shutdown at 249 hours. Heaters, which had been installed in the facility for this purpose, thawed the line. Thruster shutdowns occurred on six other occasions and were due to a circuit breaker problem or pressure rises in the vacuum facility due to loss of diffusion pump power or cooling water. A total of seven thruster restarts were successfully undertaken and normal operation was resumed without difficulty. In no event was the facility opened to atmosphere.

Automatic data sampling is done every hour at the HAC facility. A thruster performance summary is shown in table V. Unprogrammed steady state excursions in thruster parameters during July 1974 were as follows: beam current (<0.4%), accelerator current (<3%), discharge voltage (<1%), cathode keeper voltage (<5%). These typical data are based on random data points taken over the test segment 2780 - 3300 hours. The neutralizer keeper voltage reference and flow rate were 14.0 v and 37 $\pm$3 equivalent ma of mercury during the 1.7 A beam current segment (table V).

A change in neutralizer set points was required at the 1.76 A beam current operating condition. Final selection of a neutralizer reference voltage of 16.5 v and keeper current of 1.5 A gave control at a flow rate of 27 equivalent ma of mercury.

As of August 15, 1974, the thruster has logged over 4000 hours. The number of high voltage recycles is approximately 3 to 5 per day. There has been no degradation of ion optics based on accel current and recycle rates. The main cathode has exhibited extremely flat characteristics. Isolator leakage currents remain at levels less than 0.1 uA. Seven reproducible restarts have demonstrated heater and cathode integrity. Later in the life test, the test console will be replaced by a modified console and the thruster will be incrementally throttled to 2 A beam current.

Component Endurance Tests

Table VI briefly describes other life test data being generated on thruster components. The test of a main cathode has accumulated over 10,000 hours. Cathode discharge characteristics reveal no significant changes at this point in the test. The test was stopped at 8900 hours due to a terminal failure of an experimental plasma sprayed alumina heater. The heater failure was due to a facility malfunction which caused rapid loss of vacuum and backstreaming of diffusion pump oil. The cathode face and orifice exhibited no discernible pitting or erosion.

The next test listed in table VI is for a main cathode with an experimental insert. It has maintained voltage integrity and restart reliability after 5000 hours of testing.

The experimental neutralizer configuration (table VI) employs a porous tungsten insert impregnated with emissive mix (11). This cathode has demonstrated flat discharge characteristics and 21 reproducible restarts during 6500 hours of test.

An EMT main isolator has been undergoing extended thermal and electrical stress tests in a cryopumped bell jar. Isolator leakage current is less than 0.1 uA after 2100 hours of operation. An average isolator body temperature of 320° C is attained by power supplied by the isolator and vaporizer heaters.

EMT Power Processing

Power System

The maximum power capabilities for an engineering model power processor are shown on the schematic circuit diagram of figure 10. The keeper and discharge supplies provide open circuit voltages of about 1000 v and 75 v respectively to initiate the discharges. Open loop set points are provided for all supplies for start-up, recycle and throttling functions. In addition the main, cathode and neutralizer vaporizer supplies are also proportionally controlled from signals related to beam current, discharge voltage and neutralizer keeper voltage respectively. Heater and vaporizer supplies (except for the isolator heater) are direct current regulated.

Thermal vacuum breadboard power processors have been developed for the EMT by HAC and TRW. The HAC breadboard is a modularized transistor switching system whose block diagram is shown in figure 11(a). The screen supply has four active transistor bridge inverters with a staggered phase pulse width modulated drive. This configuration has stand-by inverters for both screen and discharge supplies. Final assembly of the breadboard power processor is expected in late 1974.

The TRW system employs SCR switching devices and is composed of a screen-accel inverter and another inverter stage which provides power to supplies indicated in the block diagram (figure 11(b)). The basic design uses a L-C series resonant inverter providing sine wave SCR currents and current limiting between power source and thruster (20). Resistive load and thruster integration tests are underway at LeRC. Optimization studies are also being pursued at TRW to investigate a three inverter configuration.

EMT Start Up, Recycle and Throttling

The EMT start up, which includes set point, loop reference and sequence selection, will ultimately be automated via computer algorithms. A typical start up profile, table VII, is composed of four phases for both the main and neutralizer discharges (18). The preheat phase warms propellant passages to prevent condensation and conditions cathodes for ignition. The next phase ignites both the main cathode and neutralizer. In the cathode heat phase, the main discharge heats the thruster body and brings the flow system to thermal equilibrium. During the heat phase, the main cathode and neutralizer heaters are automatically turned off after preselected discharge emission and neutralizer keeper currents are exceeded. The power demand during any segment of the first three phases is less than 530 watts. The run phase involves application of high voltage and ramping of the beam current reference. Steady state thruster operation is maintained by beam current, discharge voltage and neutralizer keeper voltage closed loop proportional controllers. The start up sequence is readily accomplished in 45 minutes or less. Investigations at LeRC are in progress to determine thermal and temporal tolerances for the start up sequence.

Reference 18 has defined high voltage recycle procedures in detail. The high voltage recycle is initiated when the screen current or accel current exceed specified comparator set points. Table VIII summarizes EMT recycle commands. The heaters remain off during the recycle and cathode vaporizers remain in proportional control although their references have been changed. The discharge emission current is cut back to approximately 0.7 A. Accel and screen voltages are then commanded on and ramped to their respective set points. The reapplication of the accel voltage leads the screen voltage by approximately 60 ms.

After the high voltages are reestablished, loop references and supply set points return to their original values as indicated in table VIII. The recycle sequence is dictated only by internal power processor hardware.

For proposed flight applications, a computer will perform thrust throttling which include selection of set points and loop references. Specific definition of throttling algorithms require extensive documentation of thruster performance and control characteristics over the 4:1 input power range. Endurance tests of EMT-701 have demonstrated long term stability at beam current set points of 1.5, 1.6, 1.70, 1.75 A.

Concluding Remarks

Two engineering model 30 cm ion thrusters (EMT) have been assembled, calibrated and have been undergoing structural and endurance qualification tests. The design of the discharge chamber, ion optics, heaters, and major subassemblies has been frozen to yield a well documented configuration for power processor and related interface definition. Structural, harness and liquid mercury feed system design changes have been incorporated to meet projected launch vehicle loads and other thrust subsystem requirements. Test results include documentation of thrust losses due to doubly charged mercury ions and beam divergence by both direct thrust measurements and beam probes. At the time of this writing, an ongoing life test of the EMT has demonstrated satisfactory operation for a period of five months. Qualification testing of the EMT will continue in the areas of performance mapping, thermal documentation, power processor and thruster array integration, and further verification of long life capability.

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Table I EMT-701 Performance Parameters

Parameter	Full Power			3/4 Power			1/2 Power			1/4 Power		
	V Volts	I Amp	P Watts	V Volts	I Amp	P Watts	V Volts	I Amp	P Watts	V Volts	I Amp	P Watts
Ion Beam	1100	2	2200	1100	1.45	1595.0	1100	0.85	935.0	1100	0.50	550.0
Accelerator	500	0.0039	2	500	0.0025	1.3	500	0.002	1.0	500	0.001	0.5
Discharge	37	10	370	37.2	7.20	267.8	37.1	4.20	155.8	37.1	2.7	100.2
Magnetic Baffle	0.68	12.0	7.8	0.65	12.0	7.8	0.65	12.0	7.8	0.65	12.0	7.8
Main Vaporizer	5.3	0.9	4.8	5.5	0.9	5.0	4.8	0.8	3.8	4.6	0.7	3.2
Cathode Vaporizer	2.9	0.9	2.6	3.2	1.0	3.2	3.3	1.1	3.6	3.4	1.1	3.7
Neutralizer Vaporizer	3.0	0.7	2.1	3.4	0.72	2.4	3.8	0.9	3.4	4.0	1.0	4.0
Cathode Keeper	5.0	0.4	2.0	5.0	0.4	2.0	7.0	0.4	2.8	7.0	0.4	2.8
Neutralizer Keeper	14.0	1.3	18.2	13.4	1.3	17.4	13.3	1.3	17.3	15.7	1.3	20.4
Neutralizer Coupling	11	2.0	22	10.8	1.45	15.6	11.9	0.85	10.1	12.0	0.50	6.0
Total Power (watts)		2631.5			1917.5			1140.6			698.6	
Propellant Flow		Amp (Equivalent)			Amp (Equivalent)			Amp (Equivalent)				
Main Vaporizer		2.00			1.456			0.902			0.561	
Cathode Vaporizer		0.090			0.108			0.134			0.158	
Neutralizer Vaporizer		0.025			0.035			0.037			0.063	
Total (eq. A)		2.115			1.599			1.073			0.782	
Electrical Efficiency %		83.6			83.2			82.0			78.7	
Propellant Efficiency %		94.6			90.7			79.2			63.9	
Total Efficiency (Meter Value) %		79.1			75.4			64.9			50.3	
Thrust Factors[a]												
Doubly Charged Ions		0.958			0.967			0.981			0.990[b]	
Beam Divergence		0.993			0.993			0.993			0.993[b]	
Efficiency Correction		0.905			0.922			0.949			0.966[b]	
Corrected Efficiency (%)[a]		71.6			69.5			61.6			48.6[b]	
Corrected Propellant Utilization (%)		87.8			85.5			76.7			60.0[b]	
Effective Specific impulse (sec)		2911			2835			2544			1990[b]	
Thrust, mN		129			94.3			56.0			33.3	

[a]Thrust factors are those measured with prototype thruster.

[b]Extrapolated values.

Table II Cathode Temperature Profile

Condition	Tip heater power, W	Discharge emission current, A	Cathode tip temperature, °C	Temperature over insert, °C
Main Cathode				
Preheat	75	0	1020	870
Run-1	0	10	870	700
Run-2	0	5	690	570

Condition	Tip heater power, W	Keeper current, A	Cathode tip temperature, °C	Temperature over insert, °C
Neutralizer Cathode				
Preheat	60	0	1200	900
Run-1	0	1.6[a]	1100	700

[a]Total emission current is 3.6 A

Table III Porous Tungsten Vaporizer Parameters

Vaporizer	Dimensions, cm	Percent density	Nominal flow rate, equivalent ma. of mercury
Main	1.5 dia x 0.11	70	500 - 2000
Cathode	0.45 dia x 0.12	72	90
Neutralizer	0.45 dia x 0.12	~77	30

Table IV Vibration Test Parameters

1. Sinusoidal Sweep (3 axes)

Frequency range	Level
5-19 hertz	1.2 cm double amplitudes
19-2000 hertz	9 g's (0-peak)

2. Random Noise (3 axes)

Frequency range	Level	Power spectral density
20-400 hertz	6.5 g rms	0.11 g^2/hertz
400-2000 hertz	18.9 g rms	0.22 g^2/hertz

3. Shock (3 axes)

Three half sine pulses of 30 g's peak amplitude for 8 msec.

4. Sinusoidal Sweep (thrust axis)

Frequency range	Level
5-19 hertz	1.9 cm double amplitude
19-2000 hertz	18 g's (0-peak)

Table V Performance Summary for EMT-701 Endurance Test (Averaged Parameters)

Time period	Screen		Accel		Discharge		Cathode keeper		Neutralizer keeper		Float voltage	H.V. trips per hour	Propellant flow rate, eq. amp. of hg.		
Hrs	Volt	Amp	Volt	Amp	Volt	Amp[a]	Volt	Amp	Volt	Amp	Volt		Main	Cath	Neut
0 to 2110	1100	1.50	500	0.003	37.1	9.0	7.4	0.5	13.0	1.33	10.8	0.14	1.56	0.103	0.037
2110 to 2750	1110	1.61	500	0.003	36.5	9.6	7.3	0.5	13.7	1.33	11.6	0.13	1.67	0.094	0.032
2750 to 3010	1120	1.71	500	0.003	37.0	10.3	6.7	0.5	14.0	1.33	12.3	-0.2	1.75	0.092	0.040
3010[b] to 3308	1110	1.76	500	0.004	37.1	10.6	6.7	0.5	14.2 16.7	1.33 2.0	12.4 14.1	-0.2	1.78	0.088	0.030 0.063
3308 to 4000	1120	1.76	500	0.004	37.2	10.6	6.5	0.5	16.5	1.5	12.5	-0.2	1.78	0.083	0.027

[a] Discharge supply current

[b] Unsuitable neutralizer keeper reference voltage selected

Table VI Endurance Test of Major Thruster Components

Component	Hours accumulated	Test condition	Comments
Main cathode (LeRC)	10,000	Emission current 12 A	Bell jar test Foil insert recessed 1 cm 30 restarts
Main cathode (LeRC)	6,000	Emission current 7-12 A	Bell jar test Impregnated insert recessed 1 cm 20 restarts Keeper voltage 10.5 ±0.5 v
Neutralizer cathode (LeRC)	6,500	Total emission current: 2.6 A	Bell jar test Impregnated insert located at cathode tip 21 restarts Keeper voltage 15 ±0.5 v
EMT main isolator (LeRC)	2,100	Voltage: 1500 v Average temperature 320° C	Bell jar test No HG flow Isolator leakage current <0.1 μA
Main cathode Neutralizer cathode Main and cathode isolators	4,000	Conditions per table IV	Endurance test of thruster 701 Isolator leakage current <0.1 μA 7 restarts Main cathode discharge characteristics flat

Table VII Start Up Power Profile

Discharge Start-Up										
Phase	Cath. tip	Isol. heat.	Cath. vap.	Main vap.	Cath. keeper	Mag. baffle	Disch.	Accel	Screen	Power (subtotal) W.
Preheat	4.5 A 1[illegible] v	4 A 10 v	off	off	off	off	off	off	off	108
Cathode Ignition	4.5 A 15 v	4 A 10 v	2 A 6.6 v	1.2 A 7 v	1 A 20 v	3.3 A 0.5 v	4 A 50 v	off	off	max. 351
Cathode heat	off	off	PC 1 A 3 v	1.2 A 7 v	1 A 7 v	3.3 A 0.5 v	12 A 37 v	off	off	465
Run	off	off	PC 1 A 3 v	PC 1 A 6 v	0.5 A 7 v	3.3 A 0.5 v	12 A 37 v	0.003 500 v	2 A 1100 v	2661

Neutralizer Start-Up					
Phase	Neut. tip	Neut. vap.	Neut. keeper	Power (subtotal) W.	Total power W.
Preheat	4.5 A 15 v	1.5 A 4.5 v	off	75	183
Neut. Ignition	4.5 A 15 v	1.5 A 4.5 v	0.7 A 25 v	max. 92	max. 443
Neut. Heat	off	PC 1 A 3 v	3 A 20 v	63	528
Run	off	PC 1 A 3 v	1.3 A 15 v	22	2683

(P.C.: proportional control)

Table VIII High Voltage Recycle Commands

Parameter	Recycle command	Recycle complete
Screen voltage	off	HV on[a]
Screen current	---	Ramp to set point
Accel voltage	off	HV on[a]
Discharge voltage reference	33 v	37 v
Discharge current	0.7 A	Ramp to set point
Cathode keeper current	1 A	0.5 A
Neutralizer keeper voltage ref.	19 v	~15 v
Neutralizer keeper current	3 A	~1.5 A
Magnetic baffle	Unchanged	Unchanged
Cathode and neutralizer vaporizers	Proportional control	Proportional control
Main vaporizer	Constant vaporizer current	Proportional control
Heaters	off	off

[a]Reapplication of high voltages precede other set point changes. Accel voltage precedes screen voltage by approximately 60 ms to prevent electron backstreaming.

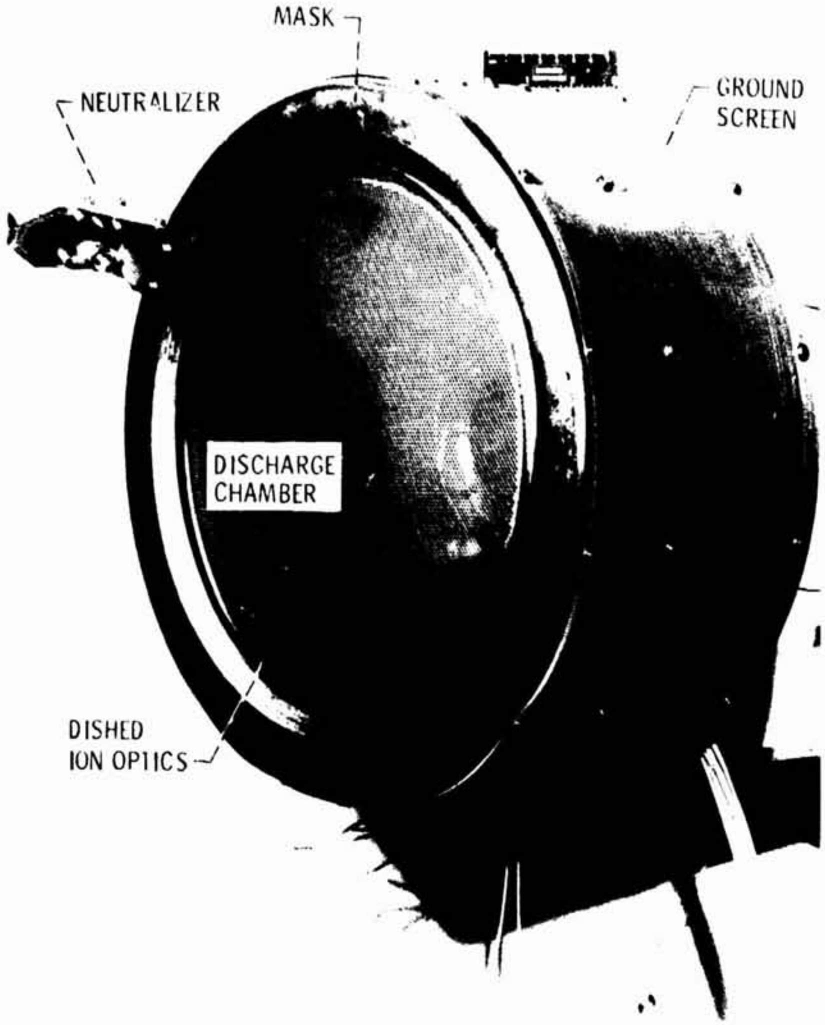

Figure 1 (a). - 30 cm Thruster - 700 series.

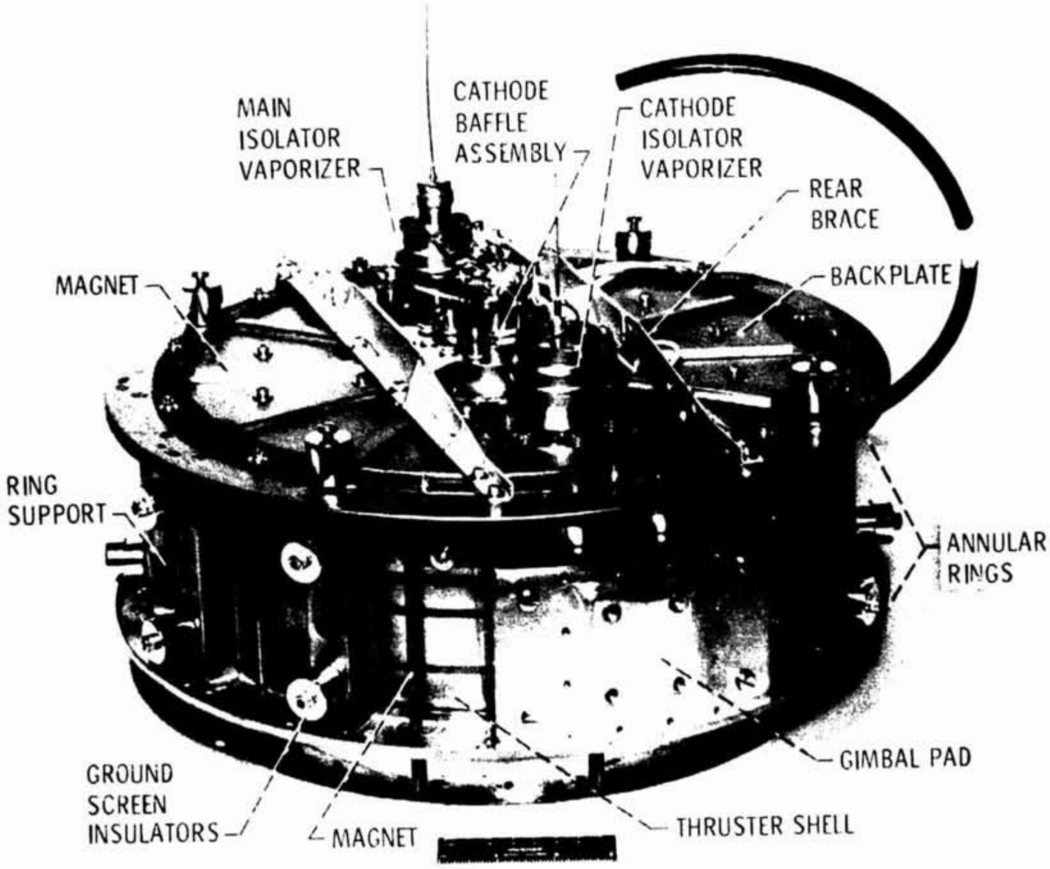

Figure 1 (b). - 30 cm Thruster - 700 series.

E-8067

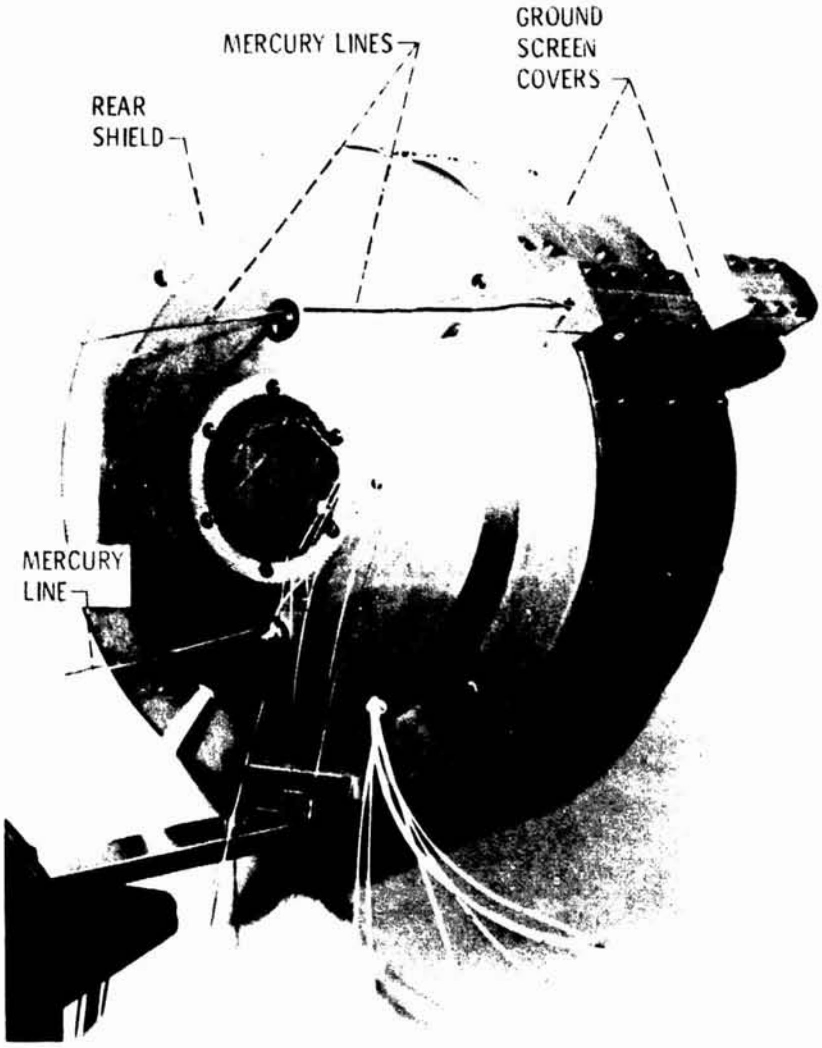

Figure 1(c). - 30 cm Thruster - 700 series (partial assembly).

E-3037

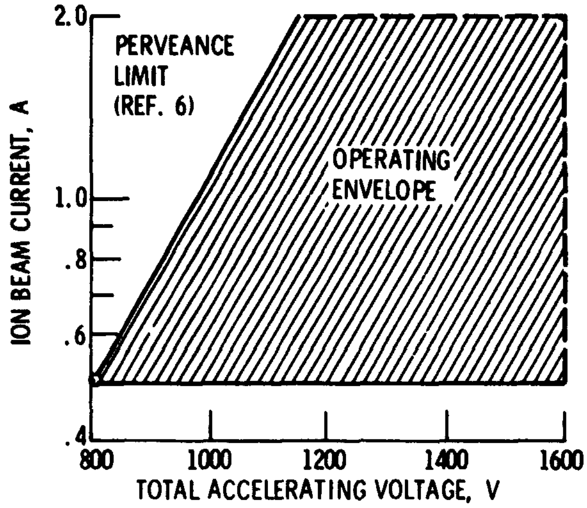

Figure 2. - Ion beam current as a function of total accelerating voltage for EMT ion optics.

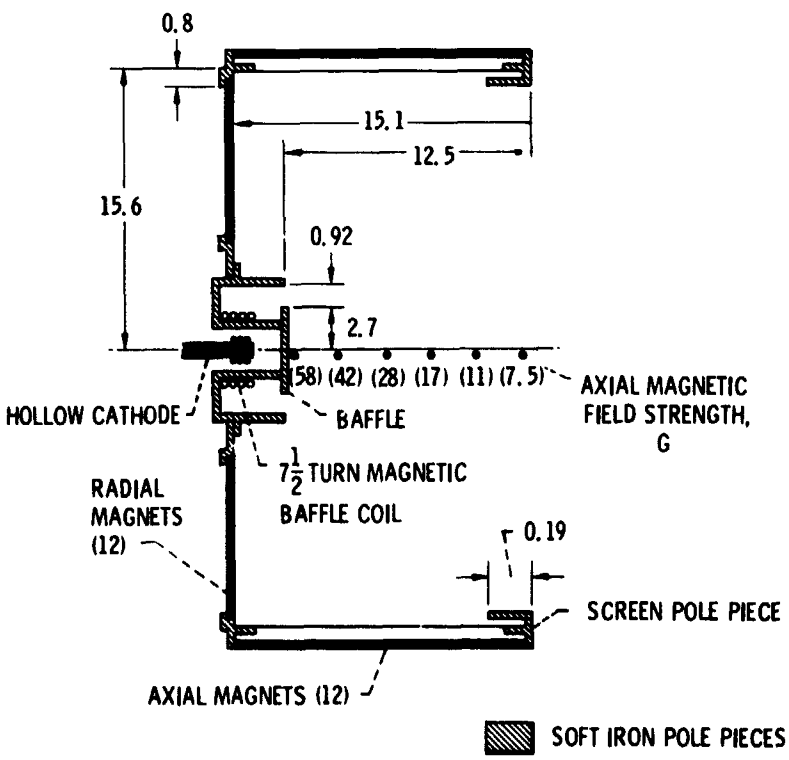

Figure 3. - EMT discharge chamber magnetic circuit. Dimensions are in centimeters.

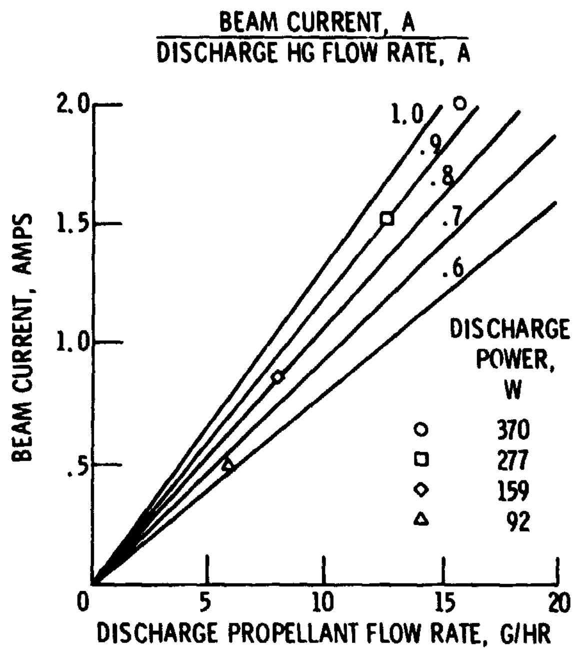

Figure 4. - Typical EMT discharge chamber performance. Net accelerating voltage is 1100 volts.

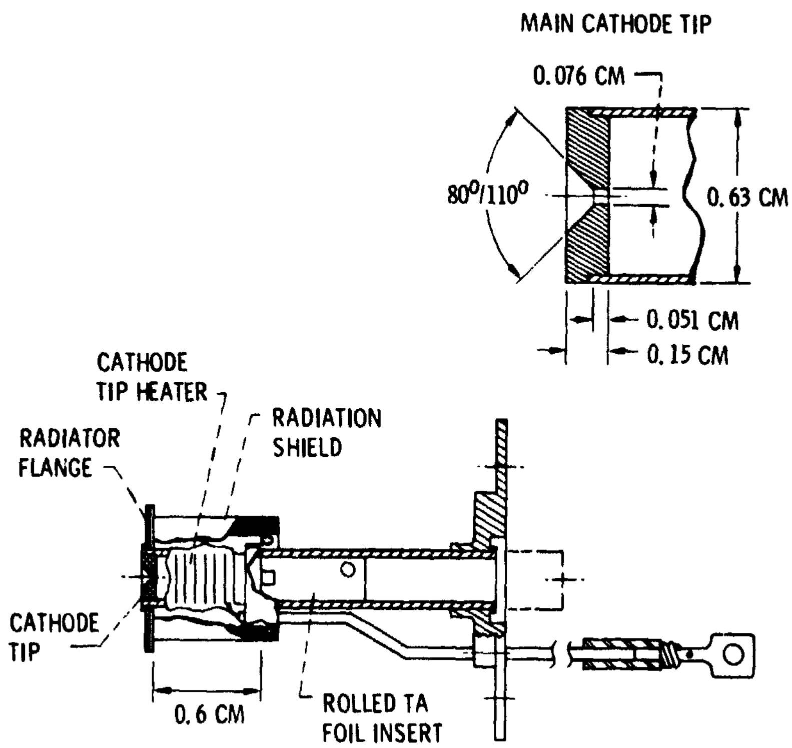

Figure 5. - Main cathode assembly.

E-3017

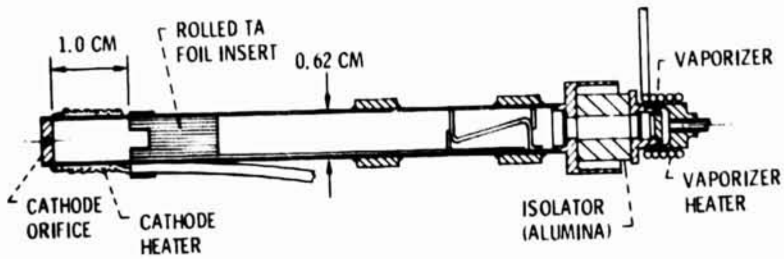

Figure 6. - Neutralizer-isolator-vaporizer assembly.

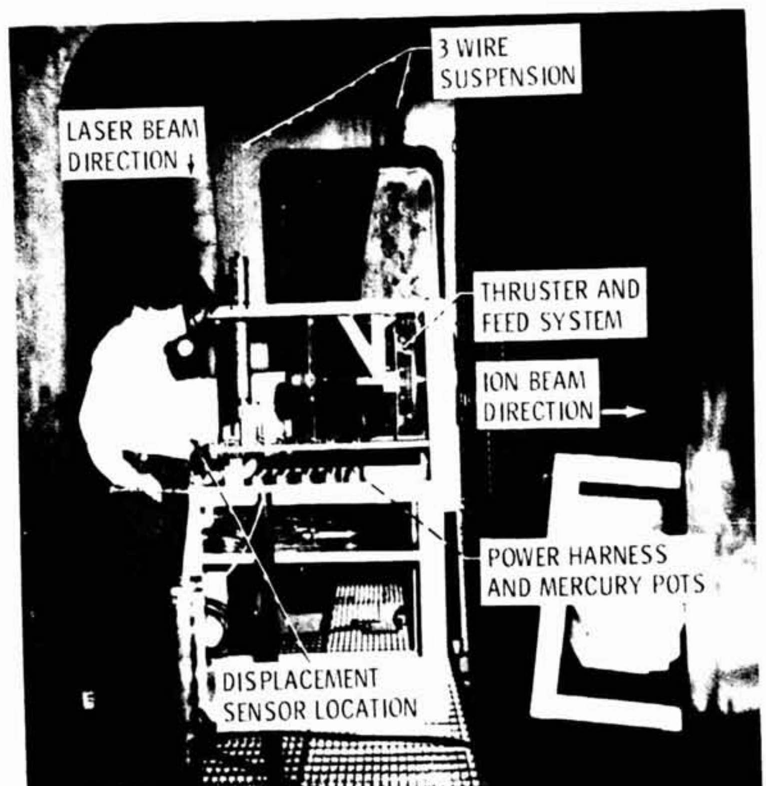

Figure 7. - Pendulum thrust stand.

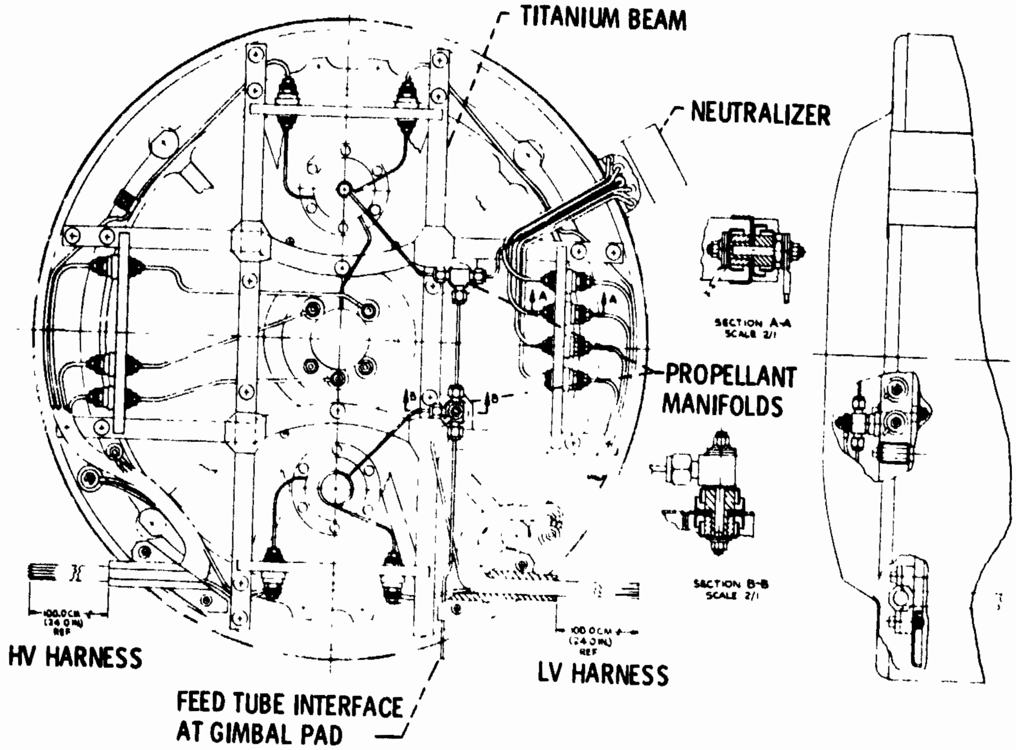

Figure 8. - EMT backplate layout, 800 series design.

E-6067

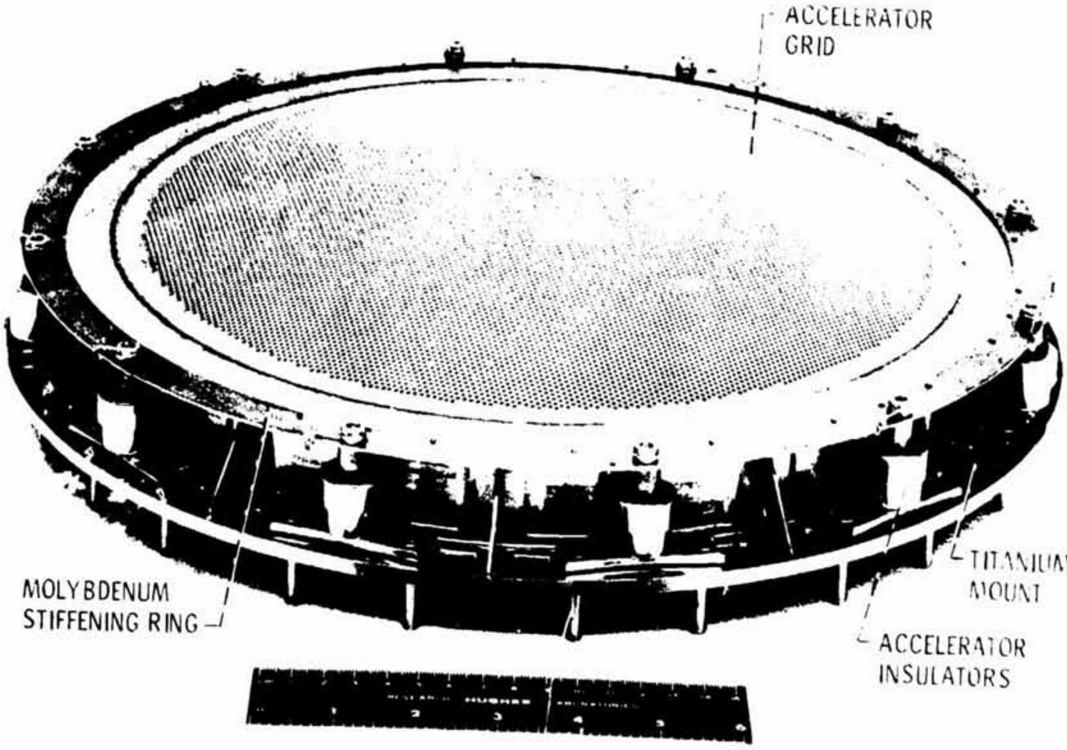

Figure 9. - EMT 800 series ion optics.

E-4087

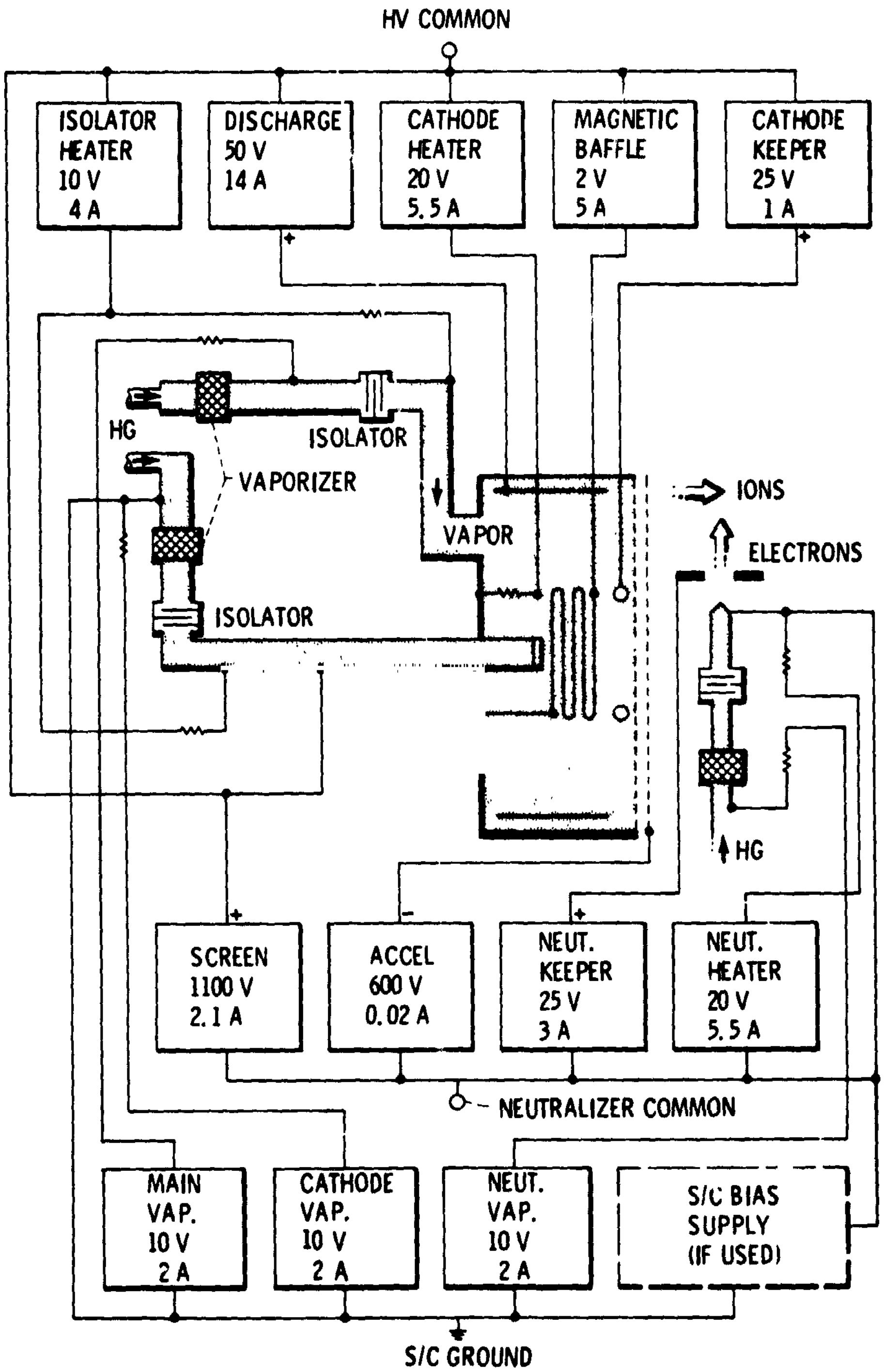

Figure 10. - Thruster power system block diagram.

E-3037

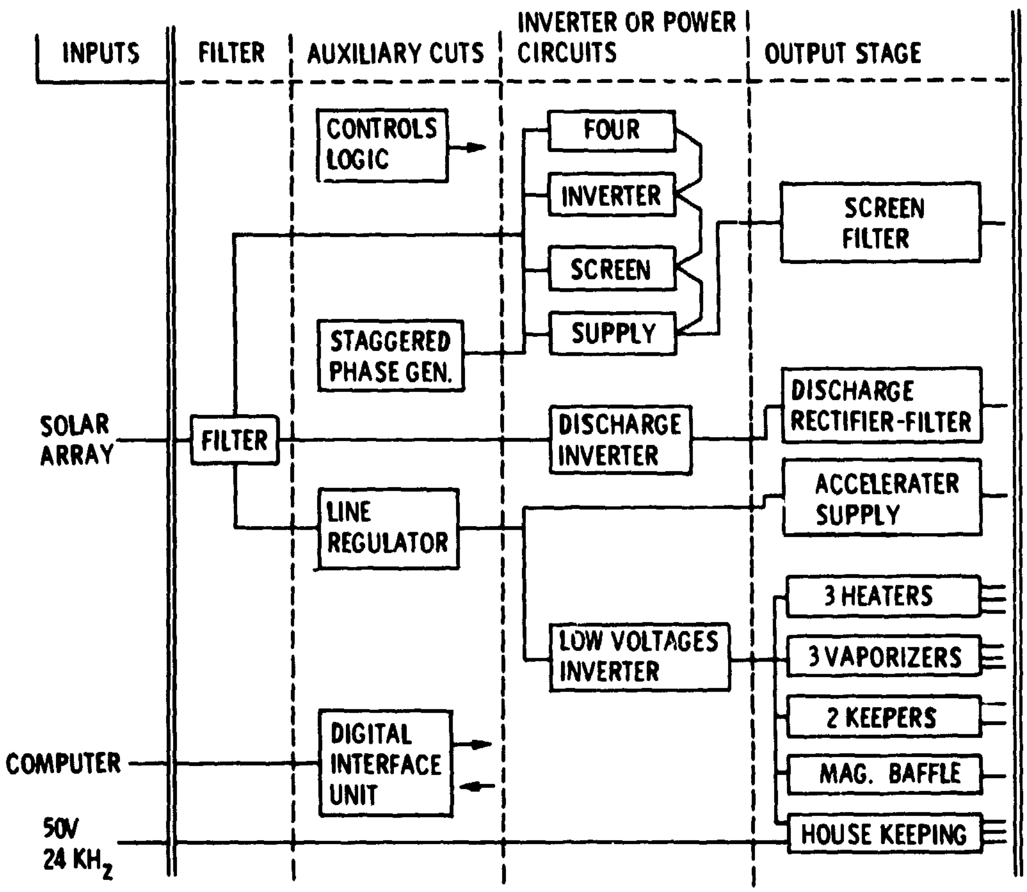

Figure 11(a). - 30 cm Transistor Power Processor Block Diagram.

E-6007

E-6087

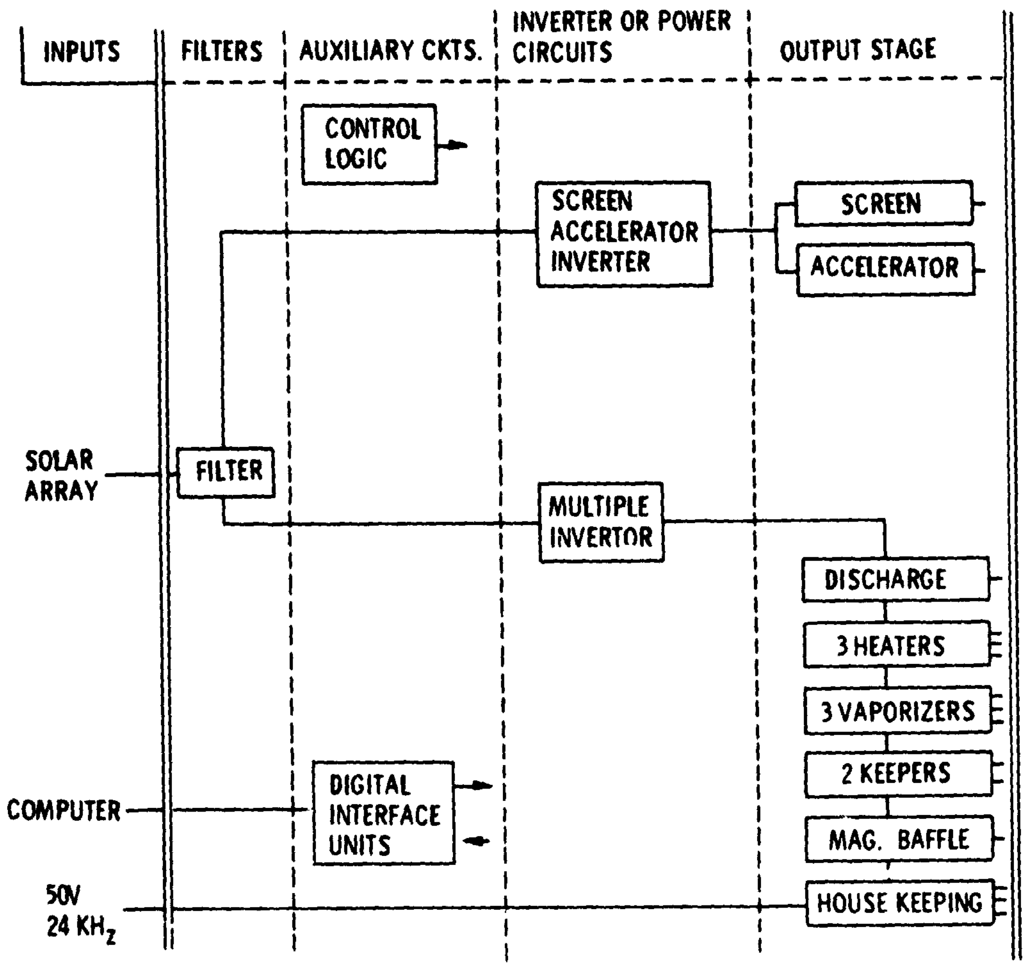

Figure 11(b). - 30 cm SCR Power Processor Block Diagram.