

**CASE FILE
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LOW VOLTAGE 30cm ION THRUSTER

FINAL REPORT

BY

**ION DEVICE PHYSICS DEPARTMENT STAFF
HUGHES RESEARCH LABORATORIES**

A DIVISION OF HUGHES AIRCRAFT COMPANY

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PREPARED FOR

**NATIONAL AERONAUTICS and SPACE ADMINISTRATION
NASA LEWIS RESEARCH CENTER**

CONTRACT NAS 3-14140

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1. Report No. NASA CR-120919		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle LOW VOLTAGE 30 cm ION THRUSTER				5. Report Date February 1972	
				6. Performing Organization Code	
7. Author(s) H.J. King, et al.				8. Performing Organization Report No.	
9. Performing Organization Name and Address Hughes Research Laboratories 3011 Malibu Canyon Road Malibu, California 90265				10. Work Unit No.	
				11. Contract or Grant No. NAS 3-14140	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Lewis Research Center 21000 Brookpark Road Cleveland, Ohio 44135				13. Type of Report and Period Covered Contractor Report O Final 3 August 1970 - 31 December 1971	
				14. Sponsoring Agency Code	
15. Supplementary Notes Project Manager: James S. Sovey, NASA-Lewis Research Center, Cleveland, Ohio					
16. Abstract The over-all goal of this program was to construct a 30 cm diameter ion thruster module (including thruster, power conditioning, and control system) capable of operating for 10⁴ hours over a 5:1 power range at an effective specific impulse of ~2800 sec. The program was composed of several interrelated tasks. The first was to compare the performance of several single grid, insulated ion optical systems and to determine which one had sufficient lifetime potential for inclusion in the final system. When no reasonable projection of the required 10,000 hour lifetime could be made for any single grid system, the decision was to employ "conventional" two-grid ion optics with a single central interelectrode support. The performance of this ion optical design was such that it was not necessary to compromise the contractual goals of over-all thruster performance, specific impulse, or throttling range that had been chosen originally for the single grid system. The next series of tasks, which were conducted in parallel, was to optimize the discharge chamber with the new ion optical system in order to gain improved efficiency and to assure that the operating power level could be throttled over a 5:1 range. It was also necessary to mechanically redesign the thruster to sustain the stresses imposed by the vibrations of the launch vehicle and to design and fabricate an analogue control system that would permit any operating power level between 500 and 2500 W to be selected by adjustment of a single control signal. Following completion of the above tasks, the newly designed thruster, control system, and recently constructed flight prototype power conditioner (10 kc inverters operating from a 250 V dc line) were integrated and tested as a complete system. During one 50 hour period, the repeatability and stability were demonstrated over a beam current range from 0.166 A to 2.0 A with single knob control. The performance map, taken over a 5:1 power range at various values of specific discharge power and mass utilization, demonstrated that thruster performance and stability were not materially affected by reasonable changes from the nominal operating point. However, it was observed that the neutralizer design and control system provide a trade-off among over-all thruster efficiency, lifetime, and stability. Finally, a thruster of the optimized design was fabricated and delivered to NASA for evaluation.					
17. Key Words (Suggested by Author(s)) Electric Propulsion Ion Propulsion 30 cm Ion Thruster Flight-Type Power Conditioner Automatic Controller Mercury Propellant				18. Distribution Statement UNCLASSIFIED - Unlimited	
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 163	
				22. Price* \$3.00	

* For sale by the National Technical Information Service, Springfield, Virginia 22151

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FOREWORD

The work described herein was performed in the Hughes Research Laboratories Ion Device Physics Department of the Hughes Aircraft Company in Malibu, California. This department is managed by Mr. J.H. Molitor. The work was performed under Contract NAS 3-14140, monitored by Mr. J.S. Sovey of NASA Lewis Research Center. Major technical contributors to this effort were:

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SUMMARY

The over-all goal of this program was to construct a 30 cm diameter ion thruster module (including thruster, power conditioning, and control system) capable of operating for 10^4 hours over a 5:1 power range at an effective specific impulse of ~ 2800 sec.

The program was composed of several interrelated tasks. The first was to compare the performance of several single grid, insulated ion optical systems and to determine which one had sufficient lifetime potential for inclusion in the final system. When no reasonable projection of the required 10,000 hour lifetime could be made for any single grid system, the decision was to employ "conventional" two-grid ion optics with a single central interelectrode support. The performance of this ion optical design was such that it was not necessary to compromise the contractual goals of over-all thruster performance, specific impulse, or throttling range that had been chosen originally for the single grid system.

The next series of tasks, which were conducted in parallel, was to optimize the discharge chamber with the new ion optical system in order to gain improved efficiency and to assure that the operating power level could be throttled over a 5:1 range. It was also necessary to mechanically redesign the thruster to sustain the stresses imposed by the vibrations of the launch vehicle and to design and fabricate an analogue control system that would permit any operating power level between 500 and 2500 W to be selected by adjustment of a single control signal.

Following completion of the above tasks, the newly designed thruster, control system, and recently constructed flight prototype power conditioner (10 kc inverters operating

from a 250 V dc line) were integrated and tested as a complete system. During one 50 hour period, the repeatability and stability were demonstrated over a beam current range from 0.166 A to 2.0 A with single knob control. The performance map, taken over a 5:1 power range at various values of specific discharge power and mass utilization, demonstrated that thruster performance and stability were not materially affected by reasonable changes from the nominal operating point. However, it was observed that the neutralizer design and control system provide a trade-off among over-all thruster efficiency, lifetime, and stability.

Finally, a thruster of the optimized design was fabricated and delivered to NASA for evaluation.

SECTION I

INTRODUCTION

The 2-1/2 kW thruster system developed and tested under this contract is intended to serve as the module from which higher powered propulsion systems may be assembled. This modular design concept¹ provides considerable flexibility and versatility and eliminates the need to develop a unique thruster for each individual mission. In particular, thrusters of this design have served as the basis for recent conceptual studies of solar electric propulsion missions to the asteroid belt, out of the ecliptic flight and Jupiter orbiter. The ability to raise a satellite from a low orbit to a synchronous orbit with a system employing these thrusters has also been studied.

The work reported here follows naturally from a previous contract², in which the basic discharge chamber design for thrusters of this size was scaled from the SERT-II geometry. The work here in many ways parallels similar work at NASA LeRC³, and the authors wish to acknowledge many helpful suggestions and discussions with LeRC personnel during the performance of this work.

This report discusses each element of the thruster system (discharge chamber, ion optics, neutralizer, control system, feed system, etc.) in some detail. It identifies the various subsystem interfaces, the mechanical and electrical system design, and finally describes the integration of the system components and the verification tests conducted to demonstrate over-all performance. A particular requirement of this program, which had not been explored earlier, was the need to throttle the thruster output over a 5:1 power

range (2.5 to 0.5 kW) to accommodate some unique missions. This added constraint significantly influenced the discharge chamber, control system, and neutralizer design.

The achievement of the goals set forth in this contract represent an important milestone in the program leading to a solar electric propulsion mission. The data presented here, taken into consideration with recent studies at LeRC³ and JPL⁴, represent the state of development of this type of thruster system. Parametric data, which defines the performance of an experimental system such as this, is intended to serve as input data for both the mission planners and vehicle designers who propose to ultimately use such a system for practical purposes.

In order to effectively assign program milestones and budgets, the work was organized into a number of tasks defined in the statement of work. It is not convenient to maintain this format in this report. Therefore, the following list of task numbers and titles (Table I) is provided as a cross reference for any task numbers which appear in the text and for the convenience of the reader who may wish to refer to the monthly reports.

TABLE I
Titles of Program Tasks

Task	0:	Grid System Fabrication and Test
Task	I:	Thruster Throttling and Design Definition Tests
Task	II:	Optimized Thruster Design and Fabrication
Task	III:	Deleted
Task	IV:	Design and Fabrication of a Laboratory Type Thruster Control System
Task	V:	Thruster System Design Verification Tests
Task	VI:	Deleted
Task	VII:	Optimized Thruster Design Calibration and Delivery

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SECTION II

COMPONENT DEVELOPMENT

This section of the report discusses each of the major subsystems of the thruster module in some detail in order to quantify the performance trade-offs and the subsystem interfaces. Section II-E illustrates how these subsystems are packaged into a functional, structural unit that satisfies the thermal constraints and the requirements for a lightweight structure without sacrificing the mechanical integrity necessary to survive the high stresses associated with the launch of a chemical rocket. The final section deals with the power conditioning and control system which has electrical, but no mechanical, interface with the thruster and feed system module.

The development of these subsystems is presented from a functional rather than a purely historical or chronological viewpoint so as to emphasize the physical principle involved. In practice, the design of the subsystems was closely inter-related and took place by the stepwise modification of the 30 cm thruster developed by HAC under an earlier contract.²

A. ION OPTICAL SYSTEM

The GFE thruster² provided at the starting point of this contract was mechanically designed and optimized to use a single insulated electrode as the ion extraction system. Experiments at both HRL and LeRC⁵ had identified an interaction between the test chamber and this type of electrode that limited the useful lifetime to a few hundred hours when tested in conventional facilities. Since the ion optical system plays a major role in determining the mechanical

structure, discharge chamber performance, startup sequence, and power distribution in the thruster, it was necessary to define this subsystem before the remainder of the optimization and development program could proceed.

In order to perform this evaluation, four different single insulated electrode systems were fabricated and compared with a high perveance conventional dual grid system during a series of 50 hour tests. The end results, which are discussed in detail below, prompted the decision to use the conventional dual-grid system for the rest of the program. A successful 450 hour test of this system verified the 50 hour performance data and the extrapolated lifetime estimates.

1. Optical System Design and Fabrication

The several ion optical systems tested are defined in Table II and illustrated in Fig. 1. All the electrodes were fabricated from molybdenum, with the apertures either drilled or chemically etched. The chemical etching was performed so that the "waist" in each aperture occurred approximately 20% of the distance in from one side rather than at the mid point (see Fig. 1). The electrodes were electropolished and carefully cleaned prior to use.

All electrodes were mounted under a light radial tension by using flexible mounting structures that could be pre-loaded during assembly. A brief analysis of this type of mounting was made using an available computer model which calculated the electrode deformation and final contour under the effects of the mounting preload and the radial temperature gradient that is generated during operation. The most important criterion for successful operation was that the mounting structure should not radially constrain the electrodes as they heat up. The mount design assures both that

TABLE II
Grid Systems Dimensions

Insulated Single Grid Systems								
Ion Optical No.	Fabrication Techniques	Accel□			Insulation			
		Thickness, mm	Aperture, mm	Dish, mm	Materials	Coats No.	Thickness, mm	Aperture, mm
1	N/C Drilled	0.41	1.90	17.0	MCR - 1k5 Mullite	5	0.75	1.32
					MC1 Glass	4	0.78	
2	Chemical Etch	0.41	1.90	6.7	MCR - 1K5 Mullite	5	0.79	1.32
		0.43						
3	Chemical Etch	0.38	1.90	8.1	Corning 1723 Glass	7	0.74	1.50
4	Chemical Etch	0.38	1.90	11.3	MCR - 1K5 Mullite	5	0.75	1.85
					MC-1 Glass	5	0.75	
□All apertures on 0.254 cm Centers in Hexagonal Pattern.								

Conventional Dual Grid Systems [†]									
Ion Optical System No.	Screen*				Accel*			Spacing	
	% Open, %	Thickness, mm	Aperture, mm	Dish, mm	Thickness, mm	Aperture, mm	Dish, mm	Edge, mm	Center, mm
0	70.4	0.51	4.00	0	2.54	3.27	0	1.58	0.69
5	65.5	0.46	2.16	0	1.27	1.93	1.53	1.91	0.51
*Apertures on 0.254 cm centers in hexagonal pattern									
6	71.0	0.46	2.80	0	1.27	2.58	0	1.91	0.51
*Apertures on 0.317 cm centers in hexagonal pattern.									
†These systems used one center support and was supported at six points around the periphery. The screen electrode was loaded under a radial tension of 680 g at each support point as measured with the system cold.									

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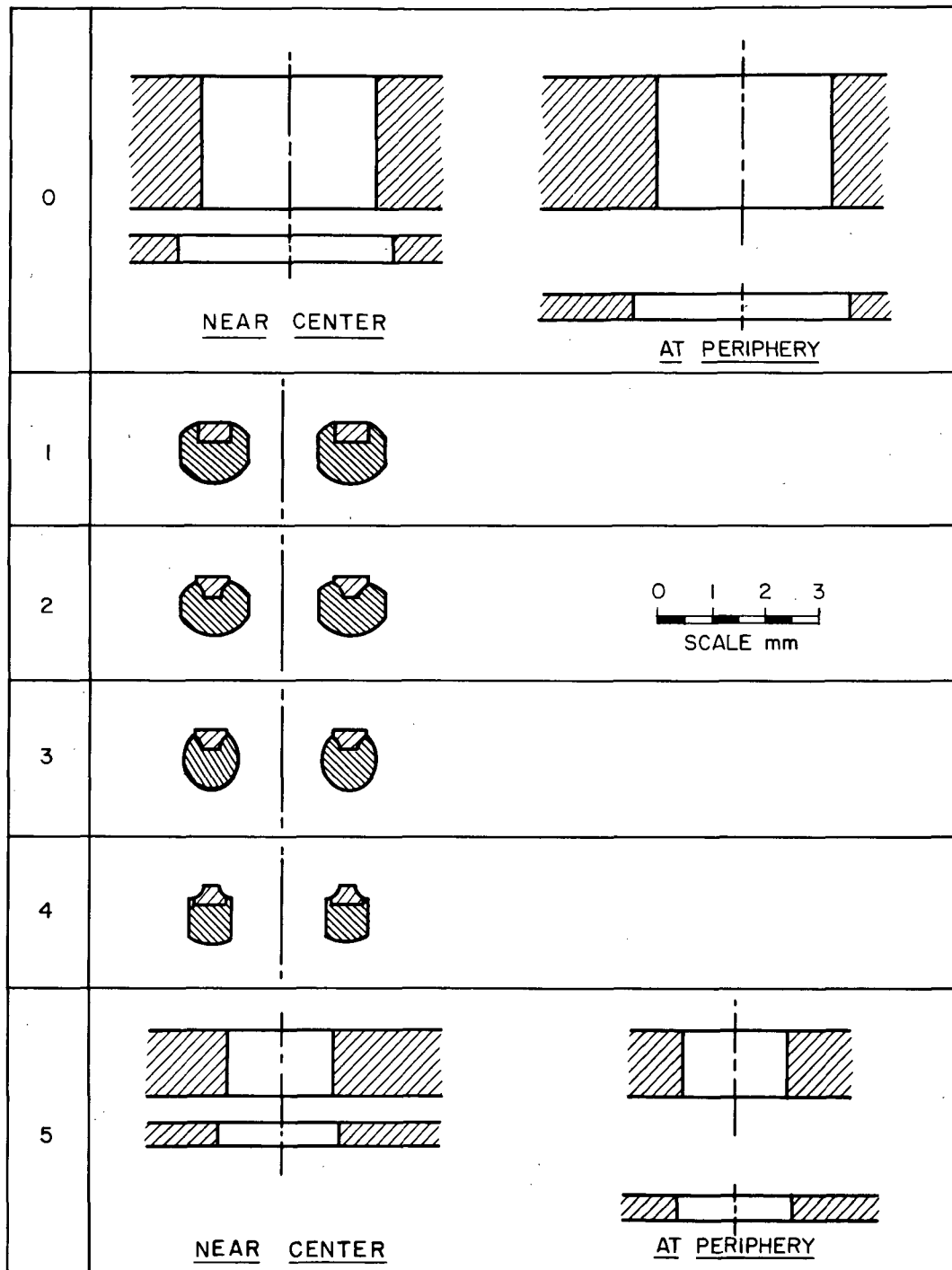


Fig 1. Ion Optical System Tested During Task 0.

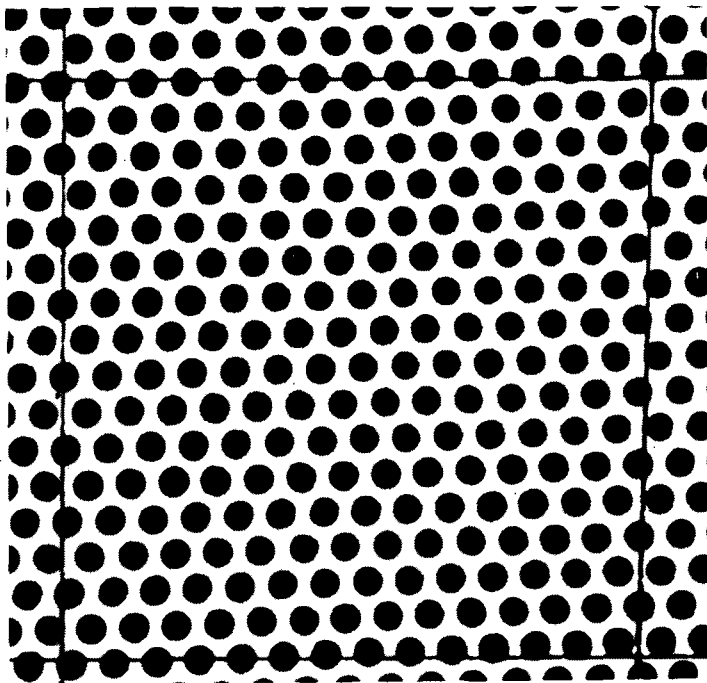
this criterion will be fulfilled and that the periphery of the electrode is held in a plane perpendicular to the axis of the thruster. This helps reduce the effects of residual stresses in the electrodes which become more pronounced as the electrode is heated.

The thin (0.05 cm) screen electrodes of the dual grid systems are further supported by a 0.2 cm thick ring riveted around the periphery. This ring is cut into six segments to permit radial expansion.

The basic procedure used to apply the insulating coating to grids 1, 2, and 4 has been described previously.² The modified procedure used here was to apply a series of pure mullite base coats (rather than 85% mullite, 15% glass) and to then fire each coat at 1100°C for one hour. The apertures were shaped by hand drilling as required after the final mullite coat. The grid was then fired to 1400°C to further harden the coating. A glaze composed principally of Ferro 3249 glass was applied to the surface of the insulator as a water slurry, dried, and fired at 1100°C to permit it to flow into the pores in the mullite and provide a surface glaze.

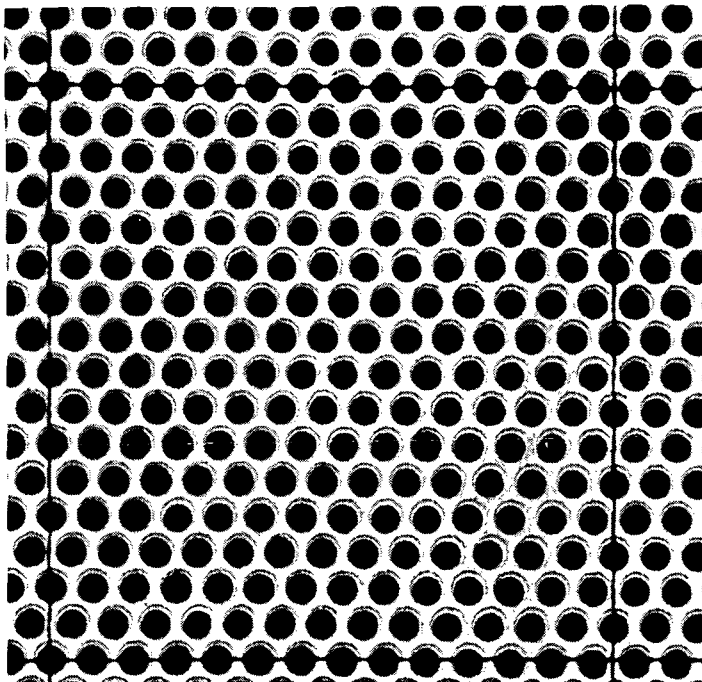
The base coating for grid 4 was applied normally, and each aperture was hand drilled from each side (a total of more than 20,000 operations) to shape them and to clean the ceramic from the conical downstream surfaces of each aperture (see Fig. 1). Figure 2 shows photographs of the two surfaces of this electrode after fabrication. One problem with this fabrication procedure is the deposition of small particles of glaze material on the previously cleaned downstream surface of the accelerator. These glass particles melt during firing and adhere tightly to the molybdenum surface and are virtually impossible to remove without damaging

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(a) Front View..

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(b) Back View.

Fig. 2. Photographs of the Front and Back Surfaces of Grid 4 Illustrating the Hand Formed Aperture Shapes.

the main insulating coating. It appears that the surface charge which builds up on these particles may be responsible for some of the arcs observed during operation.

Grid 3 was coated only with Corning 1723 glass according to the procedure developed at LeRC. While the grid integrity was on the whole very good, a large number of minute craze marks were observed in the glass following fabrication. It is thought that these may occur because of a faster cooling rate in the kiln used at HRL as compared to that used at LeRC.

Of the four single grid systems, numbers 1 and 2 compared the performance of drilled and chemically milled substrates with mullite-glass insulation, and numbers 2 and 3 compared the performance of mullite-glass insulation and Corning 1723 glass, both on a chemically etched base material. Grid 4 was designed to provide little or no exposed ceramic surface on which the sputtered material could deposit.

Following selection of the dual grid configuration, the mechanical support structure and center support were redesigned to reduce the weight and improve reliability. This is discussed in detail in Section II-E as part of the over-all mechanical design. One additional dual grid set was fabricated with screen apertures 0.280 diameter on 0.317 cm centers in an attempt to increase the fractional open area of the screen and hence the discharge chamber performance. As discussed on page 19 the perveance and structural integrity of this system made it unacceptable for the final design.

2. Ion Optical System Tests

The first five of the ion optical systems discussed here were designed, fabricated, and tested in order to compare their performance at a beam current of 1.85 A at a beam voltage of 1.0 kV. No changes were made in the thruster or test

setup during this test period so as to insure that the performance of the grid systems was the only variable. All tests were run with conventional 60 cycle power conditioning in a 3 m diameter by 7 m long vacuum tank with a full cryoliner which held the pressure below 10^{-6} Torr with the thruster operating. The second dual grid system (with 0.280 cm apertures) was tested later in the program in the same facility but with a somewhat modified thruster and power conditioner.

The average test values measured during the 50 hour tests are presented in Table III. Of the four insulated systems tested, one (No. 4) showed no visible damage to any part of the insulating coating, one (No. 2) showed local damage to the coating only in an insufficiently glazed area, and two (Nos. 1 and 3) showed unacceptable local damage to individual holes. In the case of grid 3 (Corning 1723 glass coating), the local damage to several places in the insulating coating was attributed to minute cracks in the glass coating that result from a difference in the expansion coefficient of the glass and the molybdenum substrate. The damage to grid 1 was an erosion of the insulating coating (mullite-glass) in the vicinity of four (out of 10,000) apertures. These four apertures may have been irregular or eccentric with the substrate; however, it is impossible to detect the imperfection from the photographs taken before the test. Except for the local aperture erosion, this coating showed no indication of deterioration after the 50 hour test.

The conventional dual grid system initially presented some difficulties, because the required close spacing could not be achieved using the conventional mounting system with the GFE thruster assembly. After designing and fabricating a rigid mount, which maintains the screen electrode in radial tension, the system was operated satisfactorily. System 5

TABLE III
Average Test Values

Test	Propellant			Discharge		Beam		η_{mass} , %	eV/Ion
Grid No.	Main A (equiv.)	Cath A (equiv.)	Neut	ΔV_I , V	I_I , A	V_B , kV	I_B , A		
0 (nominal)				38.0	10.9	1.0	1.6	—	262
1 (50 hr avg)	1.913	0.087	0.102	36.7	9.1	1.0	1.85	88.5	180
2 (50 hr avg)	1.866	0.094	0.063	37.8	9.0	1.0	1.86	91.5	183
3 (50 hr avg)	1.91	0.093	0.081	38.7	9.45	1.0	1.85	89.0	197
4	1.92	0.090	0.085	39.8	9.8	1.0	1.85	89.0	208
5	1.87	0.072	0.065	42.5	11.0	1.0	1.85	92.0	253
6	1.85			40.0	9.8	1.0	1.7	92.0	230

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performed very well. No significant erosion could be detected on the downstream surface of the accel electrode except in the vicinity of the center support. This erosion is attributed to distortion of trajectories near the center support and direct interception of the support fastening unit. This problem has been analyzed by Byers⁶ of LeRC and an insulated center support cap was designed which substantially reduces this erosion.

Figures 3 through 6 illustrate the performance of the various electrodes. Figure 3 shows the current handling capability of each system. This is a clearly defined quantity for the conventional electrode systems, because direct interception on the accelerator electrode occurs as the beam current exceeds the limits defined by the perveance of the system. Insulator leakage currents may be kept very small in all conventional dual grid systems. The above is not true for single, insulated grid systems where the accelerator current typically falls as the total voltage between plasma and accelerator is decreased. The perveance limit, as defined by the onset of direct interception on the accelerator, was never reached in the performance mapping of these single grid systems. In general, they appeared able to extract more current than the 1.85 A at the minimum total voltage of 1.3 kV at which the tests were run. Note in particular grid 4, which easily handled 1.85 A at a total voltage of 700 V (+400 V, -300 V) during performance mapping. The accelerator current at this point was only* 18 mA as compared to 69 mA during the extended test. Moreover, the performance mapping seems to imply that the aperture shape and diameter are better suited for thruster operation at a beam current of 1.85 A and a beam voltage of 600 V or a substantially

* Such currents are a function of time, and this 18 mA value might increase during extended operation at this point.

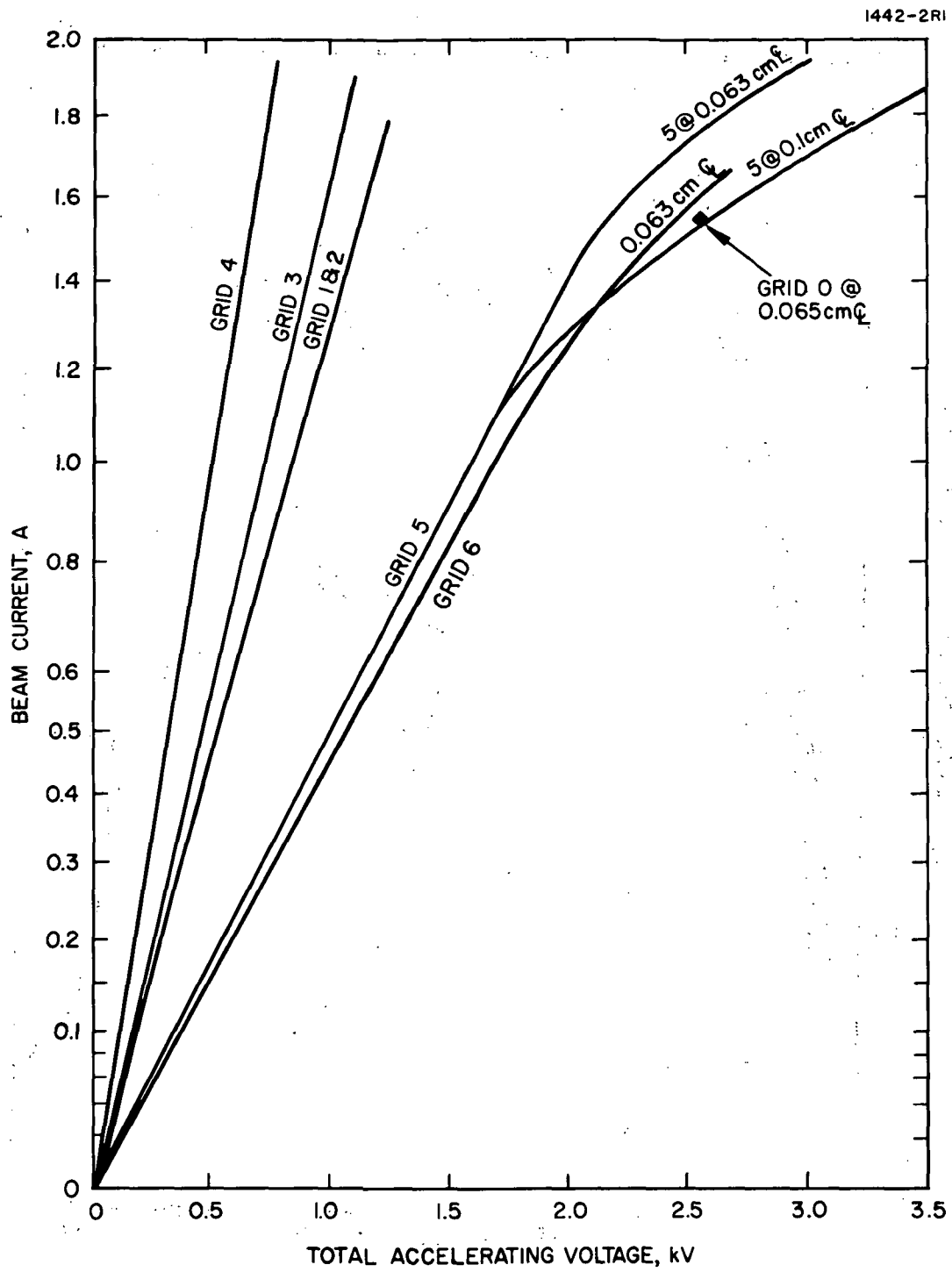


Fig. 3. Perveance of the 7-Grid System Described in Table II.

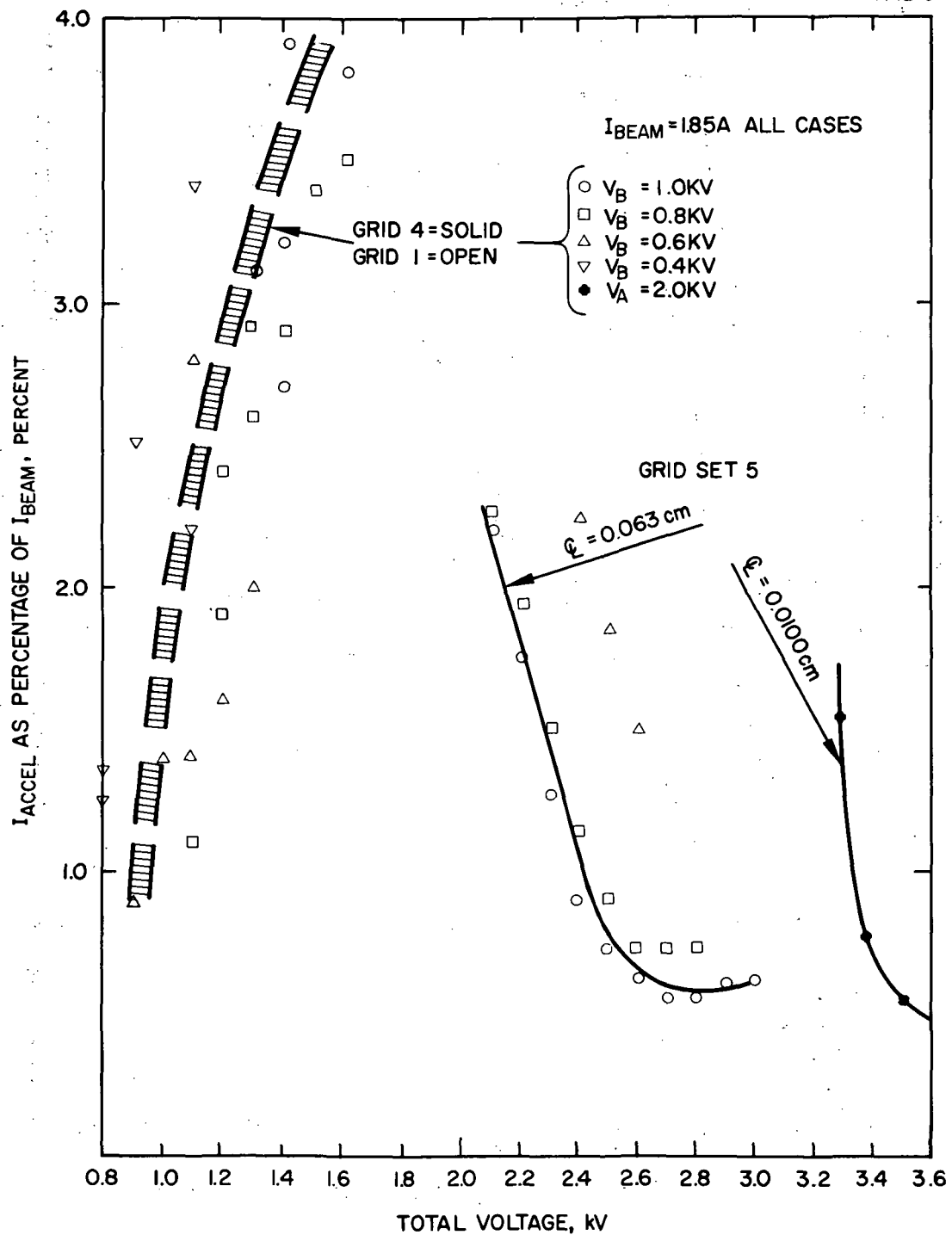


Fig. 4. Accelerator Currents Measured with Both Single Insulated and Dual Grid Ion Extraction Systems.

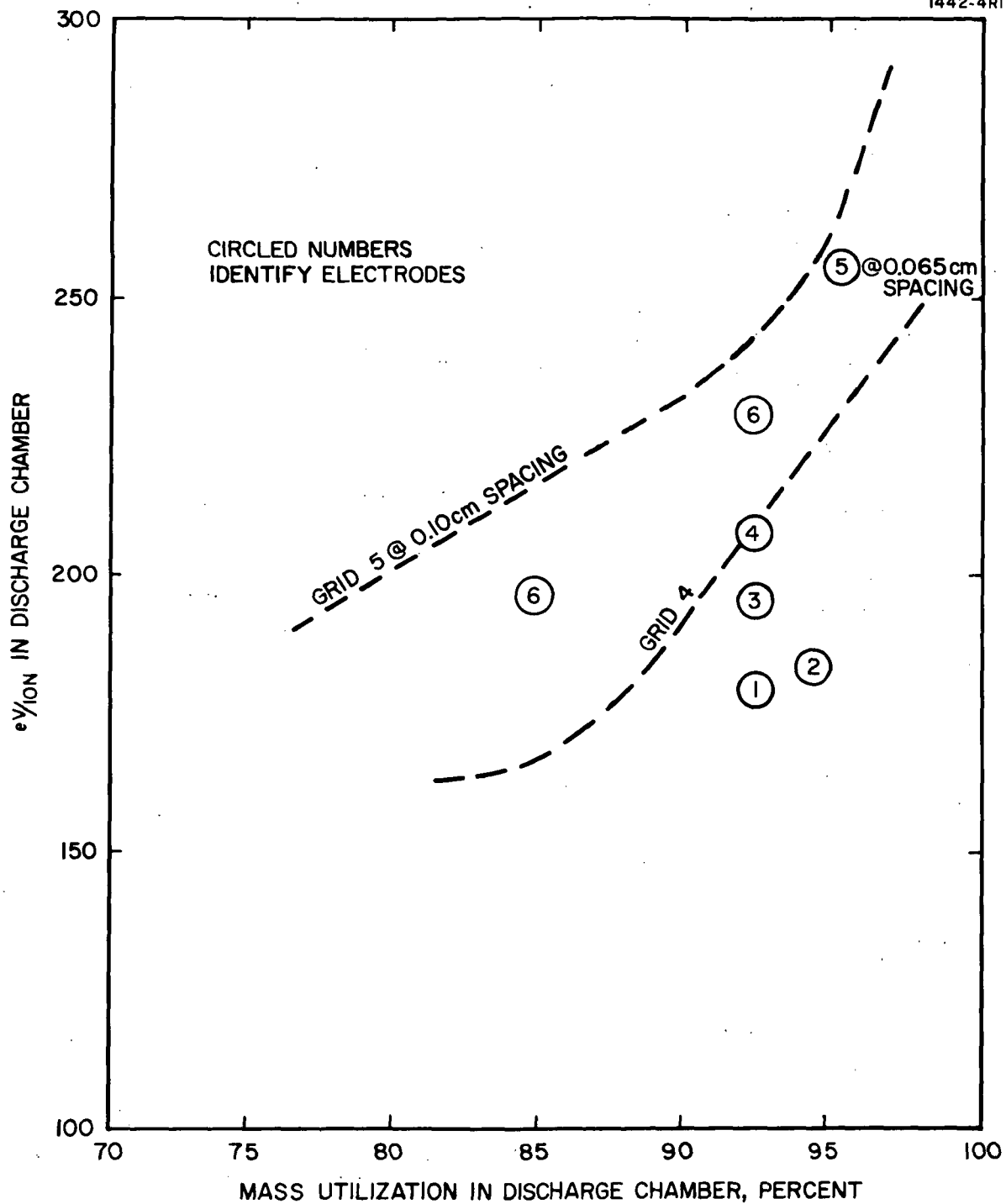


Fig. 5. Effect of the Ion Optical System on Discharge Chamber Performance.

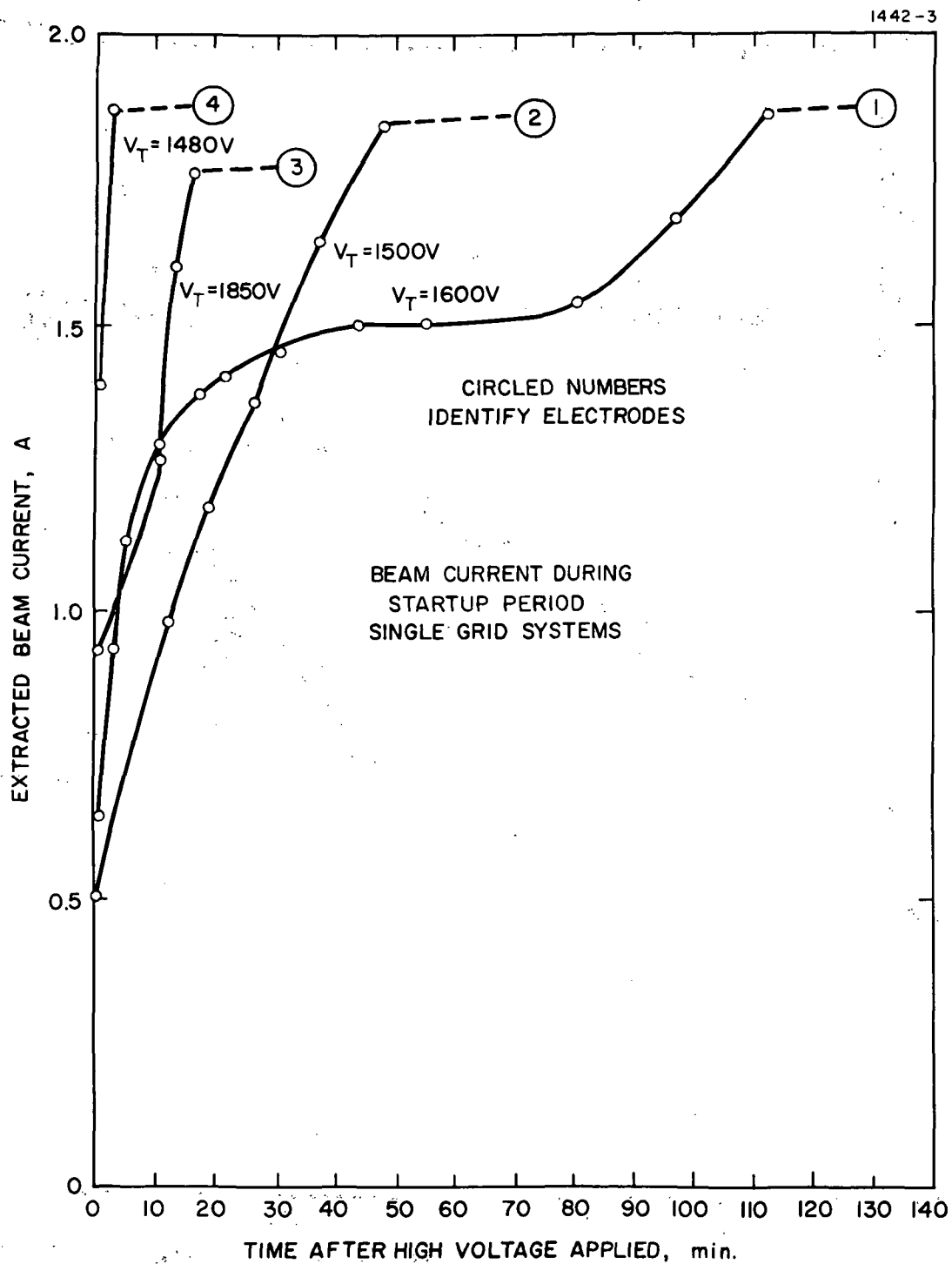


Fig. 6. Rate at which Full Beam Current could be Established for the Various Single Grid Ion Optical Systems.

higher current at 1000 V beam voltage. Operation at the higher voltage appears to overfocus the individual aperture beams and produce crossover trajectories, resulting in direct interception and erosion of the downstream edge of the accel electrode apertures to a hexagonal rather than circular shape.

Note also in Fig. 3 that the maximum beam current that can be extracted from the conventional ion optical systems is not directly proportional to $V^{3/2}$ which would be represented as a straight line on the plot. Note also that the steeper, linear portion of the curve was extended by moving the screen and accelerator closer together near the center while leaving the peripheral spacing unchanged. This indicates that, as expected from the beam profiles, the central region of the ion optical system will saturate before the periphery.

Figures 3 and 5 also illustrate the performance of grid set number 6 which has a greater open area than number 5 but fewer apertures. As expected the perveance is somewhat lower for grid number 6 and the discharge performance somewhat better. The number 6 screen electrode was structurally very weak and was judged to represent the limit to which the open area could be extended and still have a reliable system with the support mechanism employed here.

Figure 4 illustrates the accelerator current, expressed as a percentage of the beam current, for different total voltages. Only data for nominal 1.85 A beam are shown, although data are on hand for all systems for beam currents of 1.85, 1.5, 1.0, and 0.5 A. Note the difference in shape between the single insulated electrode and conventional dual grid systems. The shape of the single grid makes it difficult to uniquely define the operating limits of this system. Typically the conventional systems operated at 0.5% accelerator current and the single grids at 3% at the design test point of +1000 V screen potential. An accelerator potential of

-1500 V was required to properly focus the 1.85 A beam for the dual grid systems, whereas only -300 V was used with the single grid to prevent backstreaming. Operation at a lower beam voltage, hence a lower specific impulse, can reduce the accelerator drains for single grid systems to of approximately 1%.

Figure 5 shows the discharge chamber performance measured with the different ion optical systems. The insulated grids show a distinct advantage over the dual grid systems due to their greater open area (~85% as compared to 65% for the dual grid system). The over-all performance of the thruster using the dual grid system is approximately equal to thruster performance using the single grid when the reduced power loss in the accelerator supply is taken into consideration.

Figure 6 shows the rate at which full beam current could be established with a single grid system. These data were generated by providing excess mercury flowrate and discharge current (hence excess plasma density) and observing the rate of beam buildup with full extraction voltage applied.

While not fully understood, it is believed that the beam current cannot be instantaneously established in most cases, because some buildup of sputtered material from the test facility is required on the downstream surface of the electrode to generate the necessary field strength for beam extraction. This model is further verified by the performance of grid 4, which was designed to eliminate the presence of insulating material in the apertures. Thus the equipotentials of startup for grid 4 were approximately equal to those of the earlier insulated grids after they had been partially coated with sputtered material. Note that the startup of grid 4 was almost instantaneous.

The over-all system performance with single and conventional dual grids is compared in Table IV using data taken with grids 4 and 5. The improvement in discharge chamber efficiency achieved with the single grid is approximately compensated by the increased accelerator leakage current, thus making the total efficiency of the two systems quite comparable. The longer operating lifetime and stability of the accelerator currents with the dual grid system make it clearly superior for the current application.

B. DISCHARGE CHAMBER

The primary objective of the discharge chamber development performed under this contract was to provide stable thruster operation over a 5:1 throttling range with a minimum loss in efficiency. The change from an insulated single grid ion extraction system (~85% effective open area) to a conventional dual grid system (~65% open area) necessitated several modifications to maintain discharge chamber performance level. This was accomplished by varying the geometry of the cathode pole piece baffle. The magnetic field strength was investigated by adding or removing permanent magnets, but demonstrated only that the original number of magnets (12 axial, 8 radial) provided the most efficient and stable operation.

The baffle geometry controls the propellant flow required through the hollow cathode to obtain a given discharge voltage. Consequently the baffle affects both the efficiency and stability of the discharge chamber. Initially, the baffle variations were restricted to conventional, nonmagnetic materials like those used in SERT II. In order to maintain a constant discharge voltage when throttling the thruster

TABLE IV

Power Distribution in Thruster With
Single and Dual Grid Systems

	Single Grid, W	Dual Grid, W
Beam (1.85 A at 1.0 kV)	1850	1850
Accelerator		
Single grid 0.065 A at 1.4 kV	91	
Dual grid 0.012 A at 2.7 kV		31
Discharge		
Single grid 200 eV/ion	370	
Dual grid 240 eV/ion		445
Neutralizer Coupling 1.85 A at 12 V	22	22
Heaters		
Main cathode	25	25
Main isolator	20	20
Cathode vaporizer	4	4
Main keeper	3	3
Neutralizer cathode	10	10
Neutralizer vaporizer	4	4
Neutralizer keeper	3	3
Main vaporizer	10	10
Total Input Power	2412	2427
Power Efficiency	77%	76%
Total Mass Utilization	90%	
Effective I_{sp}	2840 sec	

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power level with this type of baffle, an increase in cathode propellant flow is required as the beam current is reduced. Excessive cathode propellant flow results in discharge mode shifts, and thus the stable throttling range is limited to at best 3:1. Moreover, the relatively low open fraction of the dual grid system's extraction grid (only about 65%) requires a higher discharge chamber plasma density and a reduction in the baffle open space (increase in baffle diameter). When operated with the conventional baffle, it was found that the discharge chamber was hard to ignite, unstable against discharge mode changes, and that the cathode propellant flow required tight control. A magnetically controlled baffle, invented and described under previous contracts NAS 3-9703 (Ref. 7) and NAS 3-11523 (Ref. 2) was found to alleviate the stability and control problems. The results of the conventional and magnetic baffle investigations are described below. The conventional baffle-pole tip geometries that were evaluated are described in Table V and Fig. 7(a). As indicated in Table V, the discharge ignition and control characteristics were only satisfactory for baffle 3. The throttling range (limited by discharge mode change instability) for this configuration was from about 1.5 to 0.6 A. Figure 8 shows the throttling characteristic of cathode propellant flow and discharge propellant utilization geometry for baffle 3 (at nearly constant discharge voltage and discharge current to beam current ratio).

The magnetic baffle geometry is shown in Fig. 7(b). Initially, the baffle control coil was operated from a separate power supply to determine the optimum ampere-turns for obtaining efficient thruster operation. About 40 A-turns at 1.85 A beam current was found to be best. The baffle control characteristic is such that increased beam current (and consequently increased discharge current) requires an increase in baffle

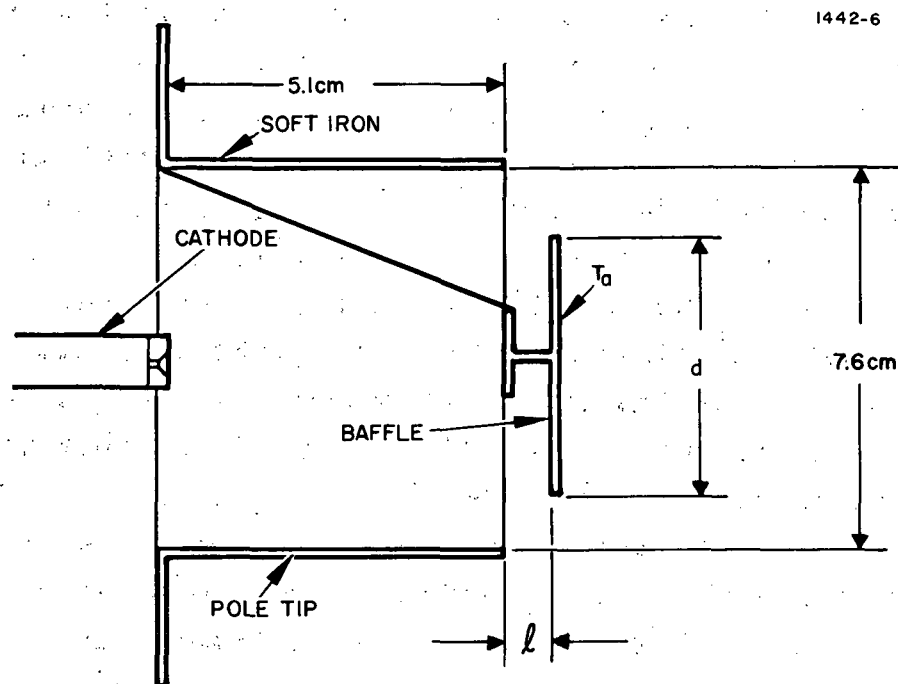
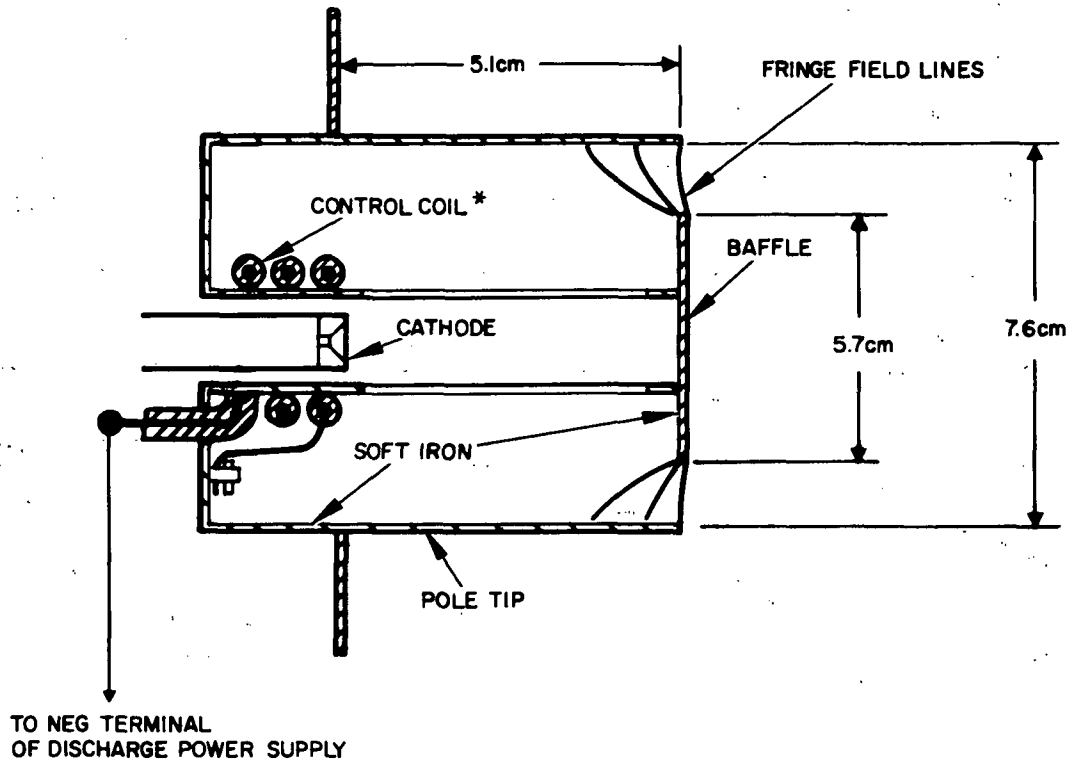


Fig. 7(a). Conventional Cathode Pole Tip-Baffle Geometry showing Parameters l and d varied during Optimization Tests.



* POLARITY DETERMINED SUCH THAT CONTROL CURRENT INCREASES THE FRINGE FIELD IN THE REGIONS SHOWN.

Fig. 7(b). Magnetic Baffle Geometry used in Final Thruster Design.

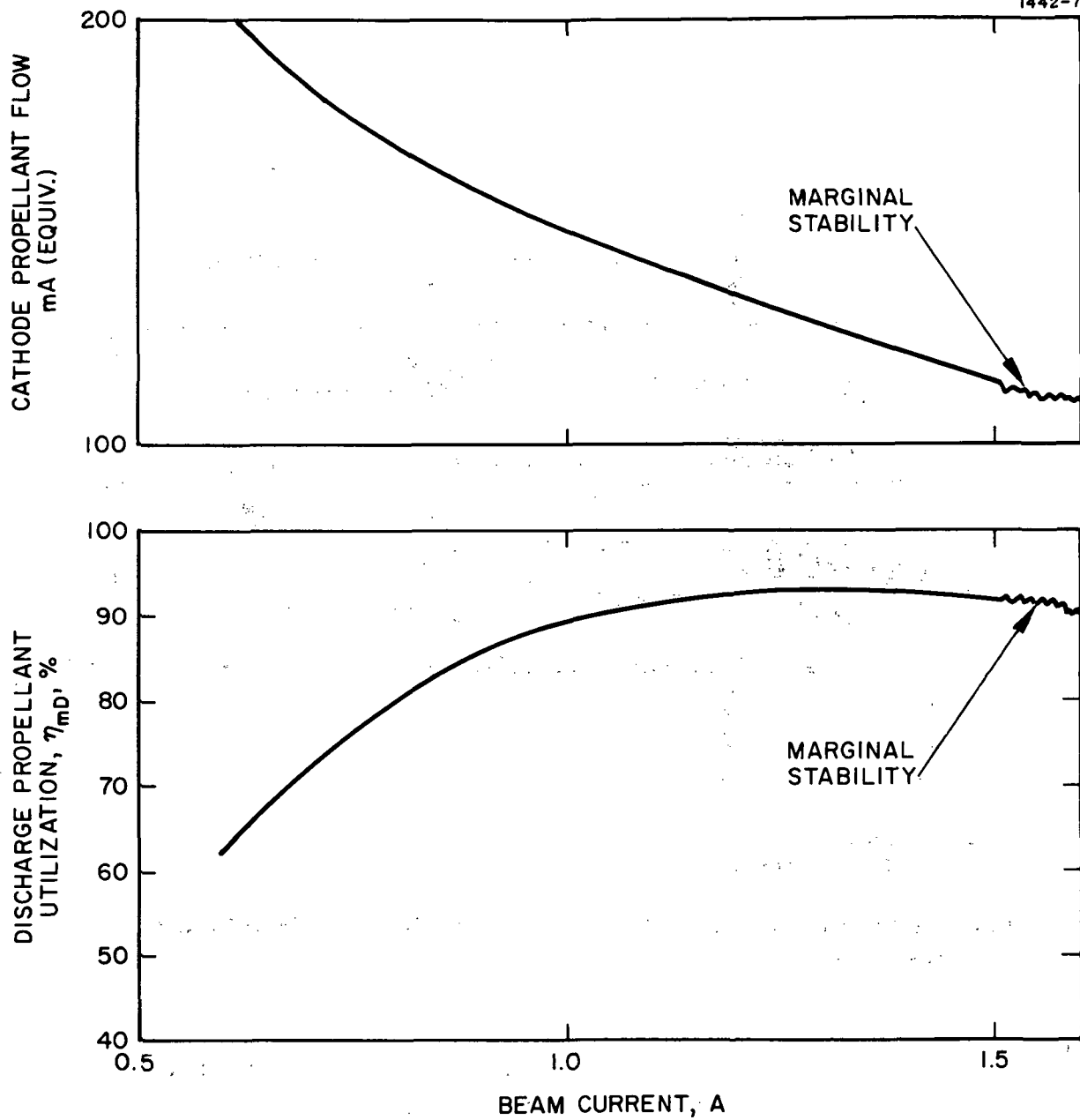


Fig. 8. Cathode Propellant Flow and Discharge Propellant Utilization as a Function of Beam Current for Baffle 3 at Constant Discharge Loss of 300 eV/Ion.

TABLE V
Conventional Baffle Parameters

Baffle	Diameter (d), cm	Spacing (λ), cm	Acceptable Cathode Propellant Flow Range, mA (Equiv.)	Discharge Ignition	Stability Against Discharge Mode Change
1	6.2	0	90 - 180	Difficult	Good ($I_B > 0.6$ A)
2	6.0	0	90 - 100	Acceptable	Poor
3	6.2	0.38	90 - 180	Acceptable	Satisfactory
4	5.7	0	Small	Acceptable	Bad
5	5.5	0	Small	Acceptable	Bad

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winding current to maintain constant discharge voltage and cathode propellant flowrate. The discharge current thus makes an excellent control parameter. The baffle coil was modified such that discharge current was passed through this winding before reaching the cathode, as shown in Fig. 7(b). Discharge chamber performance for this Task I thruster was mapped over the throttling range using coils of 1, 2, and 3 turns. Figure 9 shows the throttling characteristic of cathode propellant flow for these control coils excited by the discharge current. At this point, the baffle diameter was fixed at 5.4 cm, and the 2-turn control coil was selected for completion of the control system definition tests. Figure 10 illustrates the results of initial discharge chamber tests of the thruster constructed under Task V which had a slightly stronger magnetic field (resulting from permanent magnets obtained from a different vendor) and a consequent change in the magnetic baffle behavior. Repeating the procedure described above, it was found that a baffle diameter of 5.7 cm and a 3 turn control coil restored the desired throttling characteristic, as is also shown in Fig. 9. Figure 11 shows a magnetic field plot of the Task V thruster.

A brief discussion of the physical aspects of the discharge chamber and the magnetic baffle is required to provide a basis for the conclusions which can be drawn from the development described above. In the typical thruster with conventional baffle geometry as shown in Fig. 12, the flow of electrons between the hollow cathode plasma and the main plasma is governed by the strength of the pole tip fringe field that intercepts the baffle, the baffle-pole tip annular area, and the relative plasma and neutral densities in the cathode and main plasma regions (especially in the locality of this annulus). A change in any one of these quantities

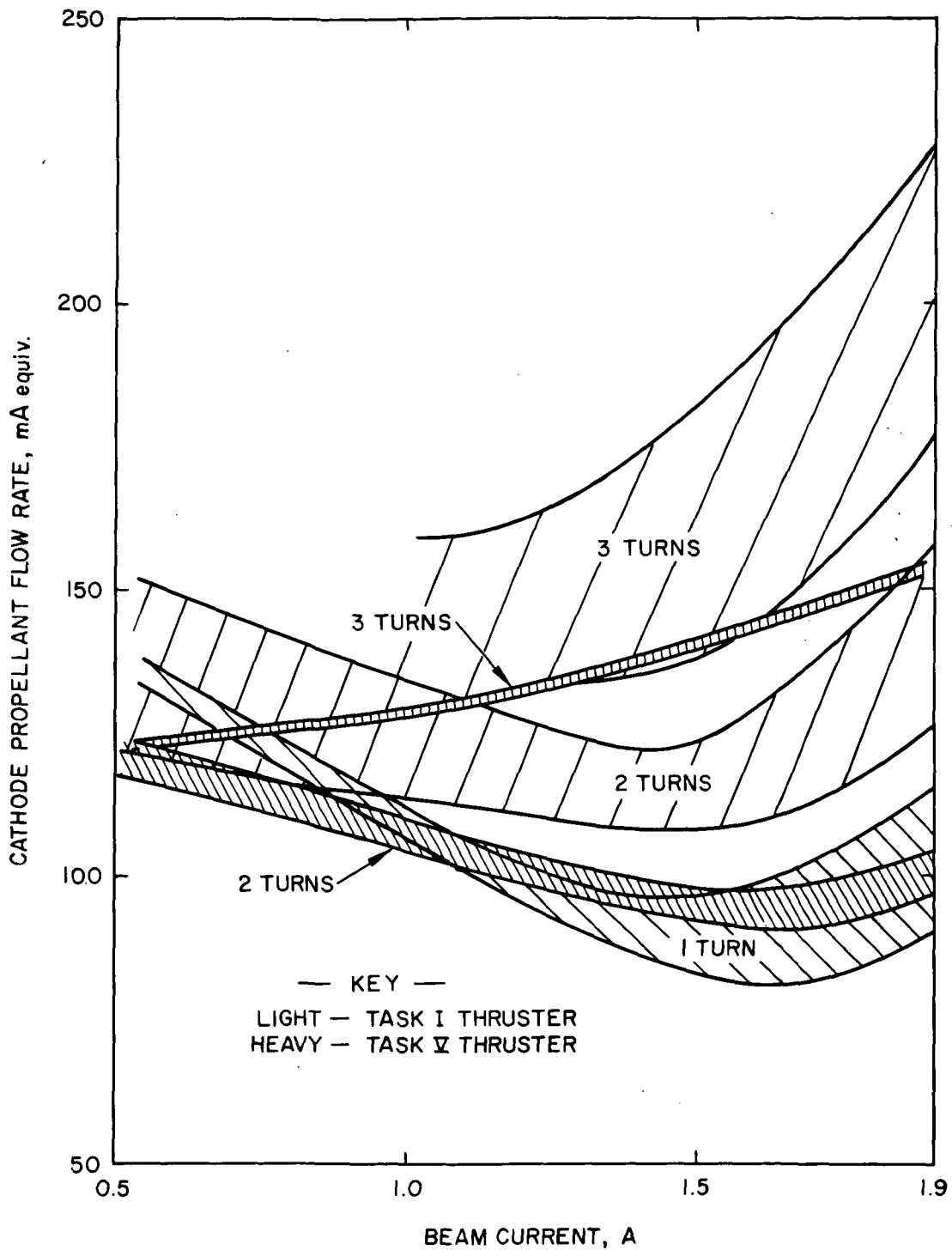


Fig. 9. Cathode Propellant Flowrate as a Function of Beam Current for Tasks I and V Baffle Geometries.

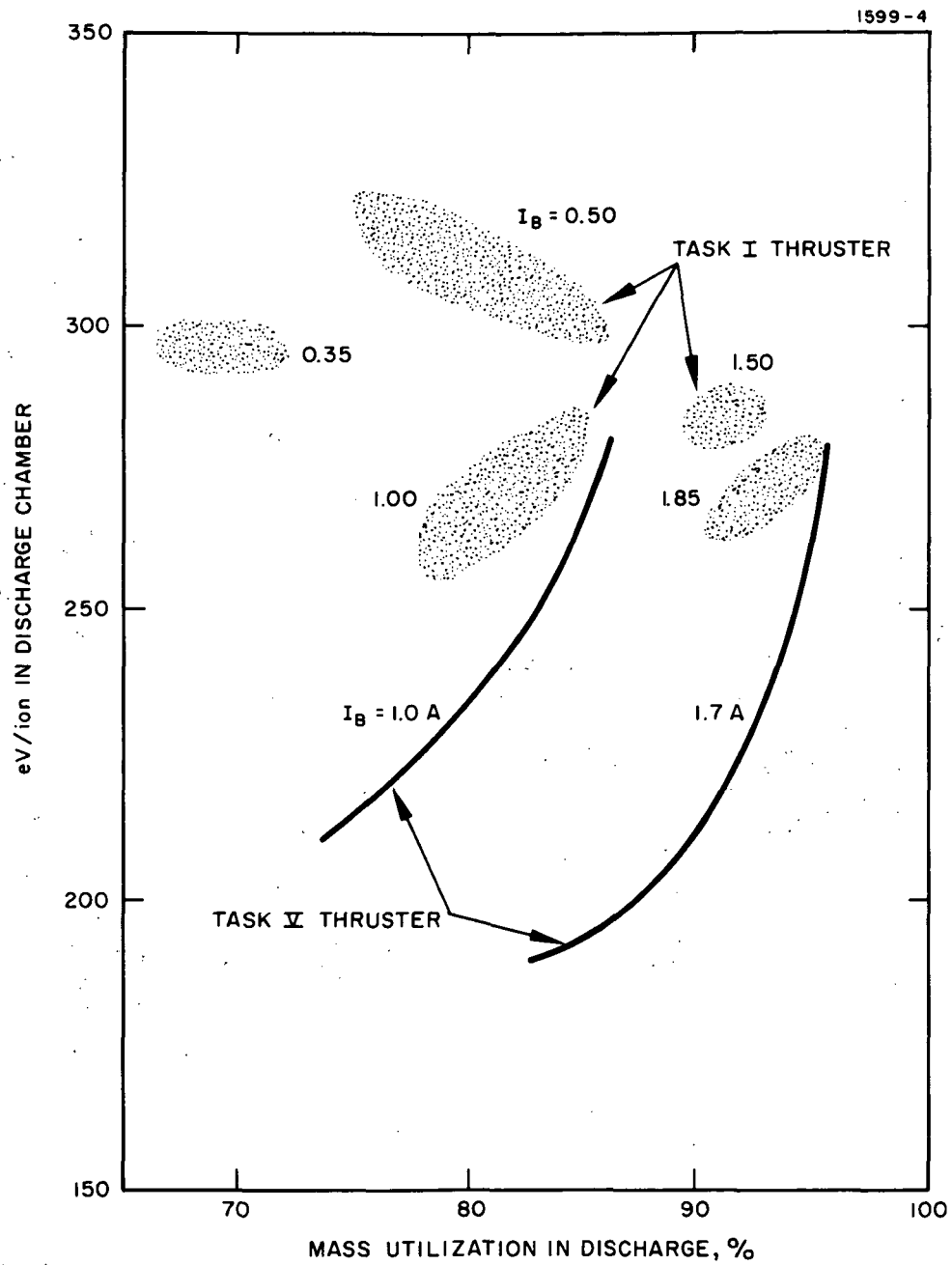


Fig. 10. Comparison of the Discharge Chamber Performance of the Task I and Task V Thrusters.

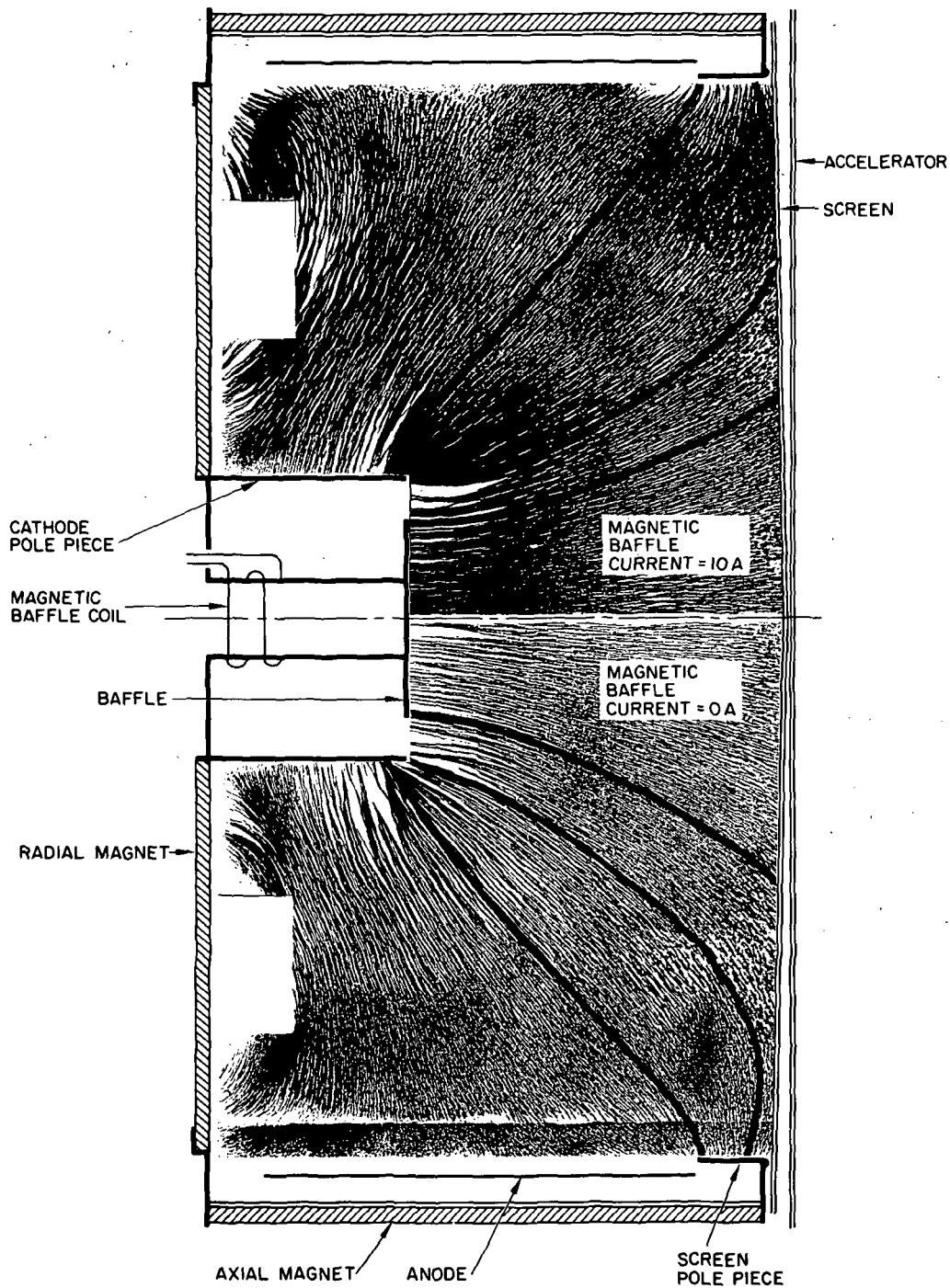


Fig. 11. Iron Filing Maps of Magnetic Field Lines in the Discharge Chamber for Zero and 10 A Magnetic Baffle Excitation Current.

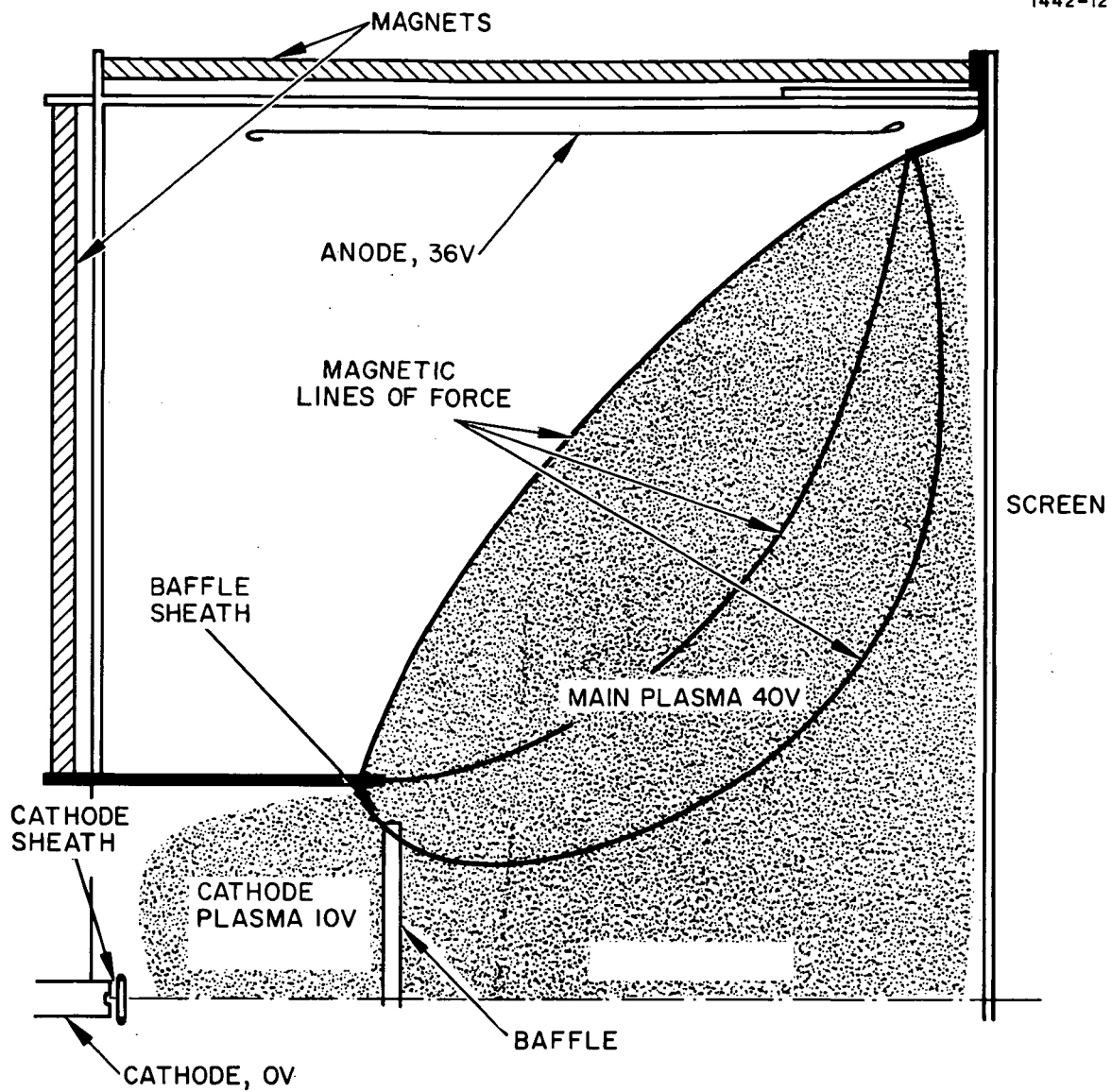


Fig. 12. Plasma Distribution for Typical Discharge Chamber.

results in a change in the electrical impedance (potential difference/cathode current) between the cathode and main plasma regions. Changes in the neutral atom and plasma density in the main plasma region which arise from changes in thrust level or extraction screen open area must be compensated by offsetting changes in either the baffle annular area (baffle diameter), the cathode plasma parameters (cathode propellant flow) or the pole tip fringe field (magnetic baffle). For any given change in main plasma region parameters, a change in only one or all three may be desirable, depending on the magnitude and condition of the change. When the thruster output is reduced, the neutral and plasma density in the main plasma region decrease, and in general, the electrical impedance between the cathode and main plasma region increases faster than is desirable. If, in order to compensate for this impedance change, only the cathode propellant flow is changed, the introduction of excessive propellant directly into the primary electron injection region will result in an unfavorable plasma density distribution. Provision for modification of the fringe magnetic field of the cathode pole tip provides a control which results in less perturbation to the main plasma region. Moreover, when controlled in direct proportion to the discharge current, the magnetic baffle facilitates discharge ignition, because with no discharge current, the strength of the fringe field in the annular gap is minimal.

Thus it can be concluded that:

- Any thruster modification which reduces the main plasma region density must be compensated by one or more of the following:

- (a) an increase in cathode propellant flow
- (b) a decrease in baffle diameter
- (c) a decrease in magnetic field strength in the annular baffle-pole piece gap.

- When a magnetic baffle whose strength is proportional to discharge current is used, the slope of the cathode propellant flow throttling characteristic is determined by the number of turns in the control coil (see Fig. 9).
- When the magnetic baffle field strength is proportional to discharge current, the cathode propellant flow level of the throttling characteristic is adjusted by changing the baffle diameter.
- Use of the magnetic baffle concept has provided stable throttling of beam current over a 12:1 range.

C. NEUTRALIZER*

The plasma bridge neutralizer provides a source of electrons which must be injected into the positive ion beam to maintain electrical neutrality of the spacecraft and reduce space charge effects in the beam. The neutralizer should operate at a minimum mercury flowrate but in a mode which does not require a potential of more than 20 V between the neutralizer and the beam (to prevent sputtering by ions attracted from the beam to the neutralizer). The neutralizer must be positioned out of the beam to prevent sputtering by direct interception of beam ions. It must be located far enough away from the accelerator so that ions from the plasma bridge are not attracted by the negative accelerator potential. This prevents sputtering of a local area of

* This section includes recent results from tests made under Contract NAS 3-15523 with a thruster identical to that developed under this contract.

the accelerator such as that observed on the SERT II flight.⁸

Simultaneously satisfying all of the above criteria, while at the same time providing an unambiguous transfer characteristic to the neutralizer control system, is a difficult task. Computer trajectory analysis of the paths of the ions emanating from the plasma bridge, such as that shown in Fig. 13, (Ref. 9) have demonstrated that the area of the negative accelerator electrode that is exposed between the edge of the beam and the ground screen should be minimized to reduce the number of positive ions from the plasma bridge that impinge on the accelerator.

Several neutralizer locations were investigated in search of a position which was outside the primary ion beam but which still provided good coupling at low neutral flowrates. Following the results of Bechtel¹⁰ a position 9 cm downstream and 9 cm outside the radius of the peripheral row of accelerator apertures was chosen. Closed loop operation was demonstrated by automatically adjusting the mass flowrate through the neutralizer to stabilize the neutralizer keeper voltage to a preset value. Under normal operating conditions (e.g., neutralizer keeper current less than 0.5 A) it was not possible to simultaneously achieve the desired low neutral flow and low coupling voltage over the full operating range. As reported below, recent experiments have demonstrated that by increasing the neutralizer keeper current to approximately 2.0 A, floating voltages of less than 20 V can be maintained at neutral mass flowrates of ≈ 50 mA. These results are presented in more detail in the following chronological summary.

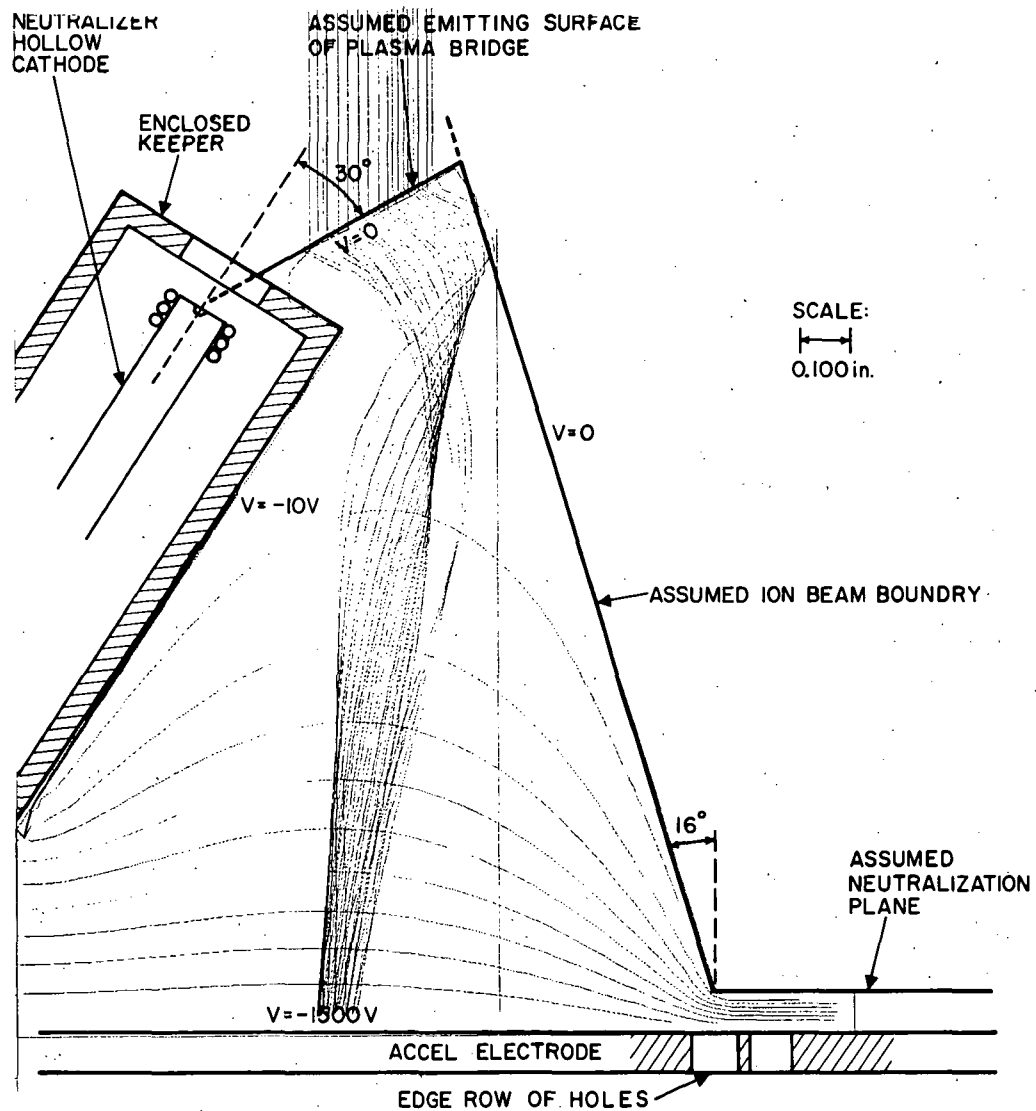


Fig. 13. Computer Simulation of Electric Fields and Ion Trajectories that Exist in the Region of the Plasma Bridge Neutralizer.

1. Configuration 1

This neutralizer configuration was used during the 450 hour test of the dual grid ion optical system conducted under Task 0. The 0.31 cm diameter neutralizer was positioned 2.5 cm outside the peripheral row of accelerator apertures and 3.8 cm downstream of the accelerator. It made a 30° angle with respect to the beam axis. The neutralizer could be operated in two distinctly different modes as shown in Table VI. The low flow mode was chosen for reasons of propellant utilization efficiency, even though the stability was such that the neutralizer would decouple from the beam every few hours and often the flowrate would have to be increased to recouple.

TABLE VI
Neutralizer Modes

	High Flow	Low Flow
Neutral Flowrate	>150 mA	<100 mA
Keeper Voltage	13 V	11 V
Floating Potential	15 V	25 V
Beam Color	Clear	Blue
Stability	Good	Fair

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Prior to start of the 450 hour test, thin molybdenum strips of varying thickness were attached to the accelerator immediately below the neutralizer and a 0.003 inch diameter wire was spot welded between the apertures. The same area after 450 hours of testing is shown in Fig. 14. Obviously the neutralizer keeper was immersed in the beam and suffered direct erosion. The sputtering of this aperture was first observed visually at 390 hours. It was necessary to gradually increase the neutralizer mass flowrate to about 125% of its original value, as the hole in the keeper enlarged during the remainder of the test.

There was only very limited erosion on the downstream accelerator face as illustrated by Fig. 15. Note that the thin wire attached between the strips is still intact, and that in general erosion is less than 0.01 cm deep, although one small spot of approximately three times this depth can be seen.

This test illustrated that this neutralizer configuration is not satisfactory, because the keeper directly intercepts fast beam ions. There is no sputter damage on the accelerator, because no surface of the plasma bridge is exposed between the neutralizer and the beam; therefore, there is no source of slow ions to be attracted back to the accelerator.

2. Configuration 2

The keeper assembly was modified to enclose (gas sealed) the keeper and reduce the exit hole to 0.25 cm diameter. The neutralizer cathode was located 2.5 cm downstream and 2.5 cm outside the beam. In this position, the neutralizer couples to the beam with $V_g = 14$ V at 60 mA (equivalent) flowrate. A planar probe, installed on the accel under

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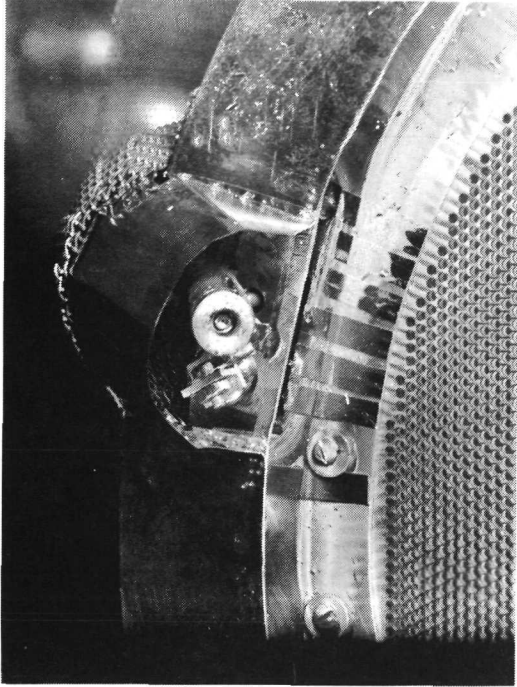


Fig. 14.
Downstream Face of the Accelerator After 450 Hours of Testing.

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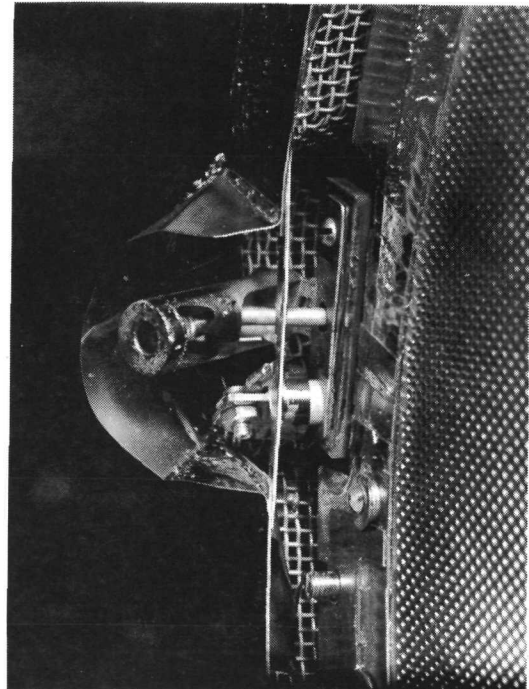


Fig. 15.
Downstream Face of the Accelerator after 450 Hours of Testing.

the neutralizer, collected from 1 to 2 mA of the 8 to 10 mA total accelerator drain current, indicating that a sizable portion of the accel current results from ions generated near the neutralizer.

3. Configuration 3

During the period of these neutralizer experiments a comprehensive study of neutralizer position was conducted by Bechtel.¹⁰ Based on these results, a neutralizer position 9 cm downstream of the accelerator and 9 cm outside the last row of holes was chosen. A semienclosed keeper was used. The first design used only a single tip heater to control the temperature of the neutralizer tip and (by thermal conduction) the neutralizer vaporizer temperature as well. A control circuit was assembled that permitted the neutralizer keeper voltage to be held to a preset value by controlling the neutralizer mass flowrate.

Typical results taken with the above system are shown in Fig. 16. Visual indications were that the neutralizer operated in the plume mode up to beam currents of 1.5 A. Above this current the discharge switched to the spot mode, and the vaporizer heated to the point that control was lost.

The mechanical design was modified to provide a better thermal heat sink and a separate heater to control the vaporizer temperature. The mass flowrate (vaporizer temperature) could then be held to a low value even at high beam currents. Data taken with this configuration are presented in Fig. 17. The floating potential remains constant at approximately 13 V up to a beam current of 1 A over the range of neutral flows tested (63 to 94 equivalent mA). It then rises sharply to 25 to 50 V as the beam current increases. Attempts to reduce the floating potential at high I_B by increasing the neutral flowrate resulted in a transition to the spot mode of operation.

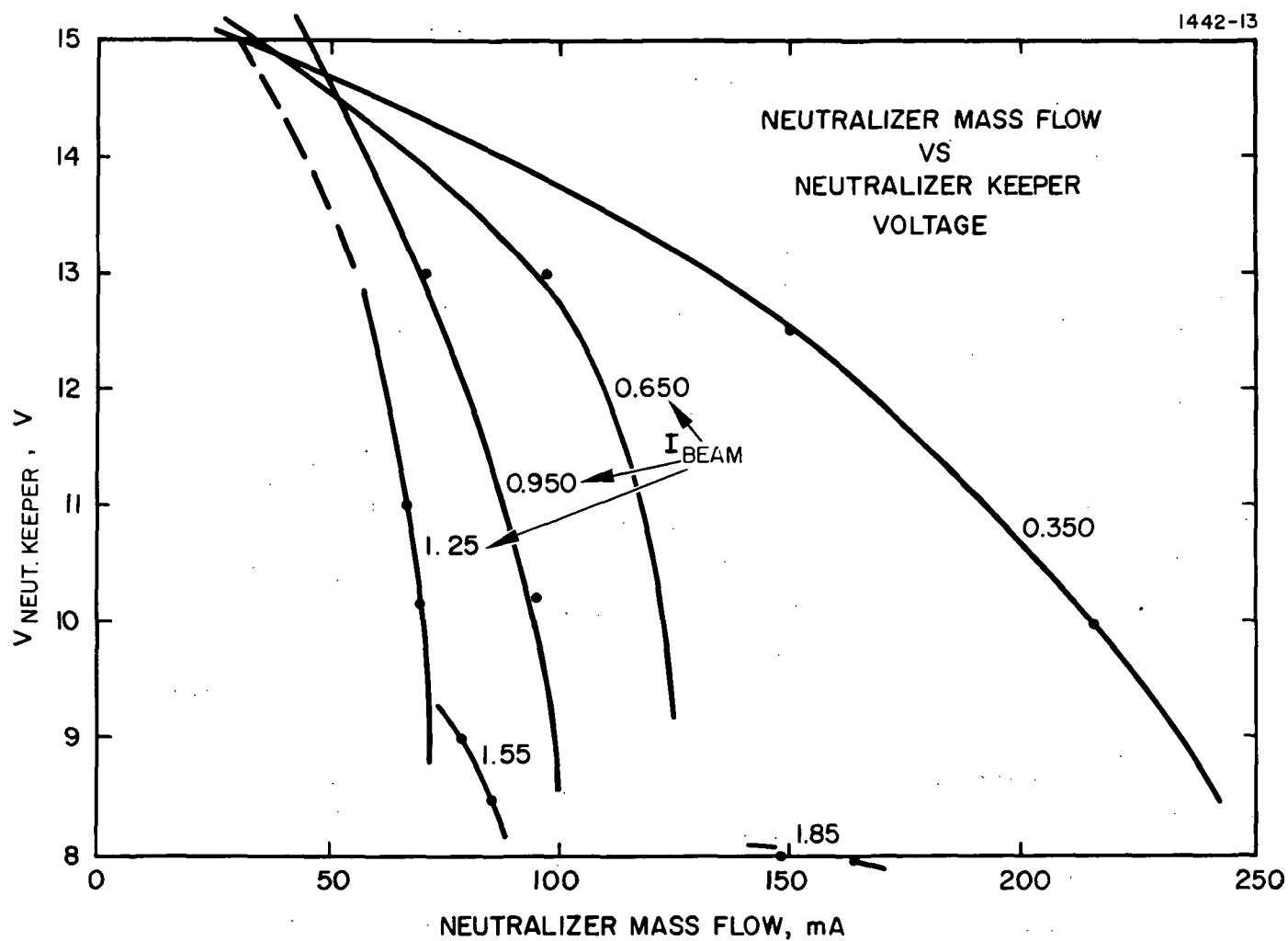


Fig. 16. Variation in Neutralizer Keeper Voltage as a Function of Mercury Flow through the Neutralizer for Several Beam Currents.

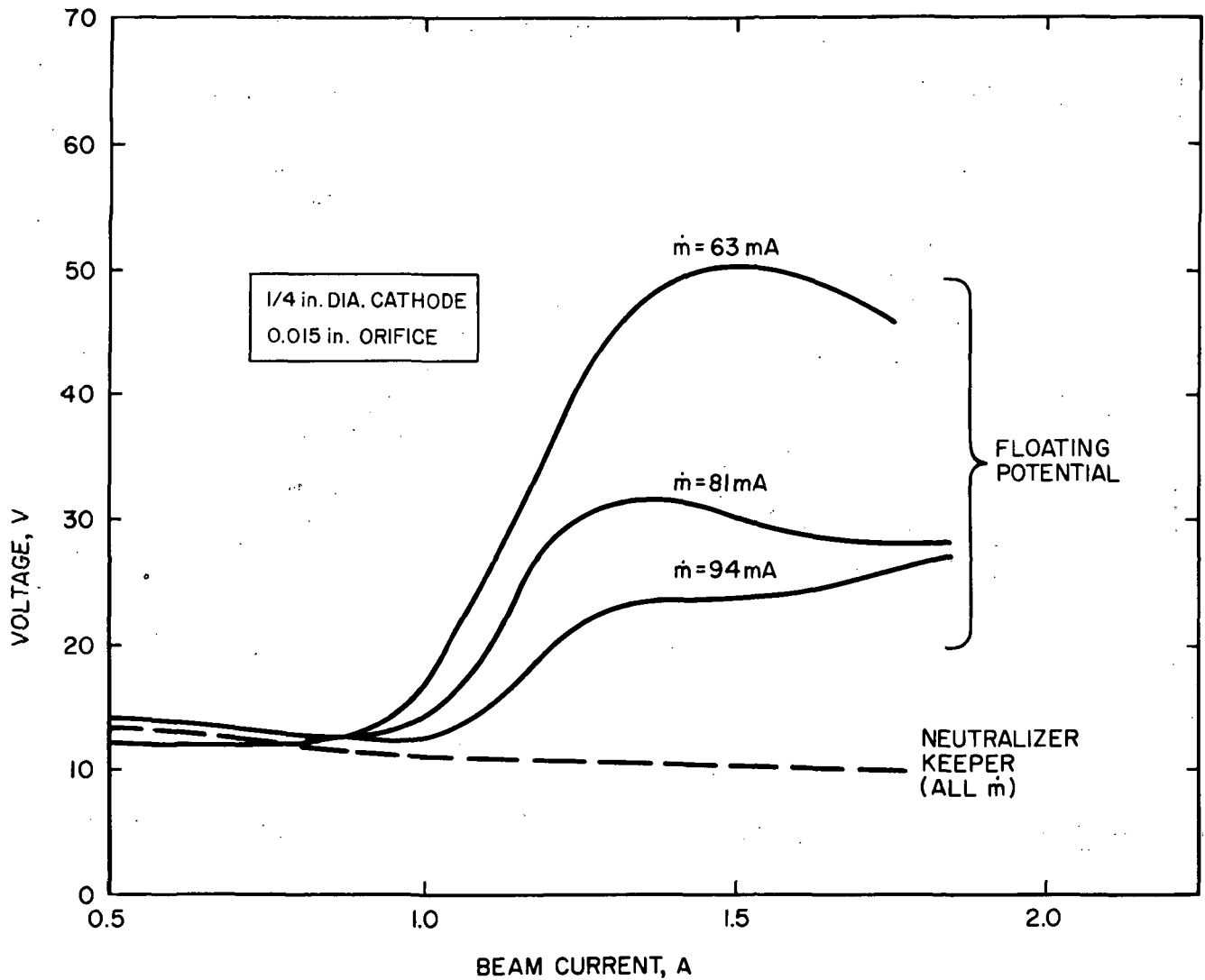


Fig. 17. Floating Potential and Keeper Voltage as a Function of Beam Current for Various Neutralizer Mass Flow-rates at Keeper Currents Less than 0.5 A.

4. Operation at Increased Keeper Current

All of the above performance was measured at neutralizer keeper currents of 0.20 to 0.60 A. Generally, it was found that at low neutral flowrates, the control characteristics were good but the coupling voltage was too high, often as much as 90 V at high beam currents. Increasing the neutral flowrate to greater than 100 mA caused transition to the spot mode, thus reducing the floating voltage but making control very difficult.

Results from recent experiments, which have not yet been completed, indicate that by increasing the neutralizer keeper current a controllable operating mode may be achieved where both the neutral flowrate and floating voltage are within acceptable limits. Table VII lists typical data taken with the cathode location and control circuitry described in Section II-C-3 above.

The change in coupling voltage as the keeper current is reduced is shown in Fig. 18 for various mass flowrates. Experiments are underway to investigate the effects of cathode and keeper geometry and of neutralizer location under these high keeper current conditions.

D. MERCURY FEED SYSTEM

The mercury feed system for the 30 cm diameter thruster makes use of two propellant vaporizers and electrical isolators to supply mercury vapor to the hollow cathode and the main discharge chamber. Under this program emphasis was placed on improving the mechanical and thermal designs and in reducing the electrical heater power requirements. The resultant main isolator vaporizer (MIV) and the cathode isolator vaporizer (CIV) designs are shown in Figs. 19 and 20. The vaporizers are fabricated from porous tungsten supplied by NASA.*

*Manufactured at Oak Ridge National Laboratory.

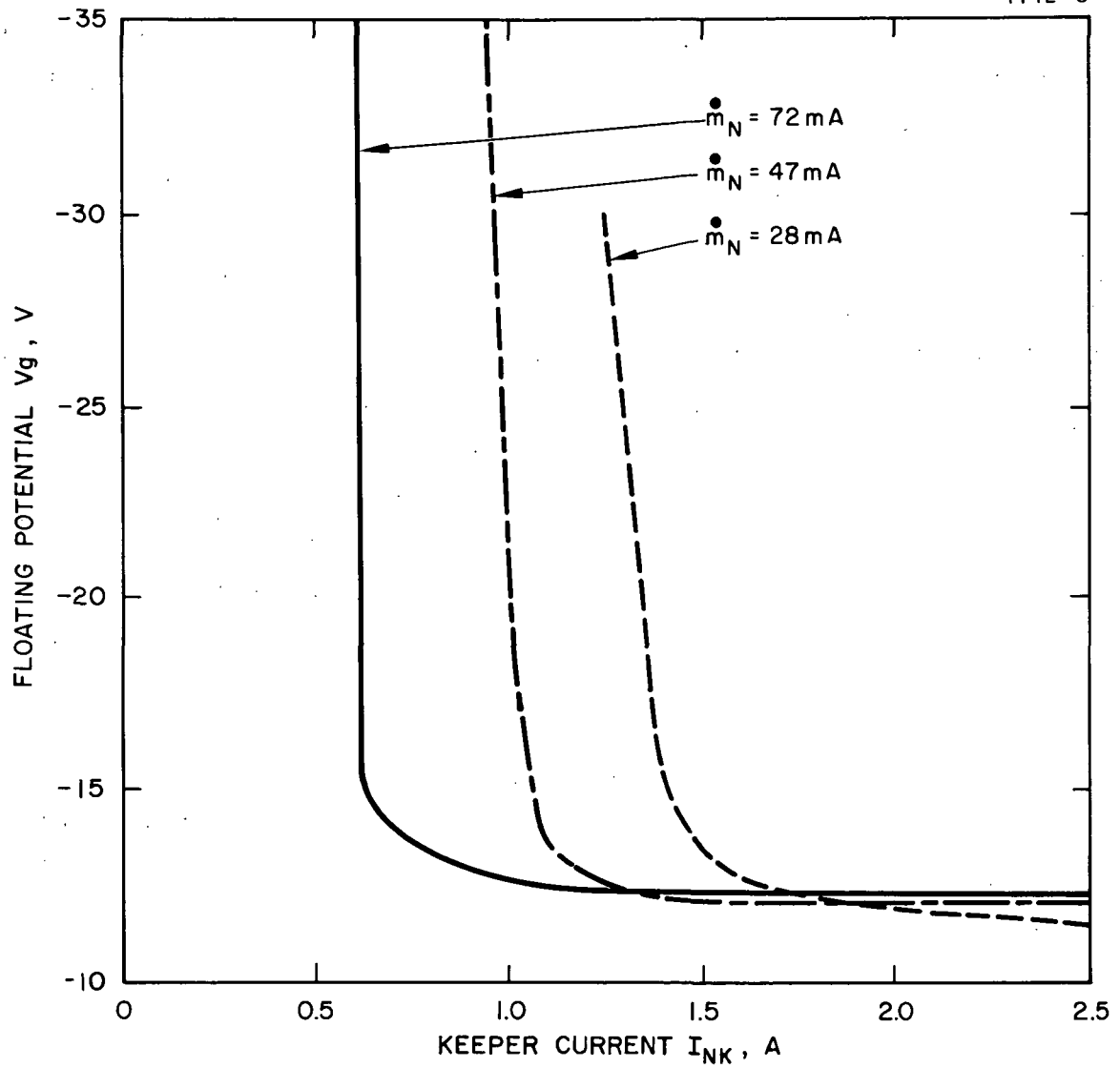


Fig. 18. Floating Potential as a Function of Keeper Current for Several Mass Flowrates.

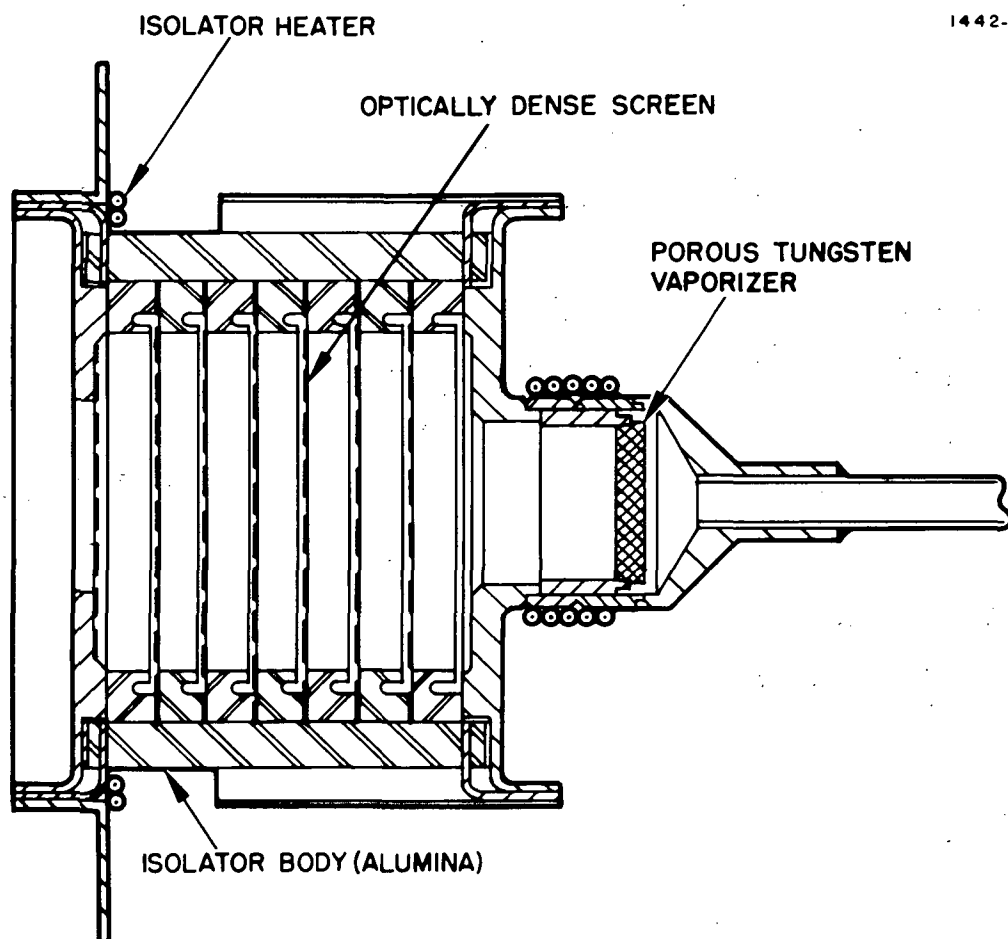


Fig. 19. Main Isolator Vaporizer Assembly.

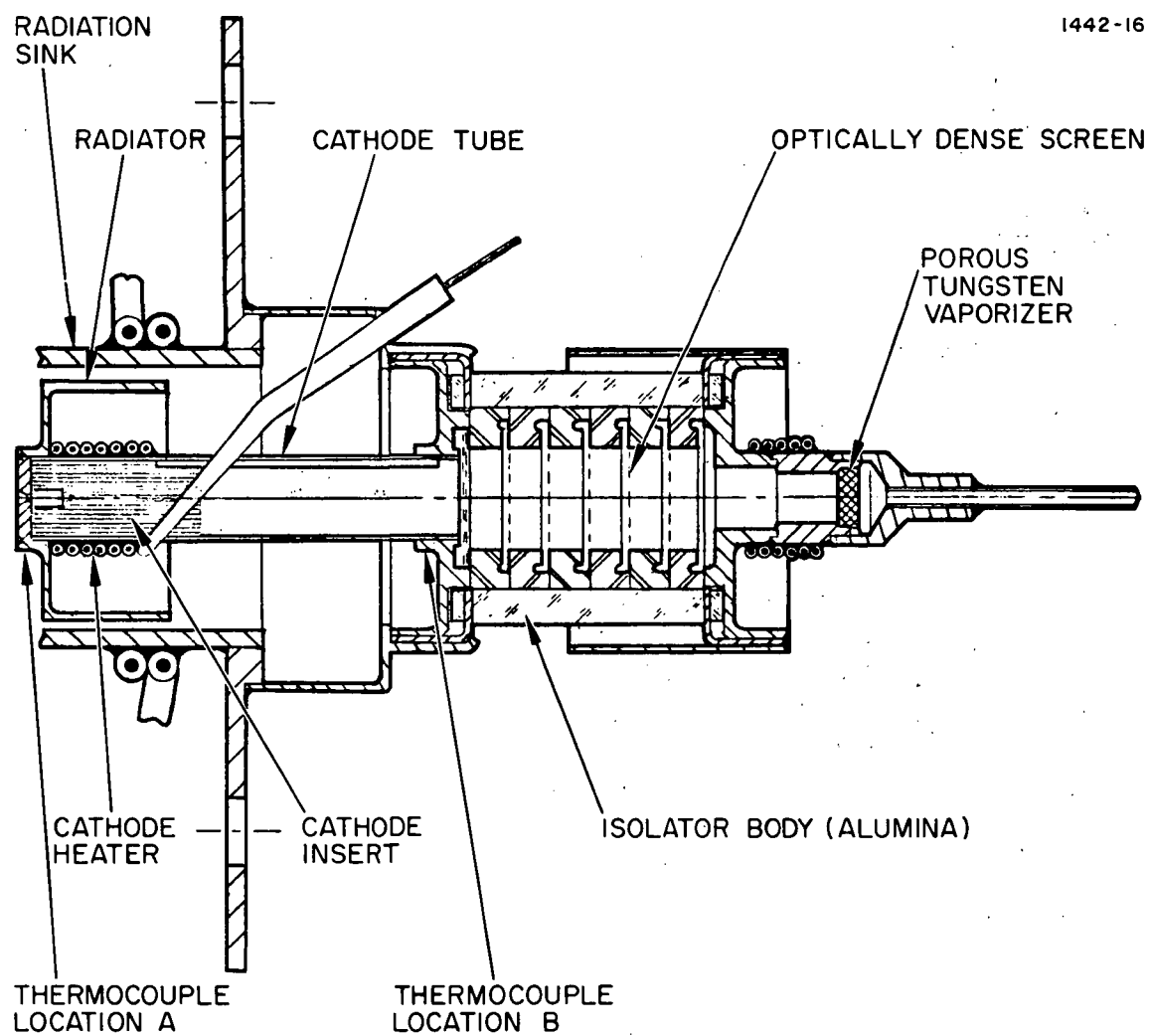


Fig. 20. Cathode Isolator Vaporizer Assembly.

The properties of the material are shown in Table VIII. The active diameter of the porous tungsten vaporizer is approximately 4.5 mm for the cathode vaporizer and 1.5 cm for the main vaporizer. The vaporizer heater is positioned such that the heat flows into the porous plug from the vapor side of the assembly. Both vaporizers operate between 250 and 300°C over the throttling range.

Both the main and cathode isolator designs are based on the same concept.* The vapor flow channel is divided into a number of short chambers by optically dense screens in a manner such that the total applied beam voltage is divided to maintain the voltage between adjacent screens below the Paschen minimum. For mercury vapor, the Paschen minimum is about 300 to 480 V, depending on the material and state of the negative surface. Design criteria are based on data obtained in the initial development program, which had specifications determined by the SERT II thruster requirements. These specifications were written as follows:

Mercury Vapor Flow (max)	400 mA (Equiv.)
Mercury Vapor Feed Pressure (max)	50 Torr
Voltage Holdoff (min)	4000 V

Experimentation determined that a mesh with openings no larger than 15 μ m is required to isolate successive gaps from one another. The conductance of this mesh material was determined empirically using nitrogen flow and an arbitrarily chosen pressure drop of 10 Torr. In designing isolators the following criteria apply:

$$\text{Number of sections} = \frac{\text{Desired Holdoff Voltage}}{300} ; \quad (1)$$

*U.S. Patent No. 3520110.

TABLE VII
Neutralizer Operation
Keeper Currents 2.2 A

$I_{\text{beam}},$ A	Neutralizer Keeper		Neutralizer Mass Flow, mA (Equiv.)	Floating Voltage, V
	Current, A	Voltage, V		
1.15	2.2	13.2	70	12.8
1.50	2.2	13.6	34	12.4
1.85	2.2	13.5	51	13.0

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TABLE VIII
Properties of Porous Tungsten Vaporizer Material
(Furnished GFE by NASA)

	Main Vaporizer	Cathode Vaporizer
Intercept $\times 10^5$	0.0601	0.0219
Thickness, cm	0.1433	0.1412
Transmission Coefficient $\times 10^4$	2.307	0.8530
Density, % of Theoretical	61.1	72.2
Void Fraction	0.389	0.269
Sintering Cycle		
Temperature, °C	1850	2100
Time, min	42	75
Pore Diameter, μm	1.8	1.9

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Pressure drop across isolator at maximum flow ≤ 10 Torr.

(2)

The following scaling law applies:

$$\Delta P = 10 \text{ Torr} \propto \frac{I (n + 1)}{d^2} = 6.8 , \quad (3)$$

where I is the maximum propellant flow in equivalent amperes, n is the number of sections determined by criteria (1) and d is the flow channel diameter in centimeters. If d is desired in inches, the design equation becomes

$$\frac{I (n + 1)}{d^2} = 44 . \quad (4)$$

Consequently, the 30 cm diameter thruster isolator has been designed to hold off a minimum of 2100 V with a pressure drop of 10 Torr or less for propellant flowrates up to 3.9 A equivalent for the main isolator and 0.6 A equivalent for the cathode isolator. Isolator leakage monitored during testing of the Task V thruster consistently indicated <1 μ A leakage current. Heaters are shown on both isolator assemblies, however only the MIV assembly requires heater power to raise the isolator temperature above 250°C during startup (to prevent propellant condensation). The CIV assembly is thermally integrated to the point that the cathode tip heater heats the isolator during the startup period and power input from the discharge is sufficient to heat both cathode tip and isolator after the discharge current exceeds 3A.

E. THRUSTER SYSTEM MECHANICAL DESIGN

The final 30 cm thruster designed and fabricated under part of this program is shown in Fig. 21. A major design change was required to provide a lightweight mechanical structure to support the dual electrode system. The CIV assembly was redesigned into a single integrated unit to satisfy mechanical and thermal requirements. To improve the power throttling characteristics, the discharge chamber was modified to include a magnetic baffle as an integral part of the CIV assembly. These three modifications were made as part of an over-all redesign, which improved the structural characteristics and reduced the length of the thruster.

The thruster system is designed such that a small number of major subassemblies are fabricated as separate units and assembled into a final configuration requiring only mechanical assembly and final wiring. The subassemblies include the following:

- Thruster shell with mounting provisions for all other subassemblies
- Ground screen
- Cathode isolator vaporizer (CIV)
- Main isolator vaporizer (MIV)
- Ion extraction system
- Neutralizer.

Each of these subassemblies is discussed in detail in the following sections.

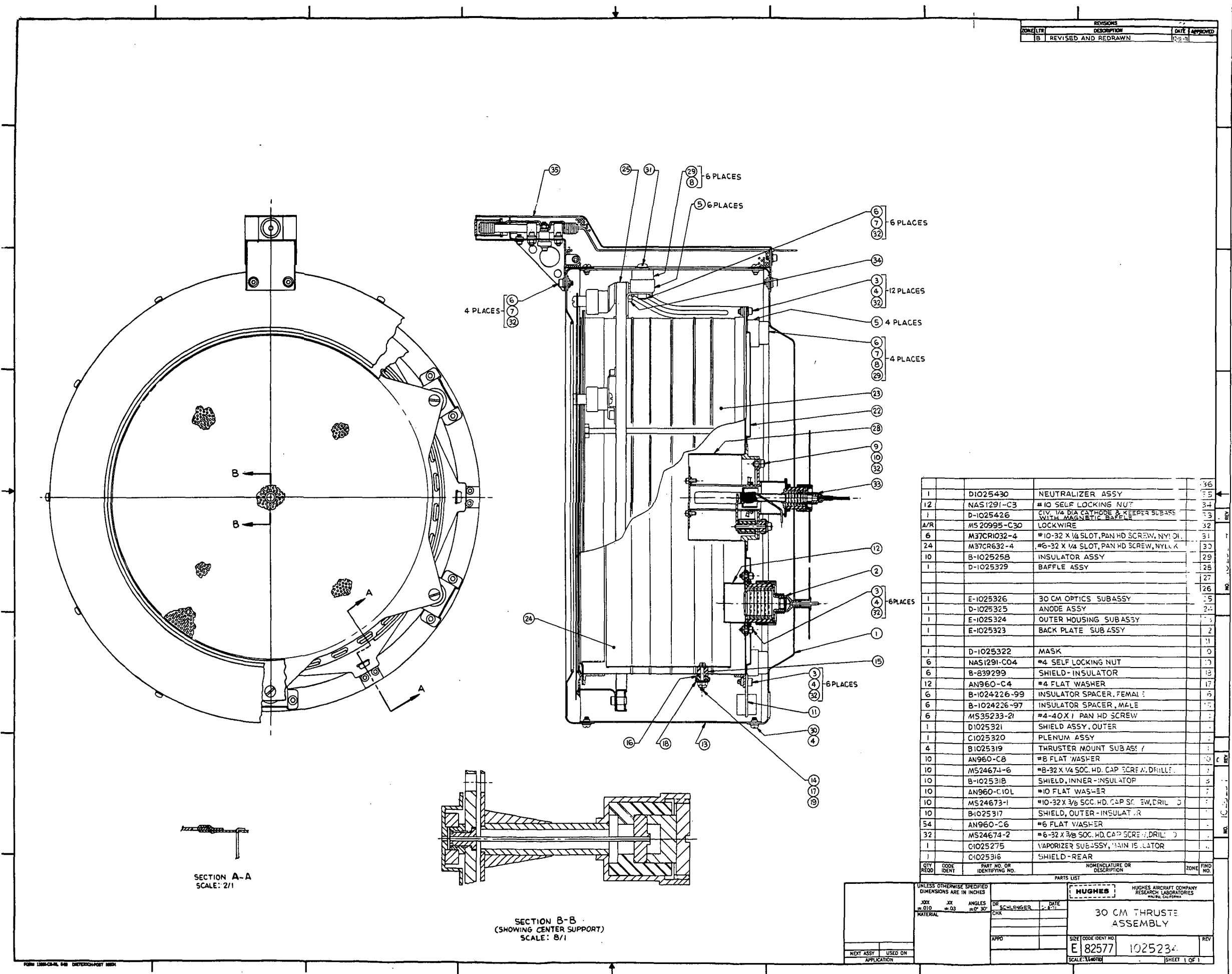


Fig. 21. Final 30 cm Thruster Design.

1. Thruster Shell

The major structural component of the thruster is the outer shell. As shown in Fig. 22, circumferential stiffening ribs and flanged end pieces provide rigidity to the thin (0.020 cm) structure. The six side brace assemblies add considerable axial stiffness, and the angle brackets at the downstream end provide a planar mounting surface for the optics subassembly. The six optics mounting pads are fitted in a locating assembly fixture and spotwelded to the thruster shell. This method assures the mounting hole location and axial spacing from the downstream pole piece remains constant for all outer shell assemblies. This fixture with outer shell and brackets in place is shown in Fig. 23.

The mild steel end flanges provide structural stability, and distribute the magnetic flux generated by twelve 0.356 cm diameter x 14.70 cm long axial magnets and eight 0.356 x 0.990 x 3.55 cm rectangular magnets placed radially along the thruster backplate. The flat stainless steel backplate encloses the upstream end of the discharge chamber and provides the mounting interface for the CIV and MIV subassemblies.

The anode shell is rolled, spotwelded, and formed with stiffening ribs to improve rigidity and roundness. It is supported within the discharge chamber and outer shell by six alumina insulators with sputter shields. The terminal is attached to the anode with a 0.075 x 1.0 x 3.0 cm current distributing plate to prevent local heating and possible failure of the thin (0.020 cm) anode.

A heavy flange in the center of the backplate serves as the cathode pole piece and mounting interface for the CIV assembly. Six 6/32 x 3/8 screws attach the CIV to the flange. The screws are accessible from the outside of the thruster assembly.

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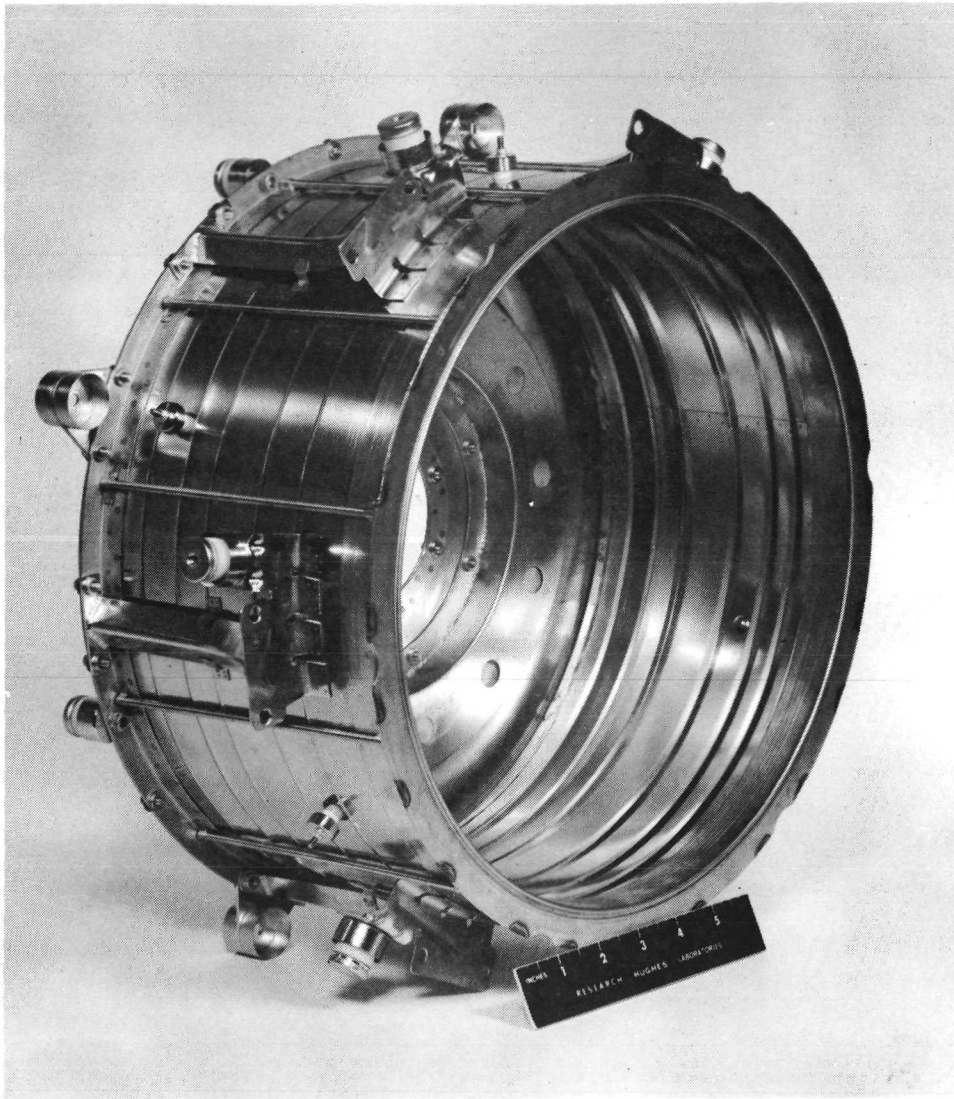


Fig. 22. 30 cm Thruster with Ground Screen Removed.

M8406

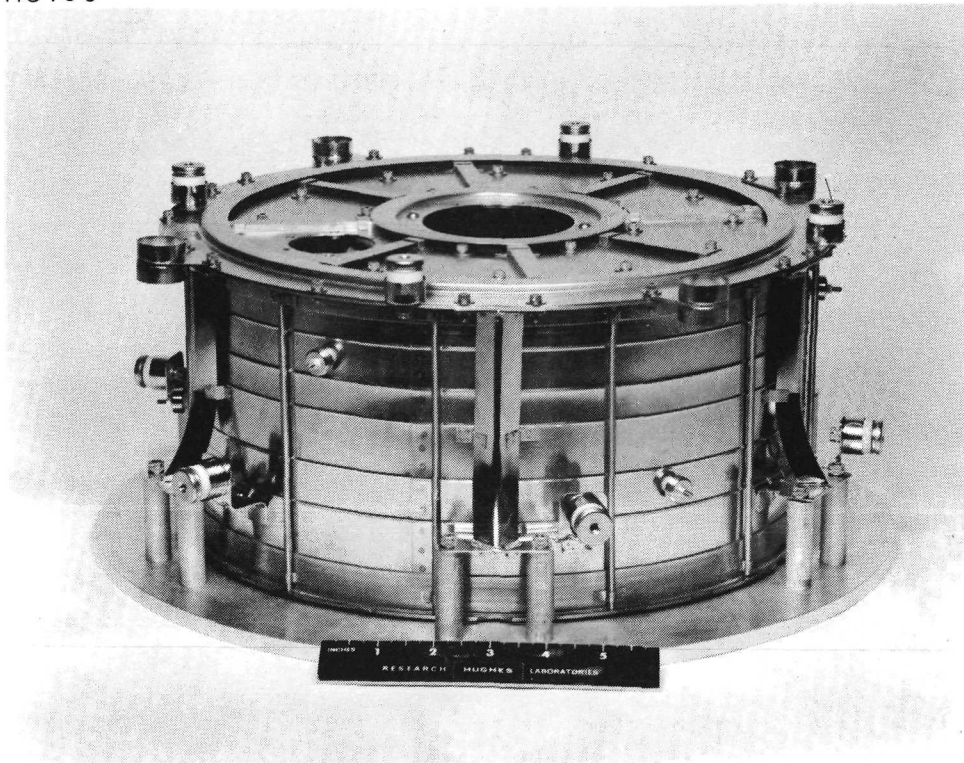


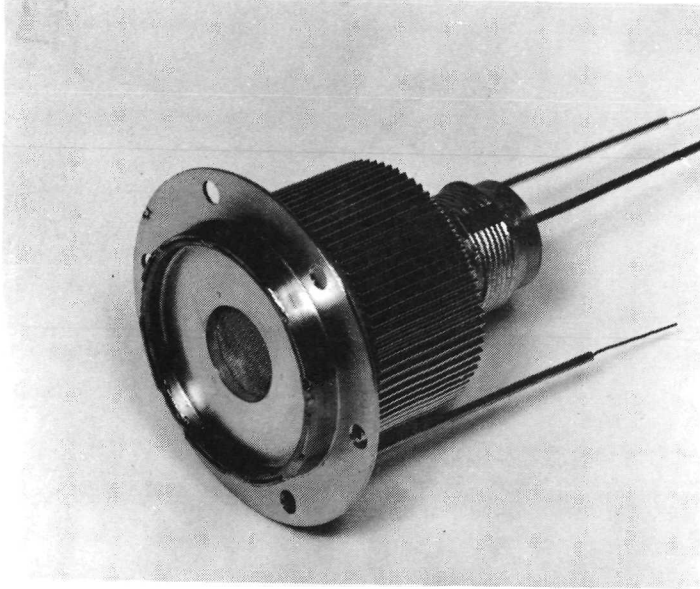
Fig. 23. Fixture used to Accurately Locate Mounting Brackets for Ion Optical System.

The main propellant distribution plenum is formed into an annular chamber with flanges for attachment to the backplate. Eight 1.5 cm holes on the downstream side are covered with 200 mesh stainless steel to distribute the mercury vapor uniformly within the discharge chamber. The inherent rigidity of this element greatly enhances the structural stability of the thruster backplate.

2. MIV — Main Isolator Vaporizer Assembly

The MIV subassembly, shown in Figs. 19 and 24, functions as the main mercury vapor propellant supply and provides electrical separation between the thruster and external propellant reservoir. The isolator section of the assembly consists of a series of insulating gaps within a 99.6% alumina outer tube. The voltage drop across each of the gaps containing mercury vapor remains below the minimum breakdown voltage to prevent conduction. To isolate operating voltages of 2100 V, a total of seven series gaps has been provided by stacking the necessary number of wire screen disks and alumina spacers within the outer tube. The screen openings are 17 μ m diameter spaced 0.30 cm apart. A cross-section drawing of the MIV subassembly is shown in Fig. 19. The outer cylinder is fabricated by brazing Kovar metal flanges onto the cylinder as shown in Fig. 25. The thin alumina backing rings prevent excessive shear stresses in the metal-ceramic seal during the brazing operation and subsequent thermal cycling. The isolator assembly is metalized and brazed at the Electron Dynamics Division of Hughes Aircraft Company under controlled environmental conditions. This manufacturing facility has considerable experience in fabrication of space qualified assemblies, resulting in a high reliability isolator assembly.

M8232



M8233

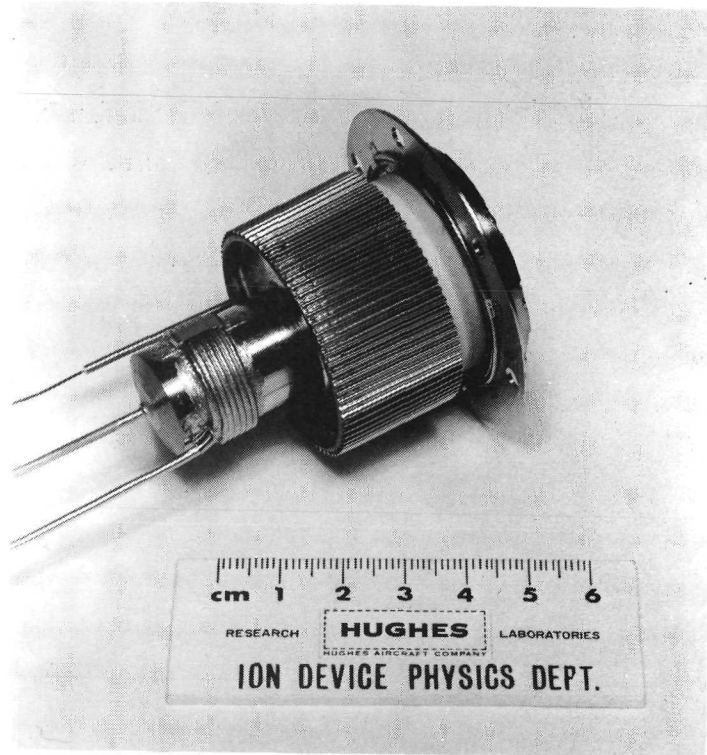


Fig. 24. Photographs of Main Isolator and Vaporizer Assembly.

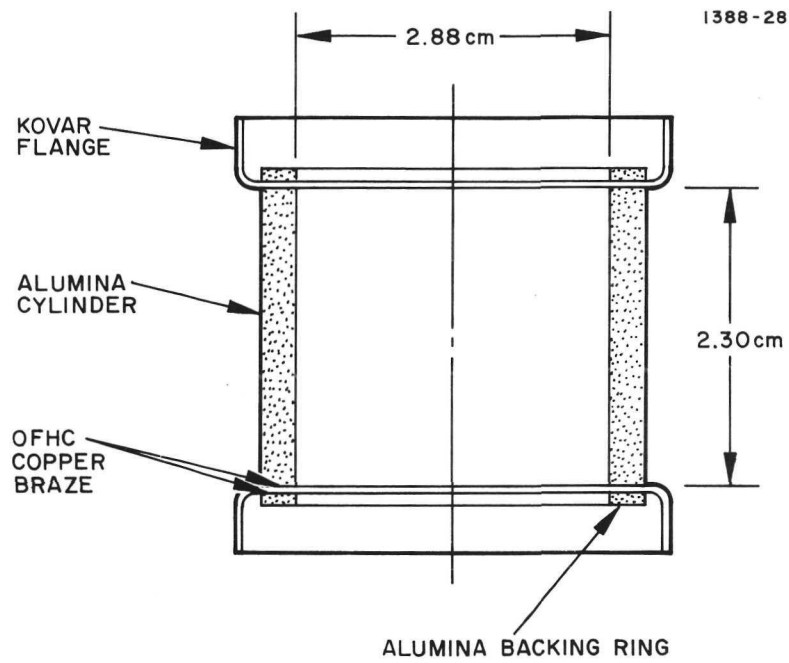


Fig. 25. Detail of Metal-to-Ceramic Bond used in Fabrication of Main Isolator.

The vaporizer consists of a porous tungsten disk (GFE supplied) electron beam welded into tantalum housings which in turn are TIG (tungsten inert gas) welded into the isolator flanges. The main vaporizer porous tungsten material is cut into 1.50 cm diameter circular disks. The specifications of the GFE material are shown in the following Table IX.

The isolator has a coaxial type heater on the downstream mounting flange to prevent condensation of mercury during thruster startup. The main vaporizer heater supplies heat to the porous tungsten plug, thereby providing propellant neutral flow to the thruster ionization chamber. Both heaters are permanently brazed to the assembly with Nicrobraz 130* alloy. The heater specifications are listed in Table IX.

3. CIV — Cathode Isolator Vaporizer Assembly

The CIV subassembly, shown in Figs. 26 and 27, consists basically of a hollow cathode, electrical isolator section, magnetic baffle, and porous tungsten propellant vaporizer. These basic elements are mounted on a common flange with the keeper bar to provide a demountable, structurally integrated assembly. It was necessary to design the CIV assembly as a single unit from both mechanical and thermal considerations. A new design was implemented to accommodate the differing thermal inputs between thruster startup mode (no discharge present) and run mode (discharge struck). Basically, heat must be supplied during startup and rejected while running. For satisfactory operation and long lifetime, it is desirable that the cathode operate in the temperature range of 900 to 1100°C, preferably near the high temperature limit to start and the low temperature for running. The isolator must

* Nicrobraz 130 available from Wall Colmonoy Co., Detroit, Michigan.

TABLE IX
Main Vaporizer Material Specifications

Sample Number	Transmission Coefficient $\times 10^4$, (As Measured)	Density, % Theoretical	Pore Diameter, μm
5433-91-2	2.31	61.1	1.8

T407

TABLE X
MIV Heater Specifications

	Main Isolator	Main Vaporizer
Part Number	B1025330	B1024917
Conductor Material	Nichrome V	Nichrome V
Conductor Diameter, cm	0.025	0.025
Sheath Material	Inconel	Inconel
Sheath Diameter, cm	0.100	0.100
Insulation Material	MgO	MgO
Number of Turns (approximately)	2	6
Resistance (Ω)	$4.65 \pm .23 @ 25^\circ\text{C}$	$6.50 \pm .32 @ 25^\circ\text{C}$

T408

M8403

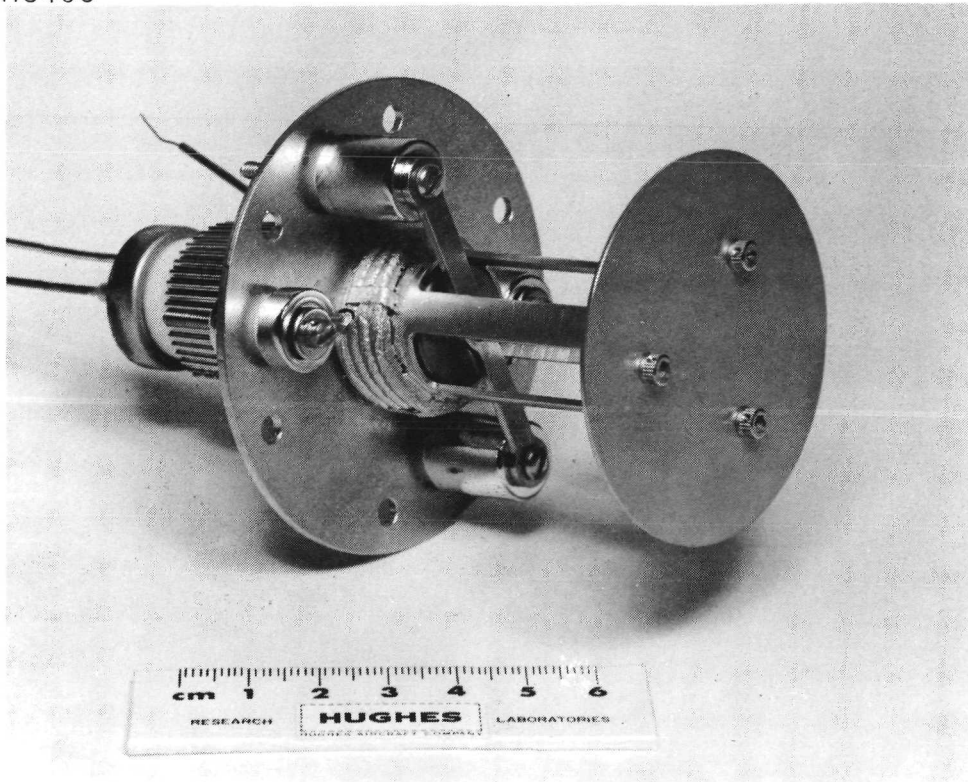


Fig. 26. Photograph of CIV Assembly and Showing Magnetic Baffle Components

M8404

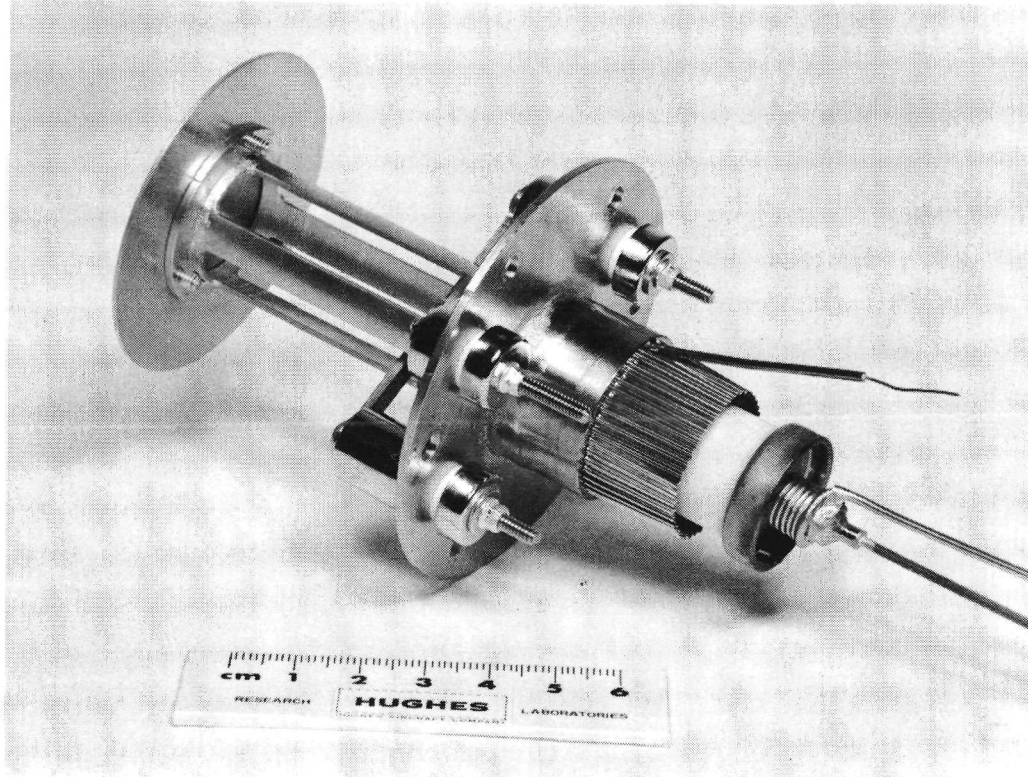


Fig. 27. Cathode-Isolator-Vaporizer Subassembly Showing Isolator and Vaporizer Detail.

operate between 250 and 400°C to prevent condensation of mercury. During operation, a heat load of approximately 50 W is estimated. A radiating cap on the cathode tip provides 5.0 cm² radiating area with an emissivity of 0.33 facing the baffle support tube that has an emissivity of 0.5. Variations in emissivity may vary power radiated by 30%, since these values cannot be accurately measured. The input power is dissipated approximately as shown in Fig. 28. The molybdenum cathode tube is 0.635 cm diameter x 4.0 cm long with a wall thickness of 0.025 cm. It is estimated that the isolator requires 6 W to bring it to minimum operating temperature. This is approximately the heat conducted along the tube as shown in Fig. 28. The primary point of heat rejection is at the rear shield, which nominally operates at 200°C. A large radiating shield is welded to the upstream end of the isolator in order to radiate a sufficient amount of power to the surrounding rear shield. This assures sufficient isolator heat during startup, since heat must pass through the isolator tube and the upstream end must reach a sufficiently high temperature for effective radiation.

A cross-section drawing of the CIV assembly is shown in Fig. 20. The 0.450 cm diameter porous tungsten vaporizer plug is made from GFE material with specifications listed in Table XI. The vaporizer is electron beam welded to the tantalum housing, to which a 0.160 cm diameter x 0.025 cm wall thickness tantalum tube is welded on the upstream end. The downstream flange is TIG welded to the Kovar flange on the isolator assembly. The voltage isolator section is fabricated in the same manner described in the previous section. This isolator also contains seven insulating gaps but is smaller in diameter, compared with the MIV isolator, since it must handle a neutral flowrate of only a few hundred milliamperes.

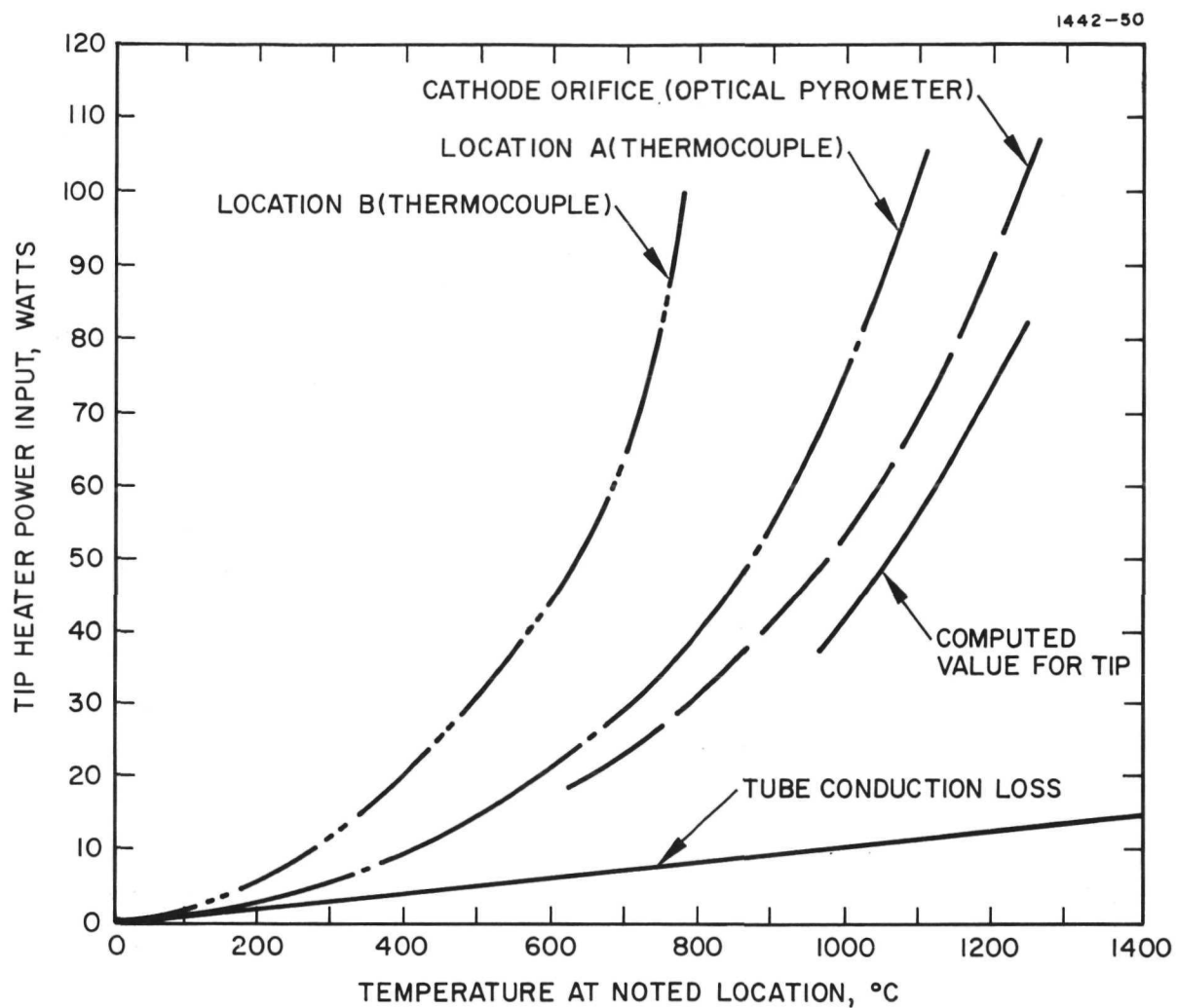


Fig. 28. Power-Temperature Characteristics for Thermally Integrated CIV Assembly (Thermocouple Locations Shown in Fig. 20).

TABLE XI
CIV Vaporizer Material Specifications

Sample Number	Transmission Coefficient $\times 10^4$, (As Measured)	Density % Theoretical	Pore Diameter, μm
5433-88-2	0.853	72.2	1.9

T409

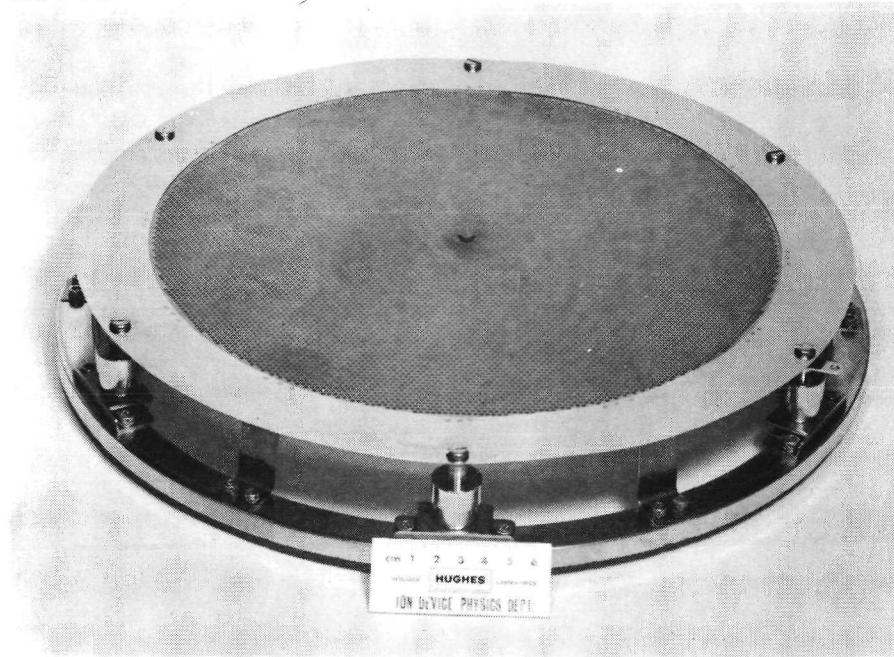
The cathode tip is heated by a tantalum-tantalum sheathed coaxial heater brazed to the tube with Microbraz 130 brazing alloy. The vaporizer heater is attached in the same manner. Heater specifications are shown in Table XII.

The magnetic baffle consists of a 2.21 cm diameter $\times$ 6.2 cm long thin walled mild steel tube welded to the main mounting flange. The 5.75 cm diameter $\times$ 0.075 thick baffle is attached to the upstream end. A coaxial magnetic coil is brazed around the tube near the backplate interface. This coil consists of approximately 2.5 turns of 0.080 cm diameter OFHC copper wire inside a 0.038 cm stainless steel sheath. The insulation is magnesium oxide. The function of the magnetic baffle was described previously in Section II-B.

4. Ion Extraction System (Ion Optics)

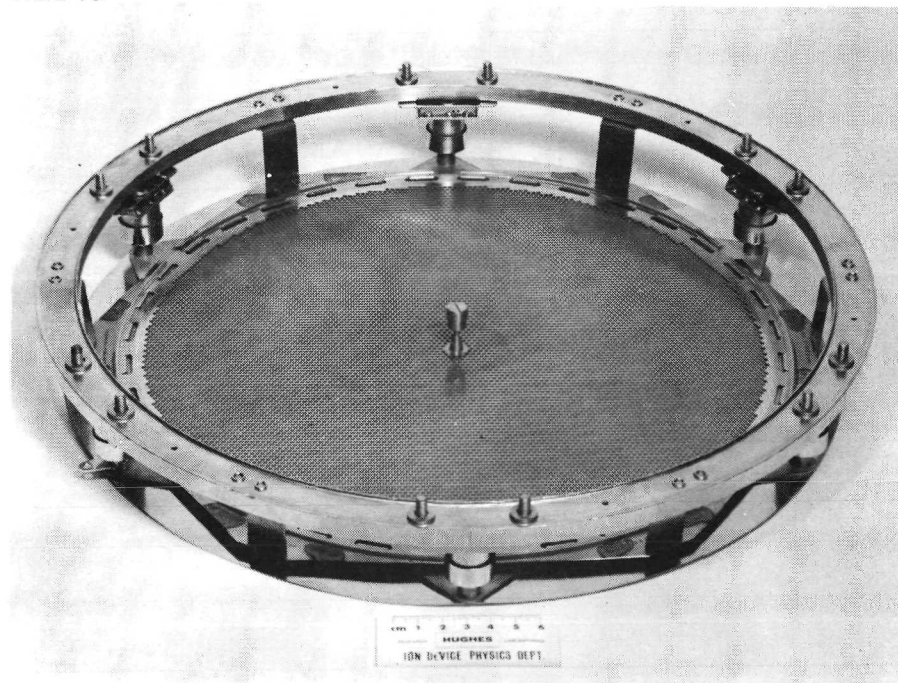
The downstream end of the discharge chamber is enclosed by the ion optics subassembly shown in Fig. 29, which consists of the screen and accelerator electrodes, main support mounting ring and associated mounting hardware. The optics assembly tested under Task V of this contract utilizes a single support at the center of the grids. Other types of grid spacing supports were fabricated and delivered with the thruster and spare parts under Task VII.

M8348



(a) Downstream Side.

M8349



(b) Upstream Side.

Fig. 29. Photographs of Ion Optical Assembly.

TABLE XII
CIV Heater Specifications

	Cathode Tip	Vaporizer
Part Number	B1025262	B1024543
Conductor Material	Tantalum	Nichrome V
Conductor Diameter, cm	0.025	0.025
Sheath Material	Tantalum	Inconel
Sheath Diameter, cm	0.100	0.100
Insulation Material	MgO	MgO
Number of Turns (approximately)	8	5
Resistance, Ω	0.520 ± 0.03 at 25°C	2.86 ± 0.14 at 25°C

T348

The optics subassembly layout is shown in Fig. 30. The screen and acceleration dimensions are as in the following Table XIII. The grids are fabricated by drilling with a tape controlled machine by an outside vendor. The accelerator holes are drilled to 0.194 cm diameter and the screen to 0.208 cm diameter within a true hole position of 0.005 cm. The outer contour is then milled to the prescribed shape, deburred and delivered to HRL. The screen grid is electro-polished to obtain a finished hole diameter of 0.215 cm. The center support is brazed in place and the grids are then stress relieved between heavy flat plates at 1000°C for 1 hour. The screen mounting brackets are attached to the screen grid and the retaining tabs are TIG welded to the mounting brackets to assure structural integrity during vibrational environment.

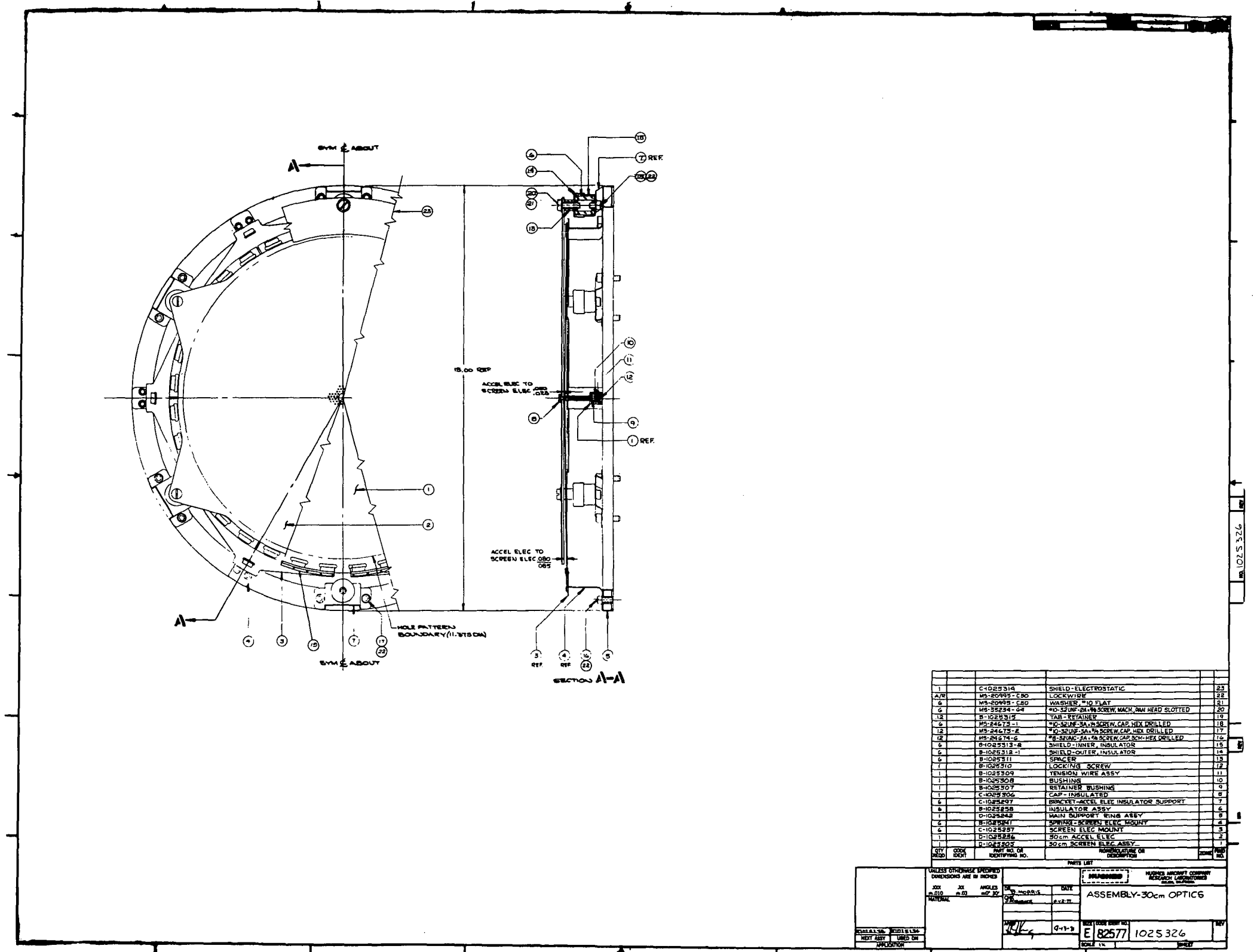


Fig. 30. Layout of Ion Optical System..

TABLE XIII
Screen and Acceleration Dimensions

	Accelerator	Screen
Part Number	D1025235	D1025236
Thickness, cm	0.128	0.046
Aperture Diameter, cm	0.194	0.215
Spacing at Center, cm	0.05	
Spacing at Periphery, cm	0.20	
Number of Holes	Approximately 11,500	

T349-R1

The flexible center support, shown in Fig. 31(a), is brazed to the screen grid with OFHC copper by heating the center area with an electron beam welder while the grid and center support assembly are supported in a special fixture. All optics assemblies tested at HRL incorporated a center support of this type. The molybdenum center support wire (0.05 cm diameter) is placed in tension when the flat grids are spaced to 0.05 cm from the unconstrained spacing of 0.20 cm.

The electrodes are mounted on a lightweight annular support ring which attaches directly onto the six mounting pads provided for this purpose. The ring has a mean diameter of 36.20 cm with a cross-section as shown in Fig. 31(b). A structural analysis was made by digital computer methods in order to provide a stiff structural element of lightweight design. The results are shown in Table XIV. The resulting stress is well below the yield strength of stainless steel under anticipated loading during vibration of ~ 9.0 g's. A

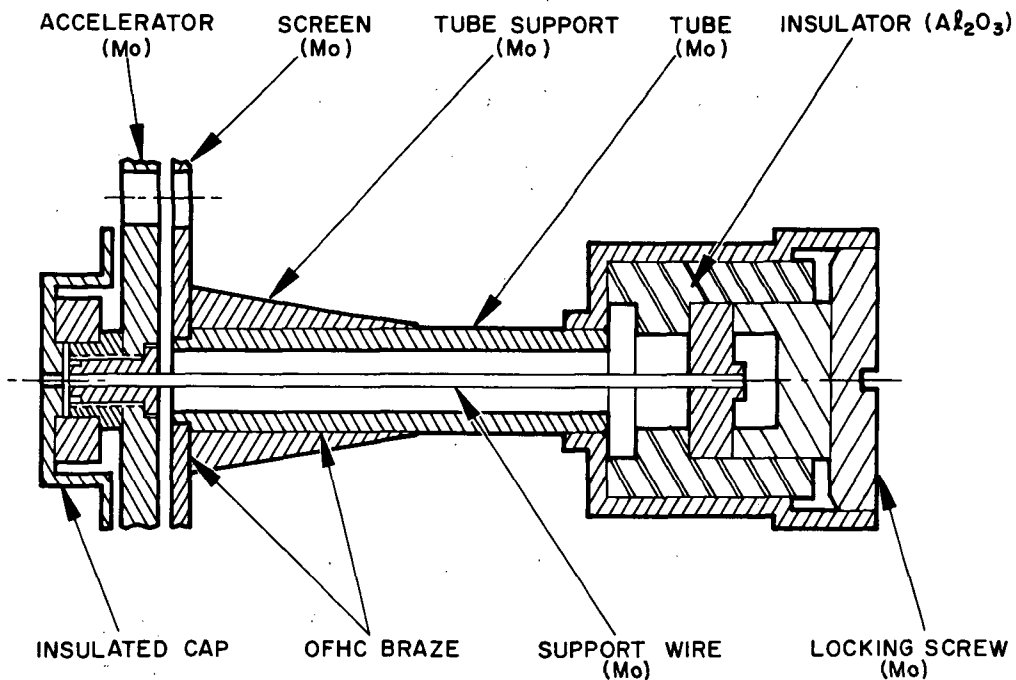


Fig. 31(a). Detail of the Interelectrode Center Support.

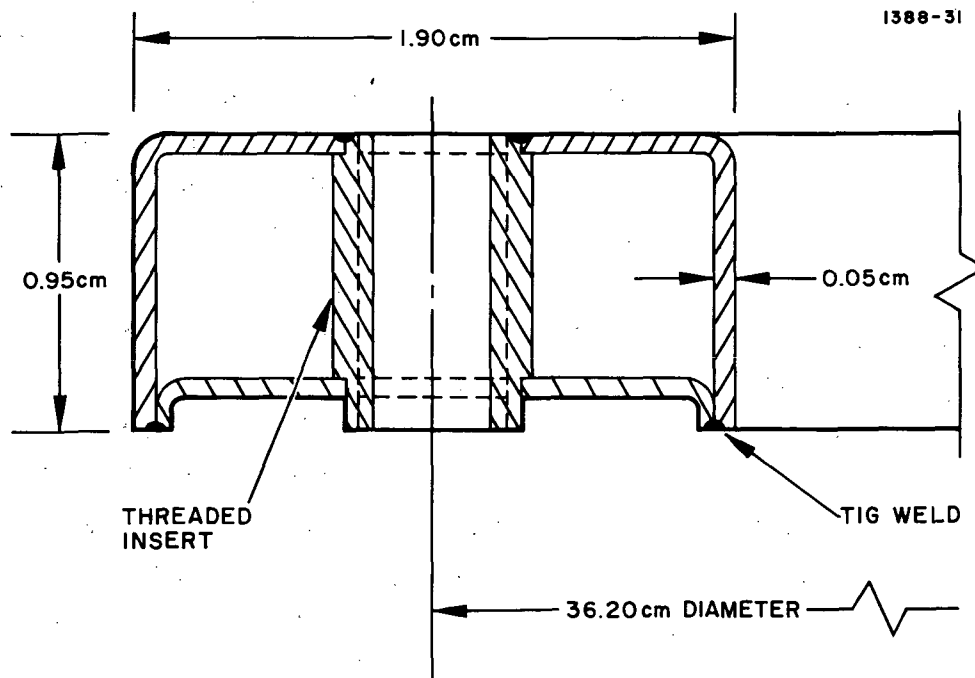
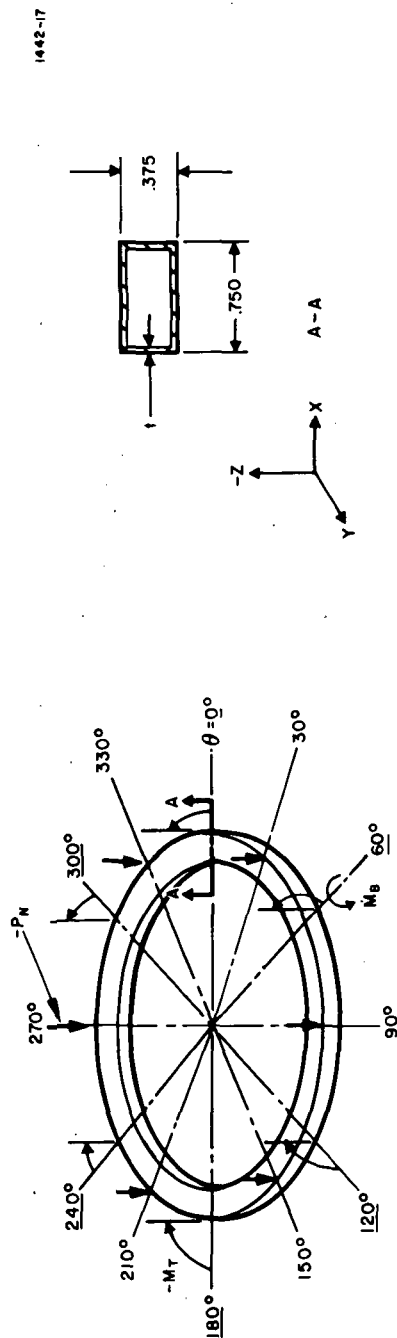


Fig. 31(b). Cross-Section of Electrode Support Ring.

TABLE XIV

Stress Calculations, Electrode Mounting Ring



Case No.	Type of Loading	t, in.	Applied Static Loads			Resulting Stress	
			P, lb.	M _B , in.-lb.	M _T , in.-lb.	Bending Stress, psi	Shear Stress, psi
1	Static loads with no supports	0.020	3.0	0.0	3.0	1726	-34.6
2	Static loads and reacting forces	0.020	1.5	-4.933	3.0	737	+15.0
2A	Static loads and reacting forces	0.020	3.0	-4.933	3.0	863	-19.6
3	Vibration in +Z direction	0.020	1.5	-4.933	3.0	1076	- 2.3
4	Vibration in -Z direction	0.020	-1.5	4.933	3.0	1746	2.3
5	Vibration in +X direction	0.020	+1.5	0.0 - 6.0	±1.5	1700	-22.9
7	Vibration in -Z direction	0.015	-1.5	4.933	3.0	2249	3.1
8	Vibration in +X direction	0.015	1.5	0.0 - 6.0	±1.5	2191	-37.8
9	Vibration in +X direction	0.015	1.5	0.0 - 6.0	3.7 - 5.4	2616	-47.0

T410

lighter weight design would perform adequately under the anticipated loading, however thinner gauge material would present difficult spinning and welding problems and is considered impractical to fabricate. The total weight of the stainless steel ring of 0.05 cm wall thickness is 0.306 kg, including threaded inserts.

The accelerator electrode is supported at the periphery by six insulators as shown in Fig. 30. The insulators are double shielded and are attached to the support ring with rigid support brackets. The screen electrode is supported by six flat springs which are placed normal to the plane of the grid as shown in Fig. 30. The springs are made from 17-4PH stainless steel and heat treated to spring hardness. The screen grid is placed in radial tension of approximately 1.0 kg at each mounting point by preloading the flat springs 0.20 cm. The screen mounting brackets are designed to distribute the spring forces more uniformly along the periphery of the screen grid. Typical temperature gradients measured in both the screen and accelerator electrodes for various discharge currents are shown in Fig. 32.

5. Neutralizer Assembly

The neutralizer subassembly, shown in Fig. 33, is basically a 0.635 cm diameter hollow cathode with a semi-enclosed keeper. The neutralizer vaporizer is identical in size and flow characteristics to that used in CIV assemblies. The first neutralizer tested under Task II was designed with a single cathode tip heater with the neutralizer placed downstream of the tube support brackets which serve as heat sinks. This neutralizer operated with no heater power during thruster operation, but produced an unsatisfactorily high neutral flowrate at high beam currents. The neutralizer was redesigned with the vaporizer upstream from the heat sink supports and a separate heater used. Performance details of this configuration were discussed in Section II-C.

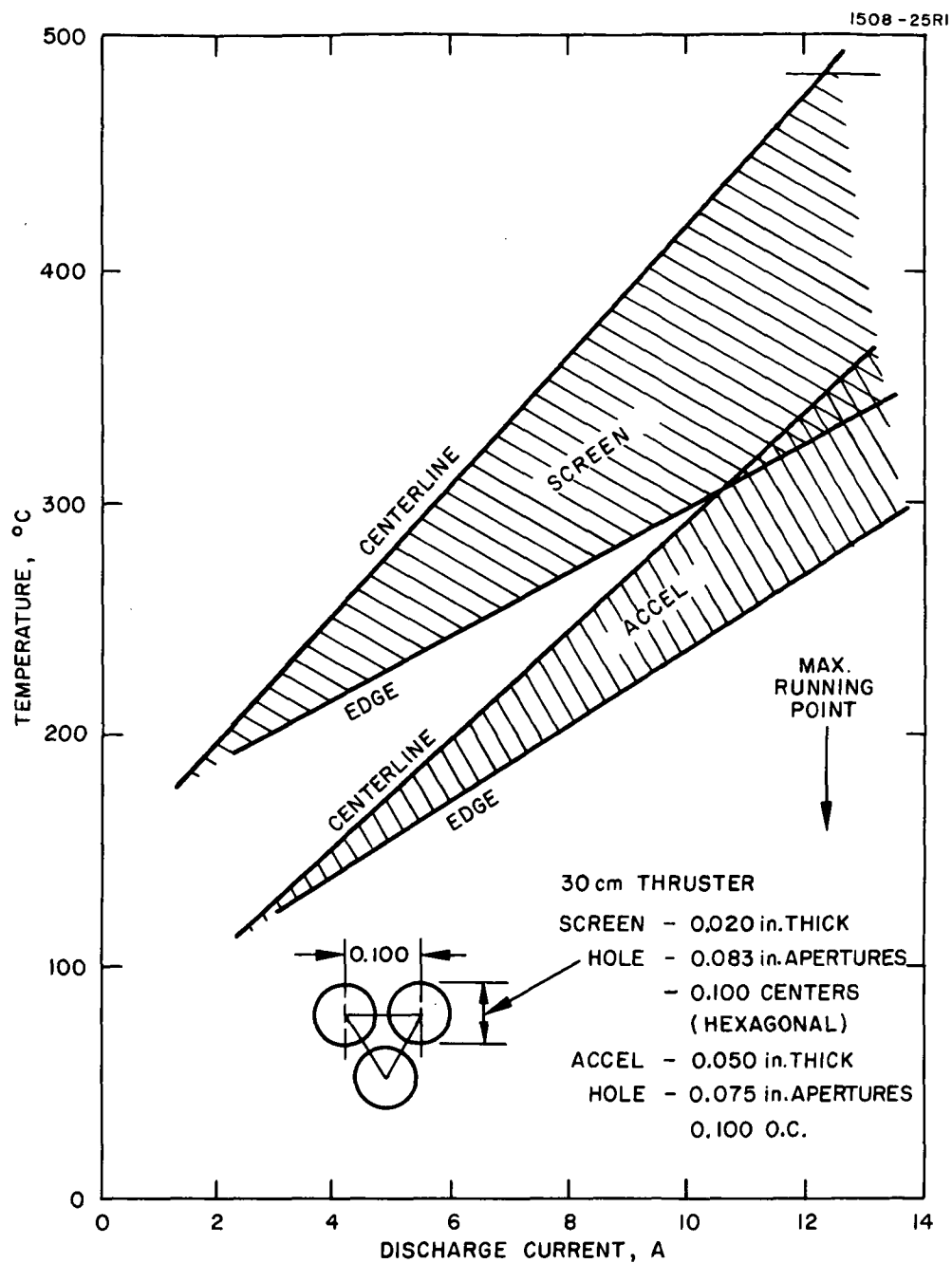


Fig. 32. Temperature Test Data.

The neutralizer tip is placed parallel to the thrust axis in a position 9.0 cm downstream and 9.0 cm radially outward from the last row of holes in the accelerator electrode.¹⁰

The cathode design is similar to the CIV assembly except that the orifice diameter is 0.038 cm, countersunk 90° as shown in Fig. 34. The tantalum foil insert consists of a 15.65 cm² area rolled into a cylinder and coated with 0.120 ± 0.005 g of triple carbonate emissive material. All materials in the neutralizer tube and vaporizer housing assembly are tantalum, except for the 2% thoriated tungsten tip and the porous tungsten vaporizer plug. The porous tungsten material is GFE supplied with the specifications shown in Table XV. The vaporizer plug is 0.450 cm diameter and is electron beam welded to the tantalum housing. All other joints including the 0.160 cm diameter x 0.025 wall feed line are beam welded.

The cathode tip is heated by a tantalum-tantalum sheathed heater brazed to the tube with Nicrobraz 130 brazing alloy. The Nichrome V-Inconel sheathed vaporizer heater is attached in the same manner. Heater specifications are listed in Table XVI.

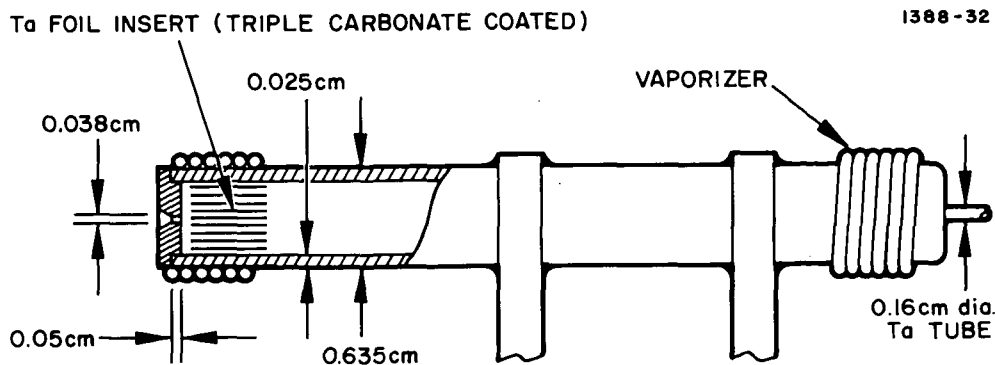


Fig. 34. Detail of Neutralizer Cathode Tip and Orifice.

TABLE XV
Neutralizer Vaporizer Material Specifications

Sample Number	Transmission Coefficient $\times 10^4$, (As Measured)	Density % Theoretical	Pore Diameter, μm
5433-88-2	0.853	72.2	1.9

T411

TABLE XVI
Neutralizer Heater Specifications

	Cathode Tip	Vaporizer
Part Number	B1025262	B1024543
Conductor Material	Tantalum	Nichrome V
Conductor Diameter, cm	0.025	0.025
Sheath Material	Tantalum	Inconel
Sheath Diameter, cm	0.100	0.100
Insulation Material	MgO	MgO
Number of Turns (approximately)	8	5
Resistance, Ω	0.520 ± 0.03 at 25°C	2.86 ± 0.14 at 25°C

T412

F. POWER CONDITIONING AND CONTROL SYSTEM

The major components of an ion propulsion system are the thruster, the power conditioning, and the control circuitry. In this section the power conditioning (made available for the program) and the control system developed during this program are discussed both in terms of their characteristics and specifications and their performance and dynamic behavior during thruster operation.

1. Power Conditioning

The various voltage and current levels required for thruster operation during development and testing phases of the program were in most cases provided by high frequency transistorized power conditioning operating from a regulated 250 V dc power bus. This power conditioning was developed with company funds to provide both a 30 cm thruster development/testing capability, using supplies with flight-type electrical characteristics, and a testbed for evaluating new transistorized power conditioning concepts and designs at higher line voltages. Functionally the power system design follows the modular configuration concept used in earlier HAC systems of this type, but the detailed circuit design is considerably different because of the higher line voltage, the power level requirement and operational characteristics of the 30 cm thruster, and the intended general laboratory use.

The power conditioning power module construction utilizes 19 in. rack panels housed internal to a standard rack. Front rack paneling contains supply V and I metering, control adjustments, and provisions for transferring to remote control. The layout of the power conditioning rack is shown in Fig. 35. All magnetic components used are special Hughes

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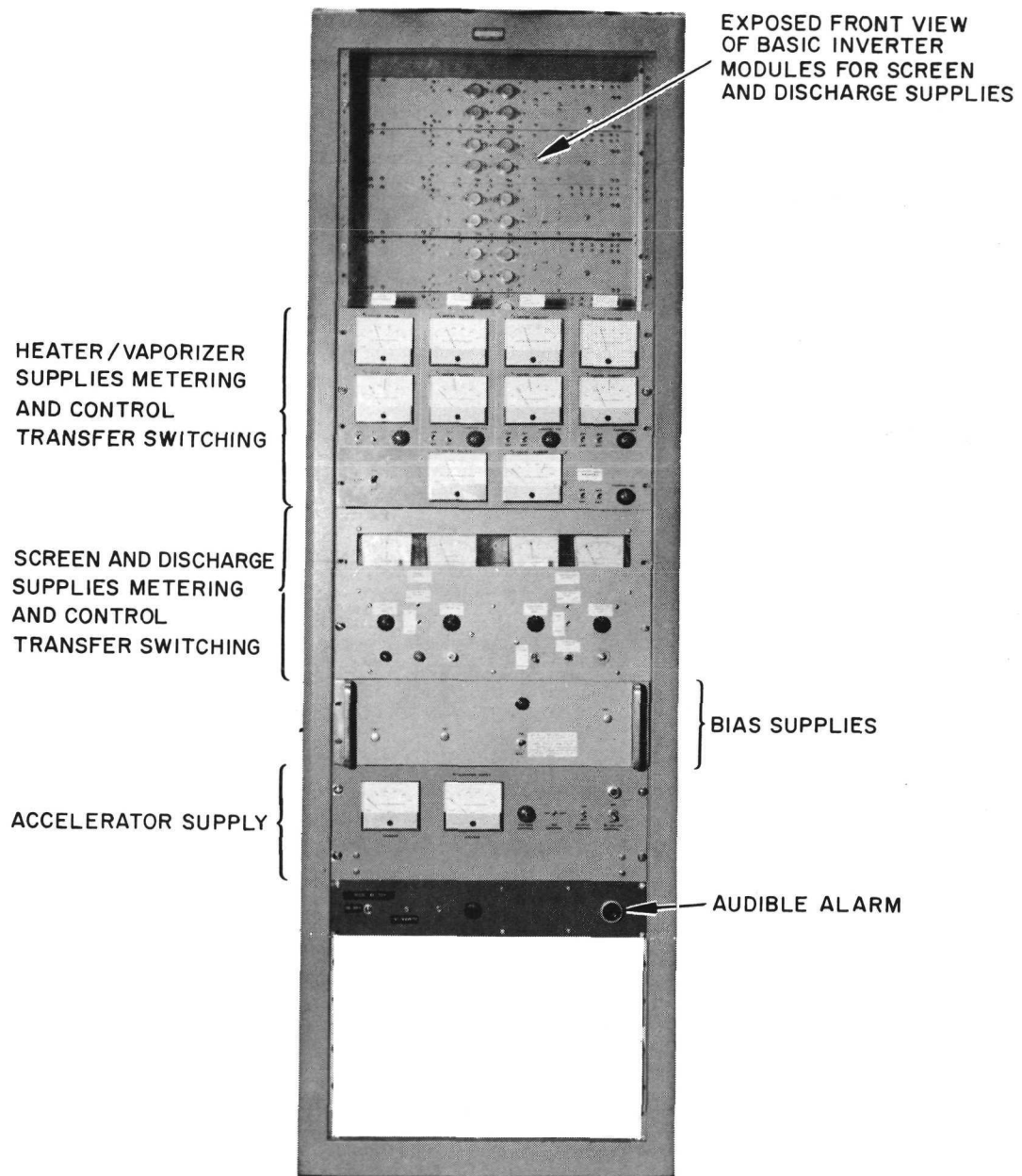


Fig. 35. Power Conditioning Rack Layout.

designs, while most of the remaining electrical components (transistors, logic elements, resistors, etc.) are unscreened commercial grade units with qualified equivalents.

A brief description of the power conditioning designs and supply characteristics is given in the following two subsections.

a. Power System Configuration

The power conditioning system block diagram is shown in Fig. 36. This system is constructed with basic building-block inverters. Eight such inverters with their rectified dc outputs connected in series are used in the screen supply. The discharge supply employs three inverters with their ac output in series. The accelerator supply consists of a single inverter preceded by regulated switching in the 250 V line to provide closed loop control. All of the above supplies operate at an inverter switching frequency of approximately 10 kHz. Heater/vaporizer power is supplied by a mag-amp controller that regulates in a constant current mode, the output of a single inverter operating at 5 kHz. Cathode and neutralizer keeper power was provided by 60 Hz supplies during the program.

Although the system was operated from a fixed 250 V dc line with minor modifications, such as the addition of a line regulator for the 5 kHz inverter and improved high voltage inverter transistors (available but expensive), the system would be capable of operating from a variable power bus in a 200 to 400 V range.

Individual supply maximum ratings for continuous operation and regulation modes are listed in Table XVII. During normal thruster testing, the supplies operate significantly below their maximum capability.

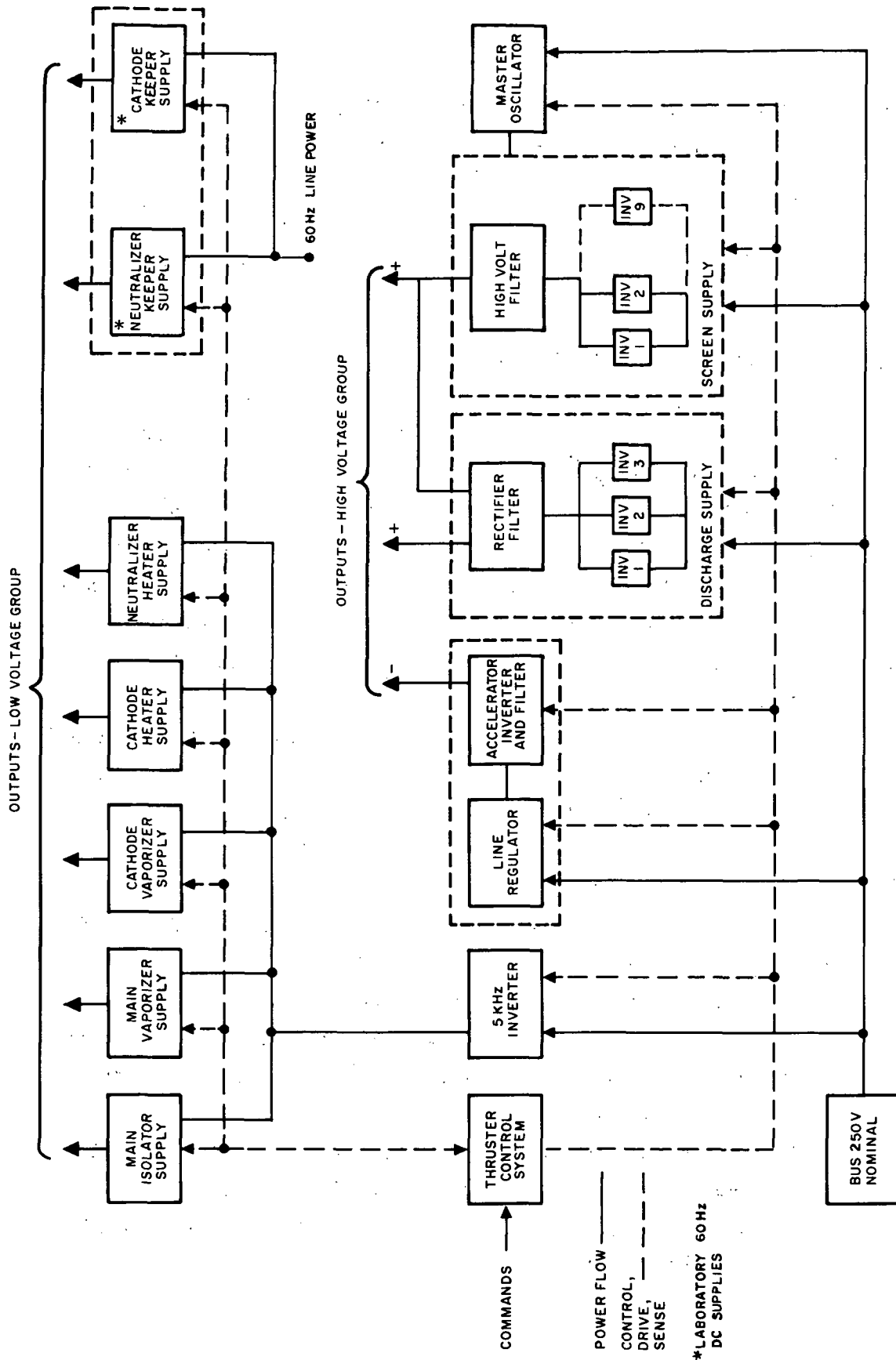


Fig. 36. 30 cm Thruster Power System Block Diagram.

TABLE XVII

Power Supply Specifications

Supply	Maximum Ratings Continuous Operation		Internal Regulation Mode, Constant V or I
	V (Volts)	I (Amps)	
Screen	1300	2.25*	V
Accel	-2000	0.2 [†]	V
Discharge	50	20	I
Main Vaporizer	20	7	I
Cathode Vaporizer	20	7	I
Cathode Heater	20	7	I
Main Isolator	20	7	I
Neutralizer Heater	20	7	I
Neutralizer Keeper**	700	R_{out} 1 k Ω	
Cathode Keeper**	700	R_{out} 1 k Ω	
*Trip level: $I_{scr} \geq 3$ A for 0.5 sec. [†]Trip level: $I_A \geq 0.2$ A for 1 sec or ≥ 0.4 A for 0.1 sec. **60 Hz laboratory supplies, $R_{out} = 1$ kΩ.			

T352-R1

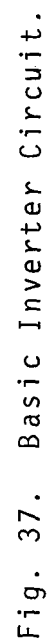
b. Basic Inverter Circuit

The basic building-block inverter circuit is shown in Fig. 37. The circuit used is a transistor bridge driven by a pair of energy storage converters. The drive power is alternately provided to pairs of opposing bridge transistors from separate windings on the drive transformers T_1 and T_2 . The pulse width drive commands enter the inverter at terminals 1 and 3 in the form of 0 or +5 V signals and are buffered by a low level stage which incorporates cross coupling to prevent both sides of the bridge from being inadvertently turned on at the same time, plus overlap protection. The overlap protection signal is derived from the output transformer and prevents the off transistors from turning on until the on transistors have turned off. The width of the drive command pulses are determined in the pulsewidth modulator circuitry (not shown) where the supply feedback level (voltage or current sensing) is compared with a setpoint reference level to establish supply closed loop regulation.

The output bridge stage of the present laboratory bread-board system utilizes 3 A, 400 V transistors. The output transformers, which are constructed of ferrite core materials, are ac coupled to eliminate the dc current path that could cause transformer saturation due to asymmetry in the switching waveforms. Total output power capability of each inverter is in excess of 400 W, but are run typically at levels less than 270 W.

c. Screen Supply

The screen supply consists of eight inverters, connected as shown in Fig. 38. All inverters are driven from one common pulsewidth modulator, and the supply output is voltage programmed with a remote reference signal in the range of 0 to 5 V dc. An integral overload detector is



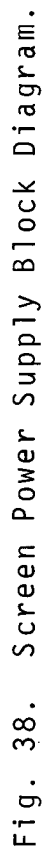


Fig. 38. Screen Power Supply Block Diagram.

provided with the supply for protection. During normal thruster operation, however, the overload detection and recycle circuitry in the control system takes precedent in processing high voltage supply overloads.

The output filter is constructed with two L-C sections. The additional section placed past the feedback voltage divider provides ripple reduction, but more importantly buffering from transient overloads common to thruster operation. Both filter chokes are fabricated using silicon steel C cores.

Figure 39 shows a back view of the screen supply, which is composed of the lower eight inverters and bottom filter assembly. Other units visible are the bias power supplies and discharge supply rectifier/filter assembly and current sensing module. The supply's regulation characteristic for an input control setpoint corresponding to 1000 V at 1.0 A is shown in Fig. 40.

d. Accelerator Supply

The accelerator supply is mechanized as shown in Fig. 41. The line regulator is controlled by an external reference signal to program the accelerator voltage. There are two regulation control loops. The minor loop prevents the output of the line regulator from increasing above the level required to achieve a preset output voltage from the inverter. The major loop is dominant and controls when the output reaches the preset level. The effect of the minor loop is to improve transient response. An integral overload circuit is provided, as with the screen supply, for protection when the supply is not part of the total system. The output filter is composed of a T section with the output inductor provided to limit the surge and circulating current when the screen and accelerator supplies are shorted together.

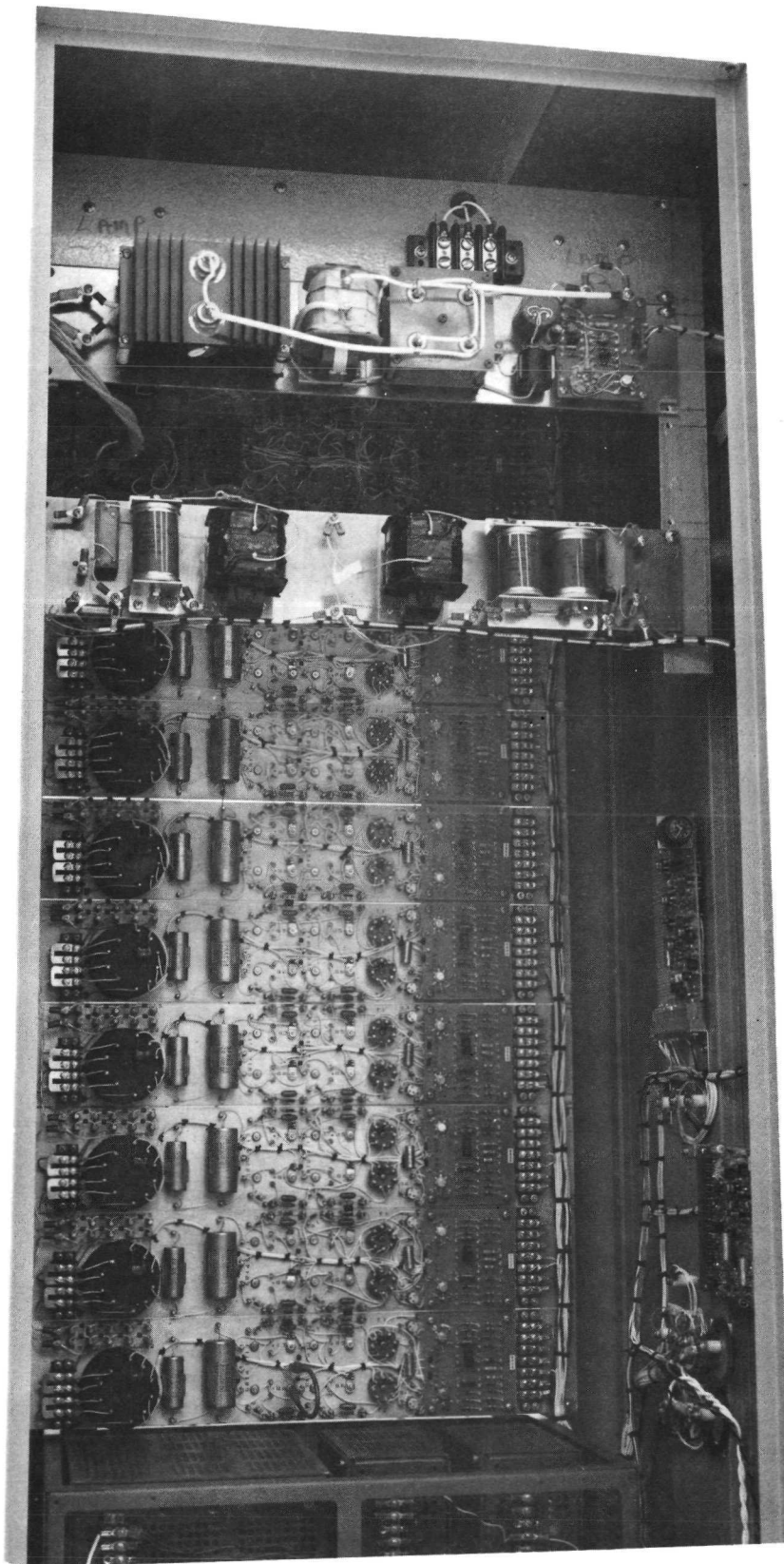


Fig. 39.
Screen Power Supply.

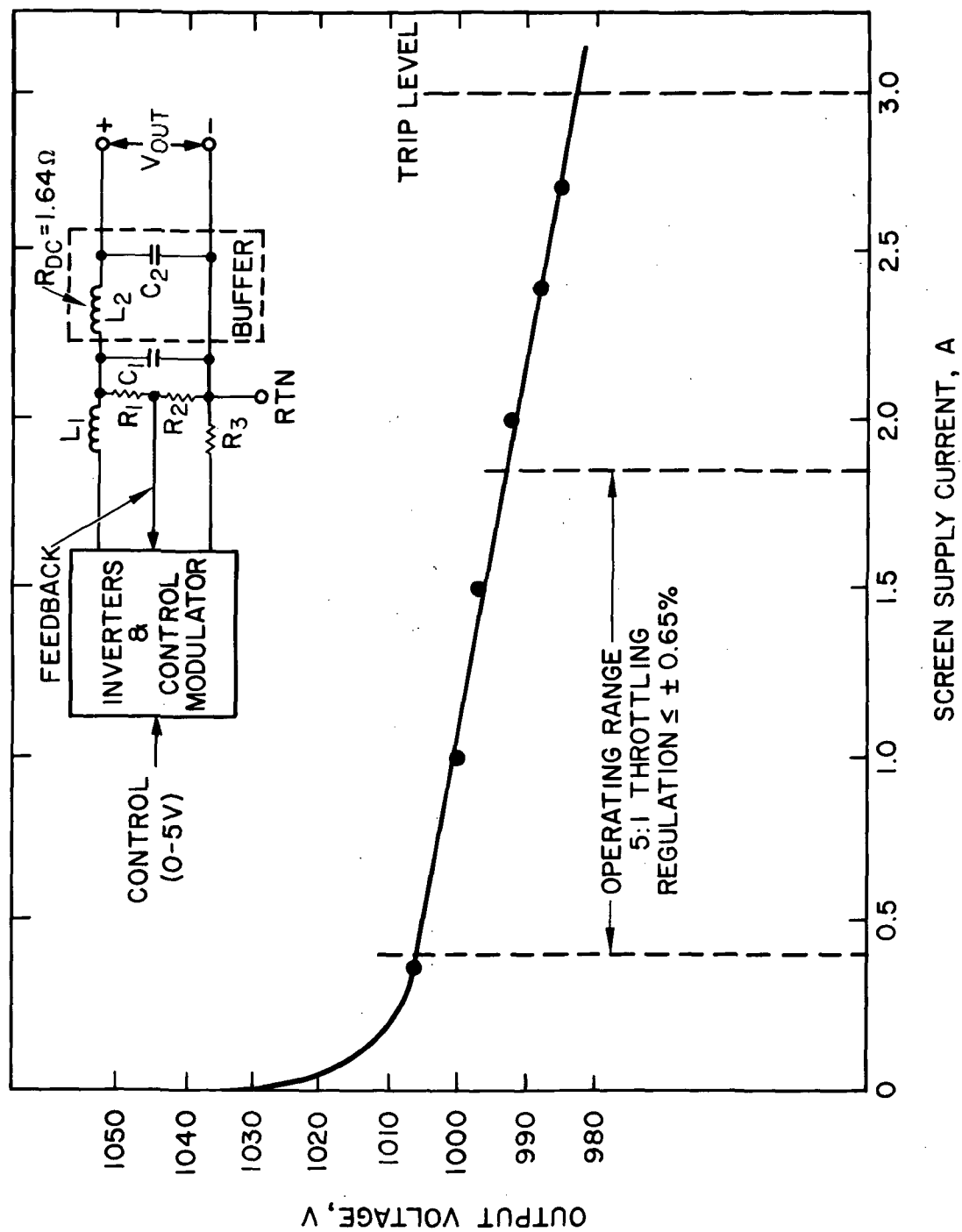


Fig. 40. Screen Supply Regulation Characteristics.

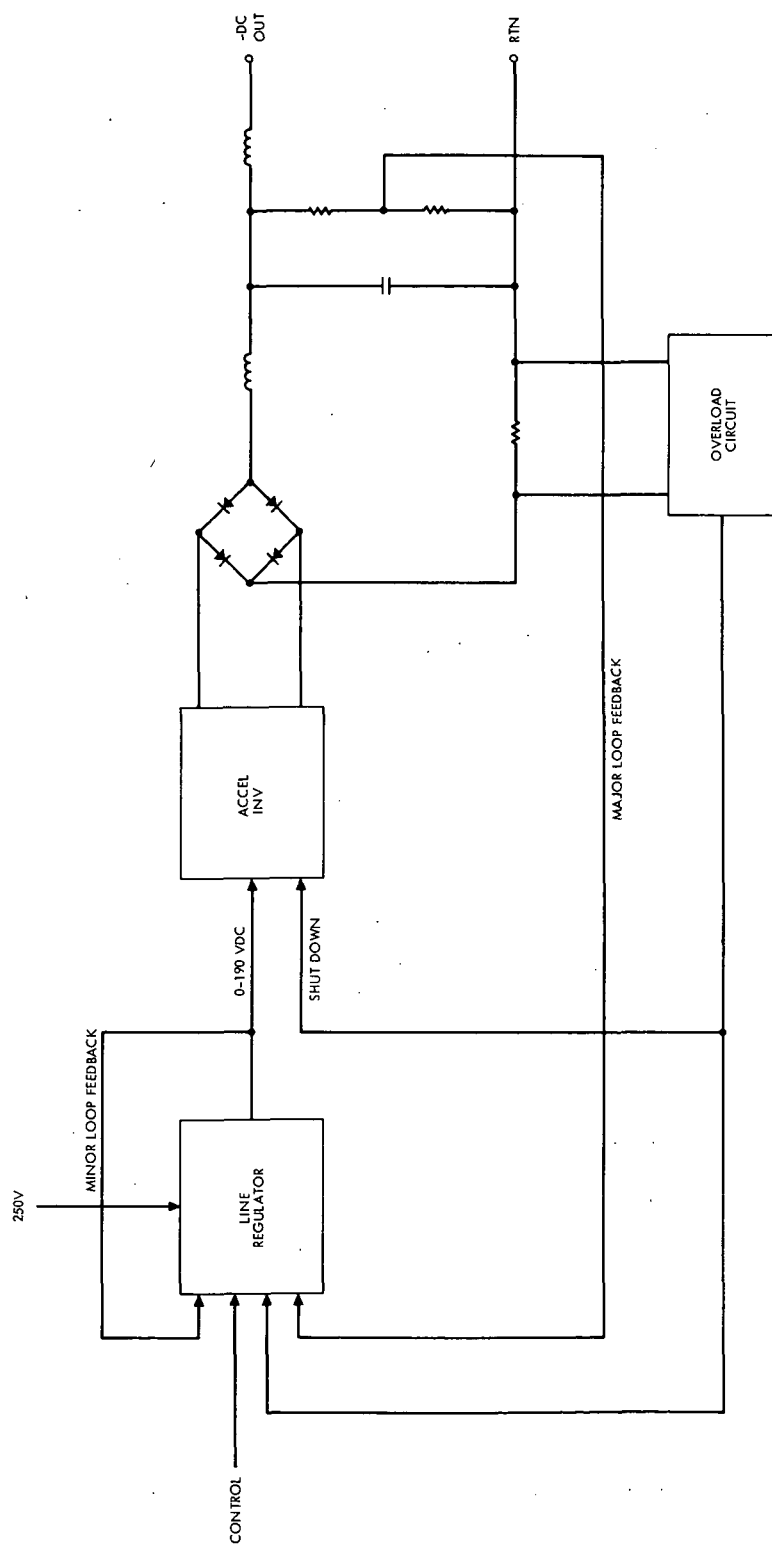


Fig. 41. Accelerator Supply Block Diagram.

Regulation for load variations from 0 to 100 mA is better than +1% and maintains an accuracy of $\pm 2\%$ for loads in excess of 200 mA.

e. Discharge Supply

Discharge power is generated by a series connection of the output of three inverters as shown in Fig. 42. The inverters pulsewidth modulator and remote control capability are typical of supplies already discussed. An additional amplifier is, however, required in the regulation circuitry to provide both current and voltage control functions. Current feedback is generated by a magnetic amplifier type current sensor, which requires an external excitation source. The advantages of the current sensor are the high voltage isolation capabilities plus good linearity. A voltage transformer (with high voltage isolation) in combination with L-C filtering is used to sense the output voltage.

The output characteristics of the supply are shown in Fig. 43. The maximum output voltage can be adjusted at the supply's front panel. During system operation, the supply functions as a current regulated supply with the output voltage determined by the cathode vaporizer control loop. Current regulation is approximately $\pm 1\%$ over its normal operating range. Open circuit voltage is 99 V dc regardless of the voltage or current control setting.

f. Heater Supplies

The heater and vaporizer power is controlled by magnetic amplifiers driven by square wave ac from the 5 kHz inverter. Figure 44 shows a schematic of the control circuitry presently used. The magnetic amplifier is controlled by the differential amplifier formed by Q1 and Q2, which compare the control signal with the feedback. Feedback is

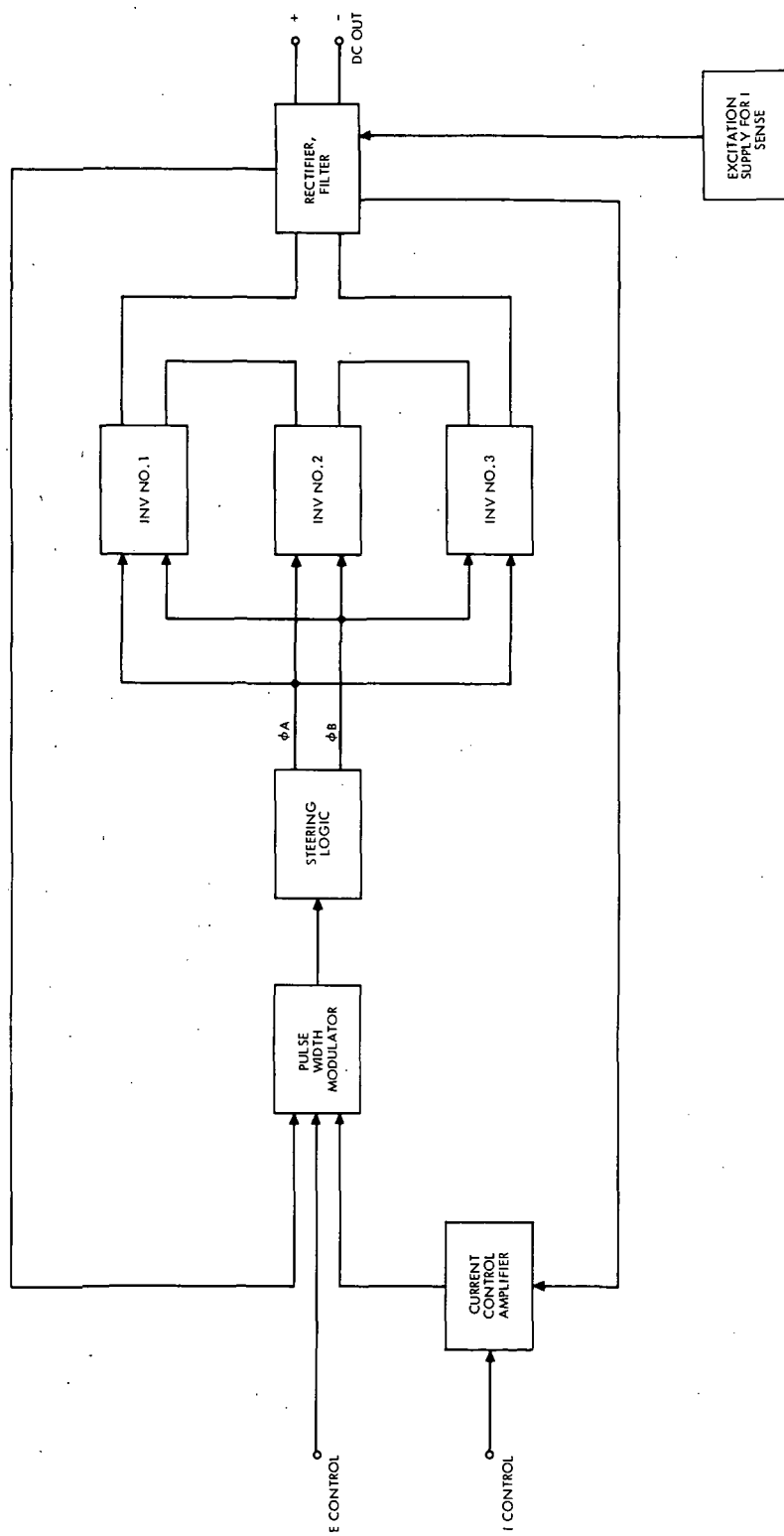


Fig. 42. Discharge Power Supply Block Diagram.

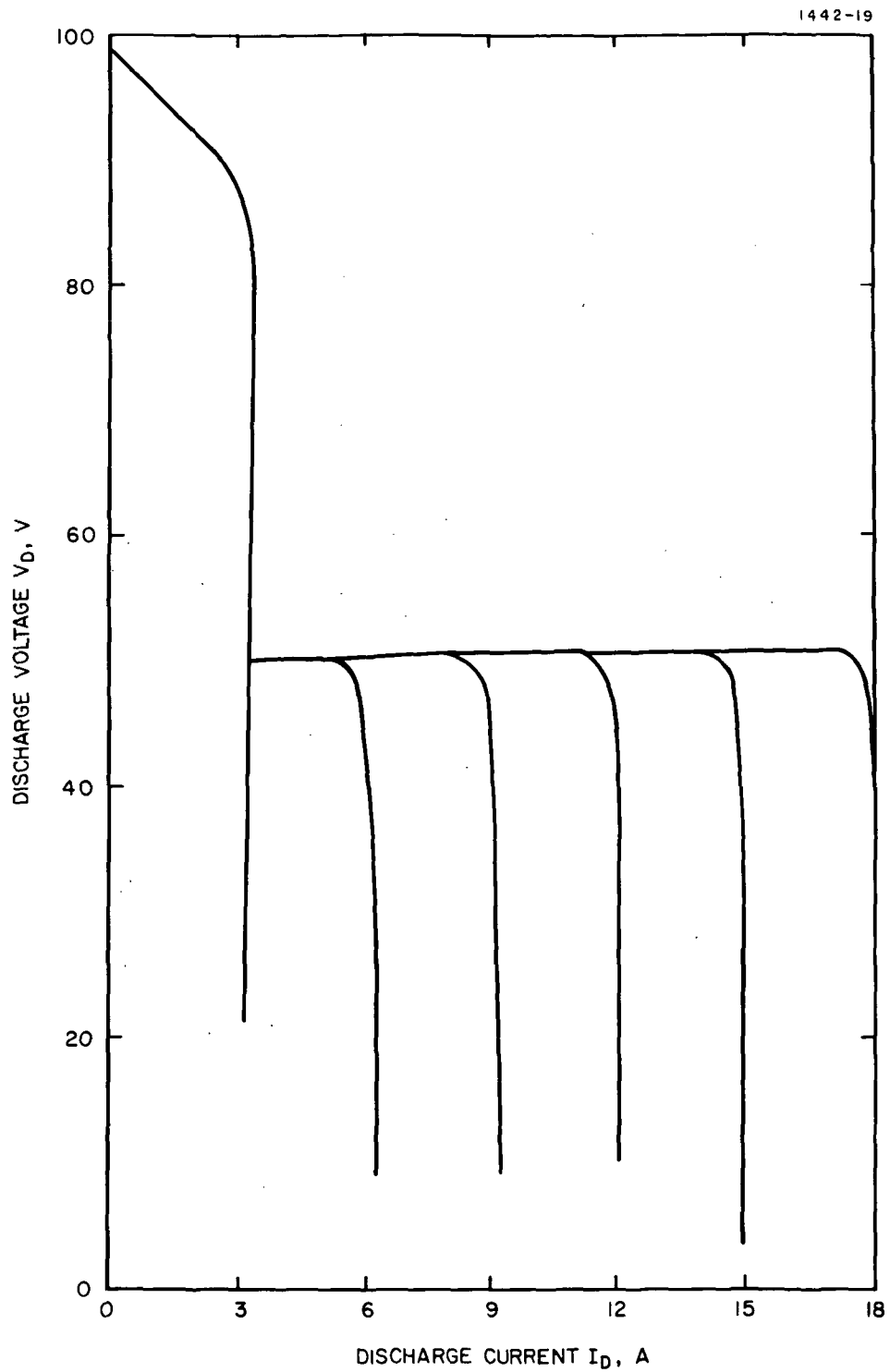


Fig. 43. Discharge Supply Output Characteristics.

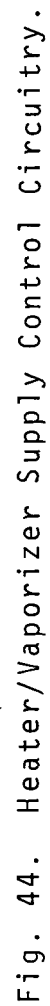


Fig. 44. Heater/Vaporizer Supply Control Circuitry.

generated by a current transformer followed by an rms shaping network. Over-all current regulation is held to within $\pm 3\%$ for near short circuit to 20 V output. The design over-all capability of each supply is 140 W; however, control signal drive limiting in the control system greatly reduces the allowed maximum power swing when operating the thruster. The output transformer of each supply is mounted at the vacuum chamber bulkhead to minimize problems of inductive reactance associated with long 5 kHz power lines between thruster and power conditioning.

g. Keeper Supplies

The neutralizer and cathode keeper supplies used during the program consisted of 60 Hz laboratory dc supplies with 1 k Ω series output resistors. For starting, the supplies are set to their full output open circuit voltage of 700 V. Following ignition, the dc power supply voltage V is adjusted to produce the desired keeper current given by the relationship $I_K = (V - V_K) 10^{-3}$ A. Because of the series resistance, keeper current is held essentially constant with only a 1 mA ΔI_K change with a ΔV_K change of 1 V.

2. Control System

This section will briefly discuss the design, testing, and performance of a control system which when used in conjunction with the high frequency transistorized power conditioning provides all required closed loop, variable setpoint, and

sequential control necessary to operate the 30 cm thruster developed on this program over the throttling range of 5:1.

a. Control System Design Philosophy

The control system developed for this program was required to satisfy a number of generalized criteria in addition to those normally associated with control performance. It first of all had to be capable of controlling the high frequency pulsewidth modulated power conditioning which has not only the advantages of a flight-type system (lightweight, high efficiency, flight system output characteristics) but the disadvantages (nonlinear control transfer and rms sensing characteristics, and a nonzero output for zero control level inputs). The design should be sufficiently flexible in control options to allow wide range independent output variations for laboratory use during performance mapping, perveance testing, etc., yet it should be capable of at least functionally and electrically approximating a flight-type system configuration during fixed point operation or throttling. In addition, it was highly desirable to have a system design that was structured to allow easy systematic growth to greater control capability without requiring redesign of earlier circuitry.

To accomplish the multifaceted goals, a general approach was taken that divided the control capability at the remote control panel into three independent levels, with transfer through the operational levels achieved by panel switches. The first level provides independent on-off and knob pot adjustment of all supplies. Level two allows independent setpoint adjustment of three dynamic loops, while level three provides full interrelated continuously variable single knob control of the thruster system over the throttling range.

The design plan used to mechanize the control system concept was first to establish general control requirements at any fixed operating point. Next, the provision was added to incorporate (after control definition testing) the necessary control signal information that would establish optimum power supply output levels and loop setpoints as the throttling level was varied. In a sense this was achieved by using a buffer output stage, which initially gave a point of remote manual control over individual power supplies and allowed the high voltage overload detection and recycle sequential control to be applied. As the individual controllers were designed and wired in the system, the thruster operator had the option of using the front panel manual control or transferring (via a panel switch) the controller output signal to the buffer to control thrusters parameters closed loop.

Individual loop setpoints are either derived from front panel manual control adjustments or (in a manner analogous to that of the buffer stage) from the variable setpoint throttling section by switching at the panel. The throttling section produces all variable setpoint levels required to establish closed loop operation points, thruster parameter relationships, and power supply outputs over the full throttling range. The throttling control adjustment is by a single front panel manual control that produces a 0 to 5 V dc signal.

The control system circuitry is physically divided into functional units, e.g., buffer section, beam current controller, overload and recycle, etc., each constructed on separate plug-in circuit cards. This construction technique has proven successful in the present development program, because it allows quick and easy modification of the individual unit characteristics without shutting down the total system, since that portion of the total control system can be temporarily placed under the manual control at the control panel.

The control input and V-I sensing voltage levels of the power supplies used with this control system were modified to establish standardized input/output system voltage levels in the range of 0 to 5 V dc. This standardization has simplified the design, checkout, and setup of the control system and makes the control system-power supply interface simpler if the hardware were to be used with supplies other than those on the present program.

b. Control System Configuration

Figure 45 shows the thruster control system as both block and functional diagrams. Each power supply output is controlled by a positive control signal (in the range of 0 to 5 V dc) from its individual buffer op-amp. The buffer as configured provides a junction for easily accomplishing in a well defined manner both analog and sequential control of the power supplies on a single control line. Its low output impedance helps to minimize noise on the control line and maintains a nonvarying interface between the control system and supplies regardless of any modification in the control circuitry, which terminates at the buffer input. In addition, by using switches provided on the control panel, the output of each supply can be controlled manually while retaining the automatic sequential control required during HV overload and recycle.

The three controllers shown compare sensed and scaled power supply voltage or current to reference setpoints. The resultant control signal is fed to the appropriate supply via its buffer amplifier. Switching has been provided to allow each loop setpoint to be controlled separately from the manual control section. When the system is operated in the automatic throttling mode, all variable setpoints, whether for controllers or individual supplies, emanate from the variable setpoint throttling control section. These variable setpoint voltage levels are all directly or indirectly a function of the beam current command reference level.

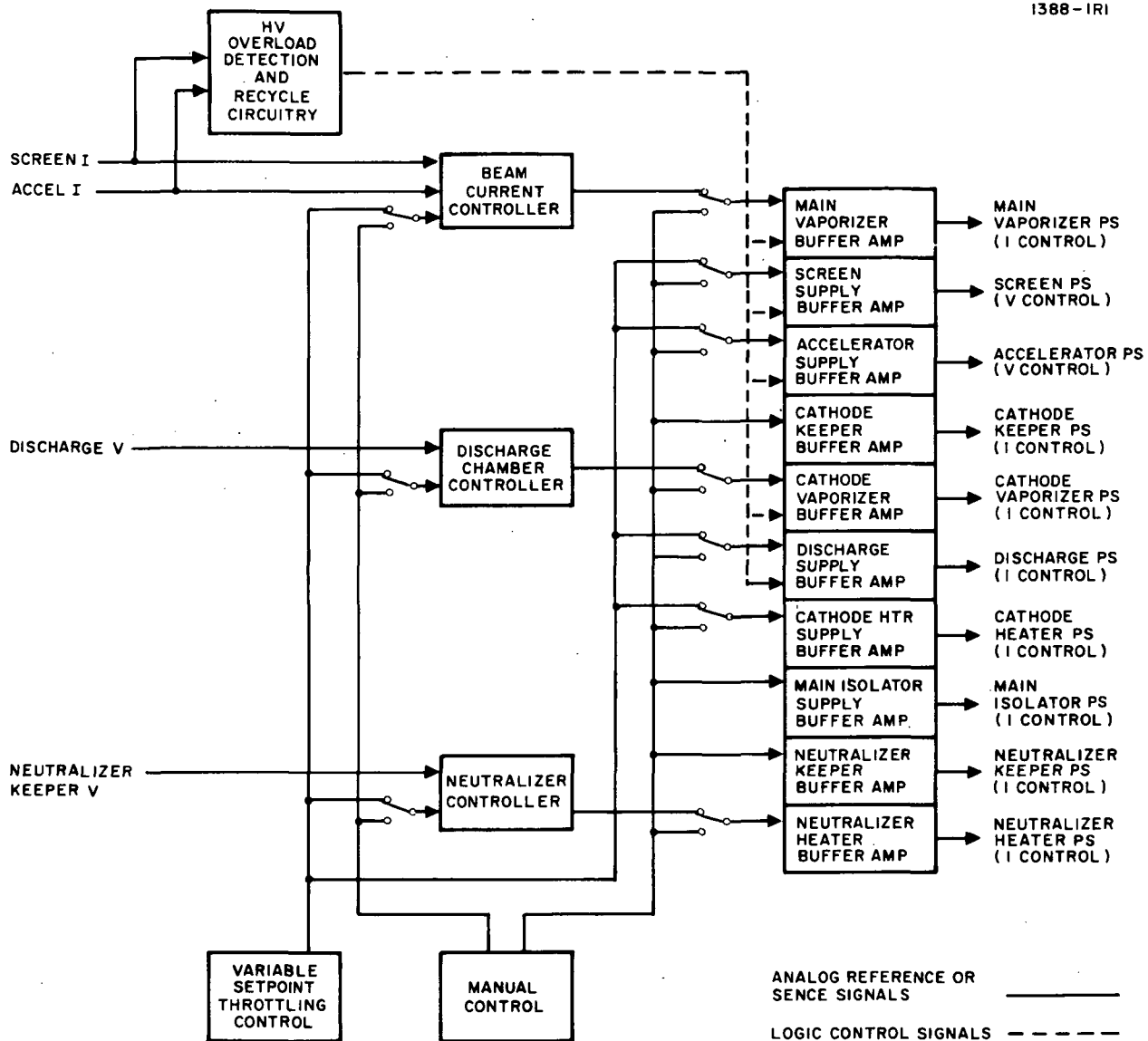


Fig. 45(a). Thruster Control System Block Diagram.

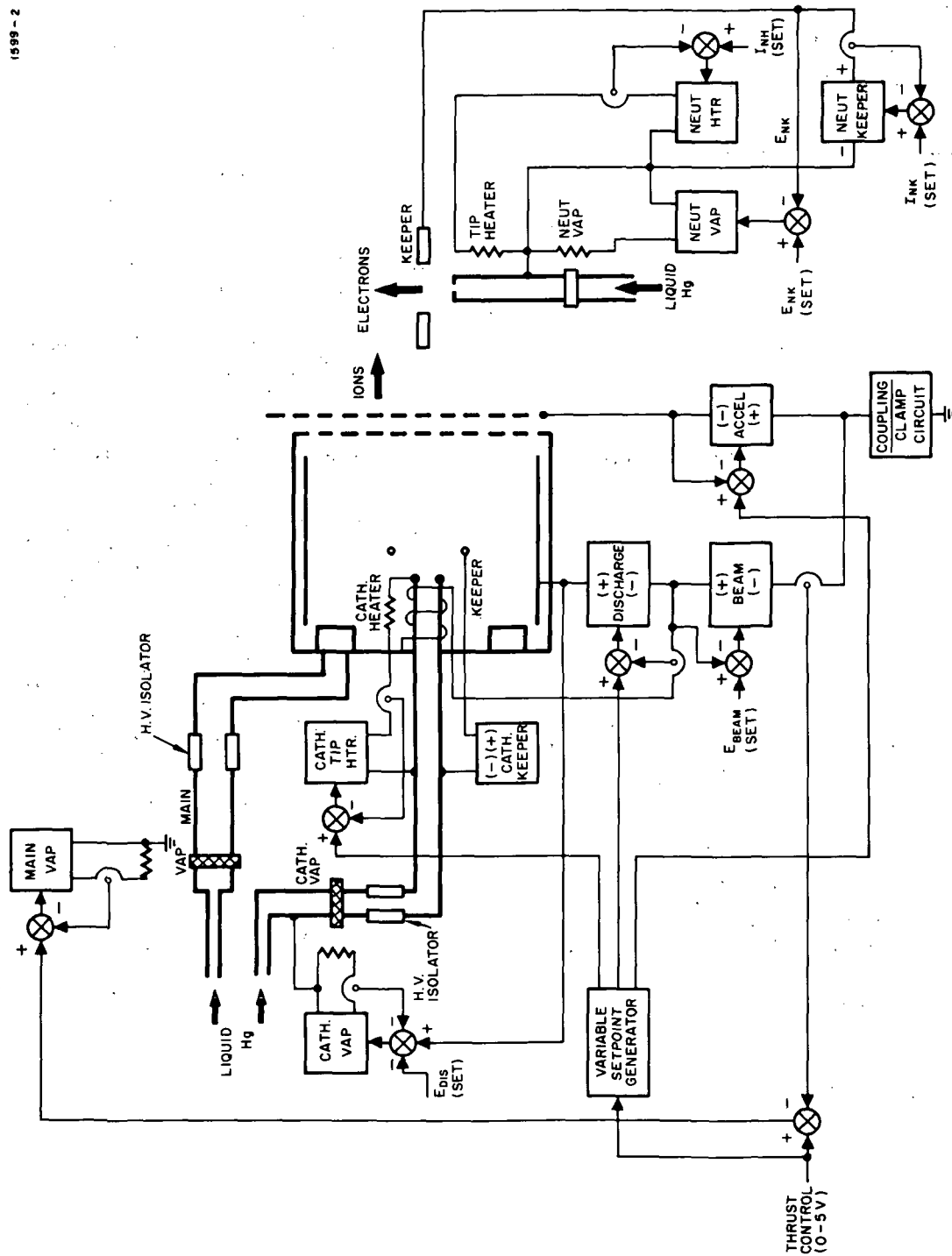


Fig. 45(b). Power Supply/Thruster Control Concept Block Diagram.

The HV overload detection and recycle circuitry senses screen and accelerator current. If either current exceeds an established level for a given time duration, the high voltage potentials are reduced to zero potential, and various supplies are commanded to their "trip" levels. The supplies are then recycled in sequential order to the run state.

Figure 46 shows the control system front panel layout and indicates the manner in which the three levels of control have been carried through to the placement of switches and control knobs. Detailed electrical designs of the circuitry represented by the individual blocks in Fig. 45 are discussed separately in the following section.

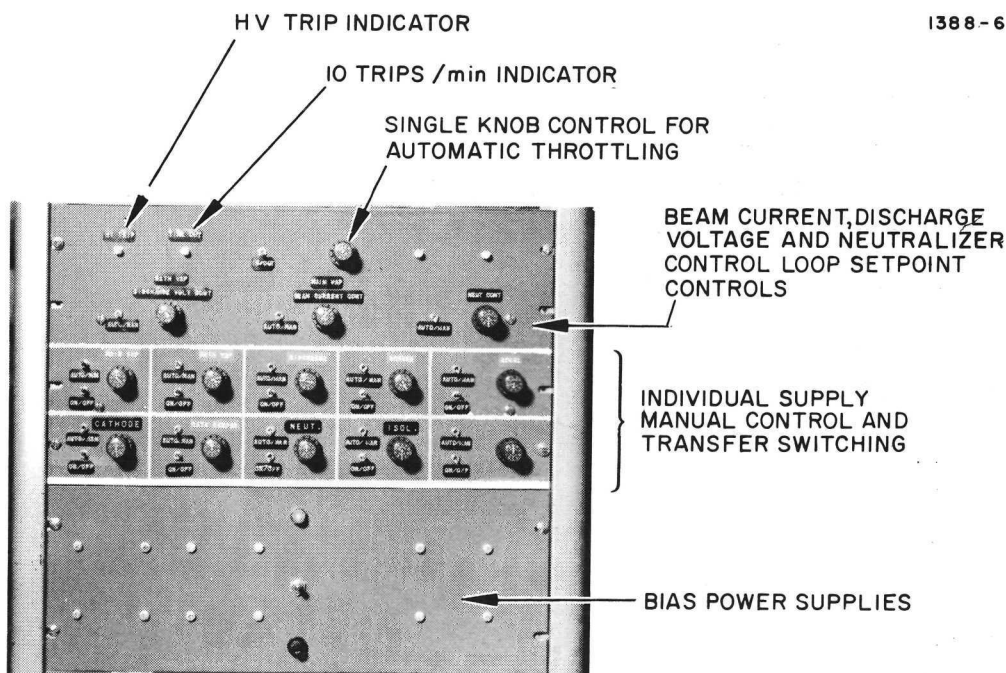


Fig. 46. Control System Front Panel Layout.

c. Control System Circuitry

Output Buffer Amplifier - Figure 47 shows the circuit configuration chosen to mechanize the buffer stage for the main vaporizer, cathode vaporizer, and discharge control. When logic levels A and B are both high (H), the control level output is zero, corresponding to power supply off. For A = H and B = Low (L) the stage has a gain of one with respect to the control level input from either manual control, a controller section, or variable setpoint throttling control. This is the typical condition during the run state. When A = L, B = H, the output level is determined by the voltage setting established at R5 and corresponds to the trip level as presently used in the control system. The logic levels A and B are established by the recycle portion of the HV overload detection circuit.

The buffer amplifiers for the remaining power supplies are simplified versions, either because the given supply does not participate in the recycle sequence or has a trip level corresponding to zero output, hence does not require a trip level adjustment.

HV Overload Detection and Recycle Circuitry -

Figure 48 shows the circuit developed for this program. Detection of screen and accelerator current overloads is performed by three $\mu A710$ differential comparators. A tripstate is established if any one of the comparators maintains a low level for a given time interval. The time interval is determined by counting timing pulses of a given repetition rate that are allowed to enter the counter section when the comparator low level is present. Gates are used to detect when a particular count (time) has been reached by state decoding. It then latches (or sets) the trip indicator latch. When this occurs, off or cutback signals are issued to the buffer amplifier

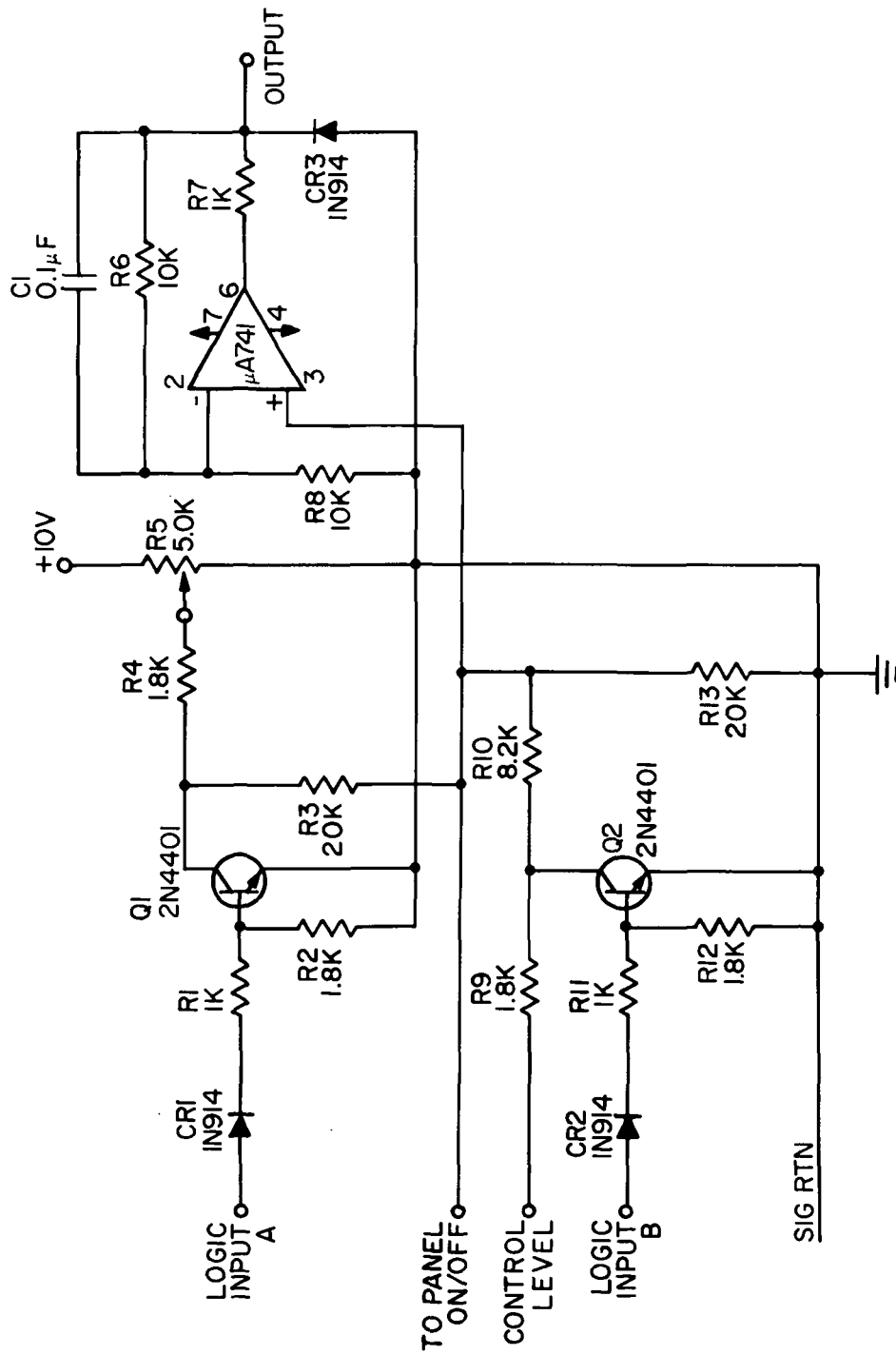


Fig. 47. Buffer Operational Amplifier.

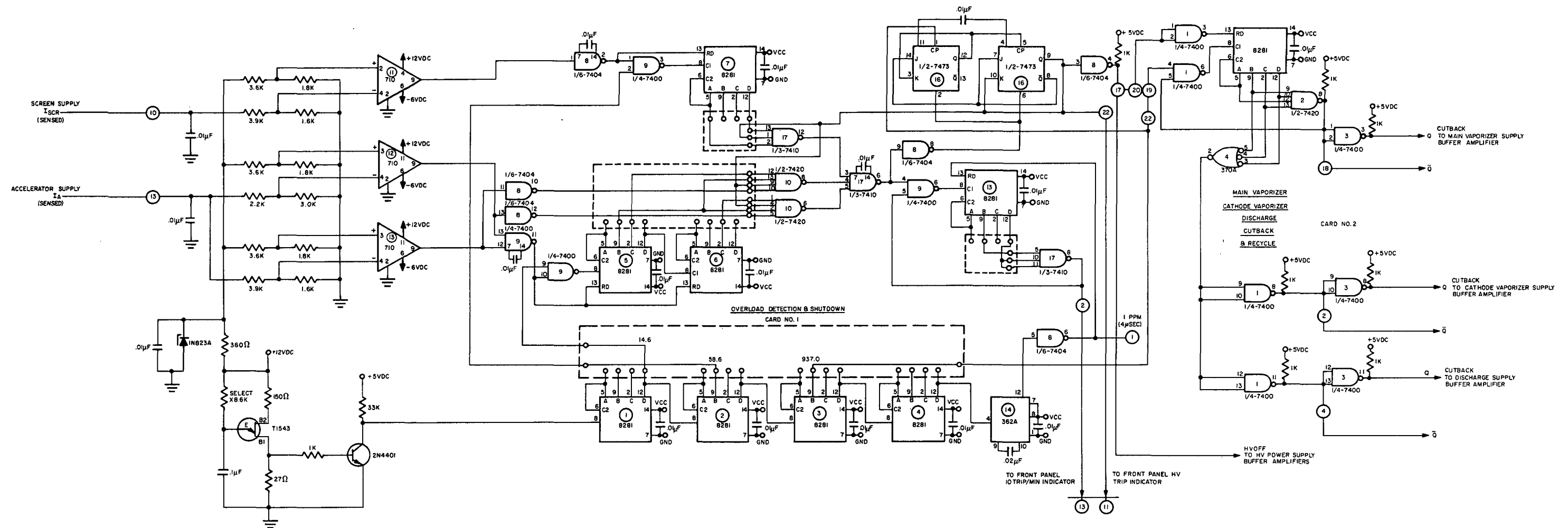


Fig. 48. High Voltage Overload Detection and Recycle Sequencer.

controlling the high voltage, cathode vaporizer, main vaporizer, and discharge supplies. Other timing signals from the 16-bit counter driven by the 1.09 kHz unijunction oscillator are used to reset the trip indicator latch and to drive the counter controlling the cutback recycle timing of the other supplies. These timing signals can easily be used when expanding the systems sequential control capability. Panel lights indicate when a high voltage trip has occurred and when 10 trips/min has been reached.

The overload detection and recycle circuitry can be easily modified with respect to trip and recycle timing by changing the count decoding format (interwiring between counters and decode nand gates associated with each dashed block). The present system is wired to provide the following response:

Trip Conditions: (HV commanded to zero potential)

Screen supply Current: $I_{SCR} \geq 3.0 \text{ A}$ for 0.5 sec

or

Accelerator supply Current: $I_A \geq 0.2 \text{ A}$ for 1.0 sec

or

Accelerator supply current: $I_A \geq 0.4 \text{ A}$ for 0.1 sec

Recycle Timing

High voltage on: Within $t_{HV} = 1 \pm 0.5 \text{ sec}$

Cathode vaporizer and discharge current to run state: $t_{HV} + 2.0 \text{ sec}$

Main Vaporizer to run state: $t_{HV} + 13 \text{ sec.}$

The HV current trip conditions are contract requirements while the recycle timing was experimentally selected. Fast recovery to a steady state running level is desirable in terms of total integrated thrust. Within the constraints of the power conditioning used, the thruster loading characteristic, and the wide range of operating conditions for which overload recovery was required due to throttling, a slower and stepwise recovery has led to better system operation in terms of additional arcing immediately following steady state recovery, control loop interactions during and following recovery, and short term peak bus power demand. This is an important consideration for systems destined to operate from solar arrays.

The selected timing minimizes beam current overshoot at the high beam current operating levels. For the high voltage supplies to recycle on following a trip without overload or excess component stress, the discharge current setpoint level is reduced to approximately 2 A. When the discharge current level is reestablished after the trip, the discharge voltage overshoots. When both the discharge voltage and beam current controllers are released to their run condition prior to establishing near stable discharge chamber operating levels, strong control loop and thruster parameter interactions occur because of the inherent coupling of the main vaporizer and cathode vaporizer neutral flows and because of variations in propellant utilization with discharge voltage at fixed discharge current. The recycle times indicated above have produced very smooth trip recovery by having the fast discharge voltage controller establish near ideal chamber conditions before the beam controller is released to reestablish the desired beam current.

Recording traces of various power supply voltages and currents documenting recycle sequencing response at $I_B = 1.5$ A are presented in Figs. 49 and 50 for two recording speeds.

Beam Current Controller - The thruster beam current is controlled at a desired fixed level in the throttling range by the main vaporizer-beam current controller. The controller compares the relative magnitudes of sensed screen current I_{SCR} and accelerator current I_A to the beam current reference (loop setpoint) I_{BR} , and the resulting amplified signal is routed to the main vaporizer power supply via its unity gain buffer amplifier.

Figure 51 shows the beam current controller (amplifier) used in the present system, while Fig. 52 depicts the beam current closed loop block diagram and lists typical gain values of the electronic circuitry employed. The transfer gain from sensed beam current to main vaporizer current is $I_{MV}/I_B = -20$ A/A. This leads to the $I_B - I_{MV}$ transfer characteristic for variable I_{BR} in the throttling range shown in Fig. 53.

The thruster transfer characteristic I_B/I_{MV} (for I_D , V_D , etc., fixed) has not been investigated in sufficient detail to establish a continuous graphical representation; however, open loop perturbations $\Delta I_B/\Delta I_{MV}$ for I_B in the range 0.5 to 2.0 A has produced typical small signal gain values of 2 A/A and 5 A/A. These values give an open loop gain lying between 40 to 100 A/A, which can lead to a closed loop transfer characteristic variation (including precontroller scaling) between 0.498 A/V and 0.504 A/V over the throttling range. For the present system the variation from the ideal transfer characteristic of 0.5 A/V is considered acceptable, since the maximum deviation is less than $\pm 1\%$ from a linear slope.

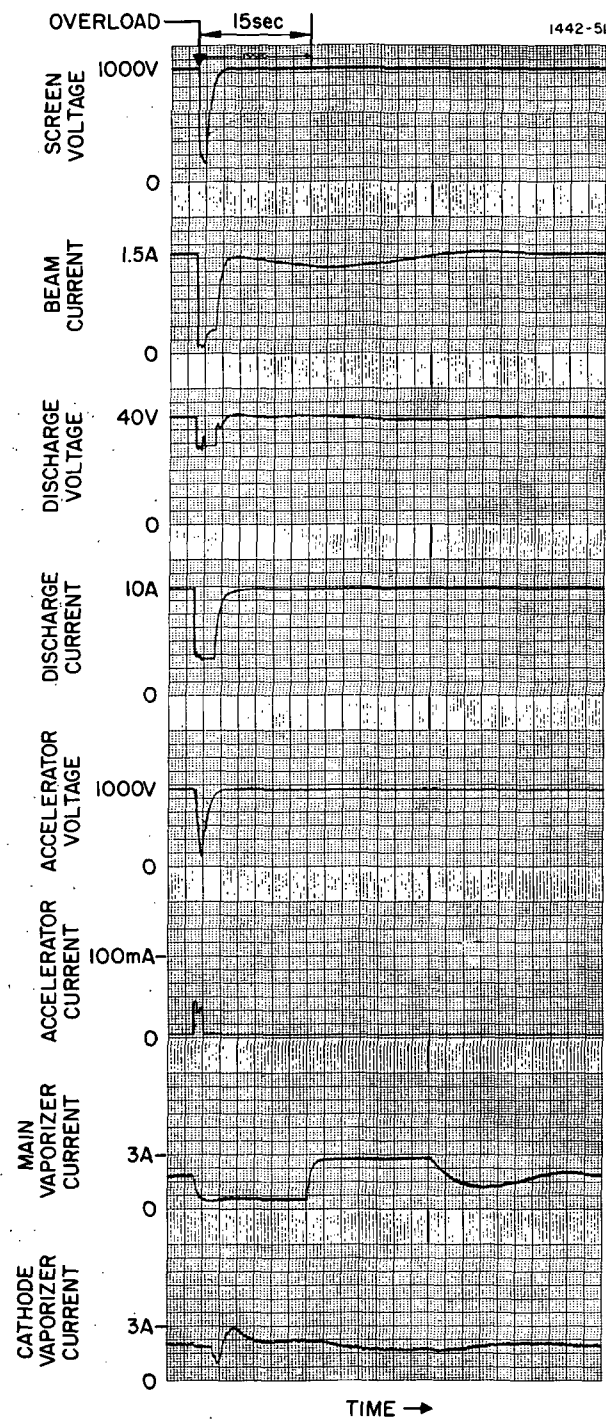


Fig. 49. System Recovery from High Voltage Overload (Fast Speed).

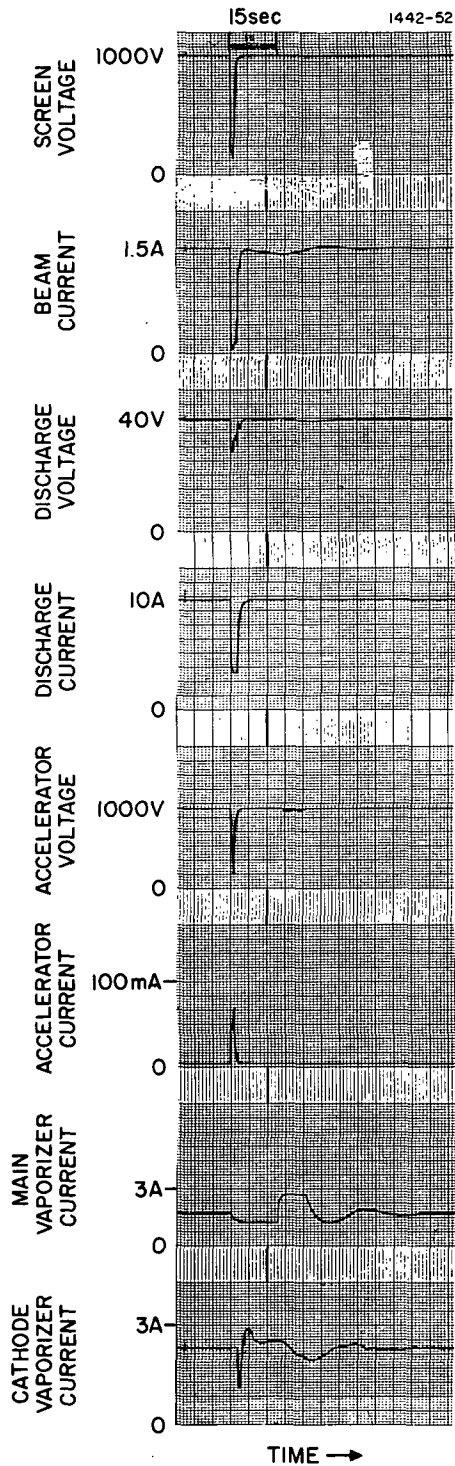


Fig. 50.
System Recovery from High
Voltage Overload (Slow Speed)
Recorded from Power Supply
Telemetry Outputs.

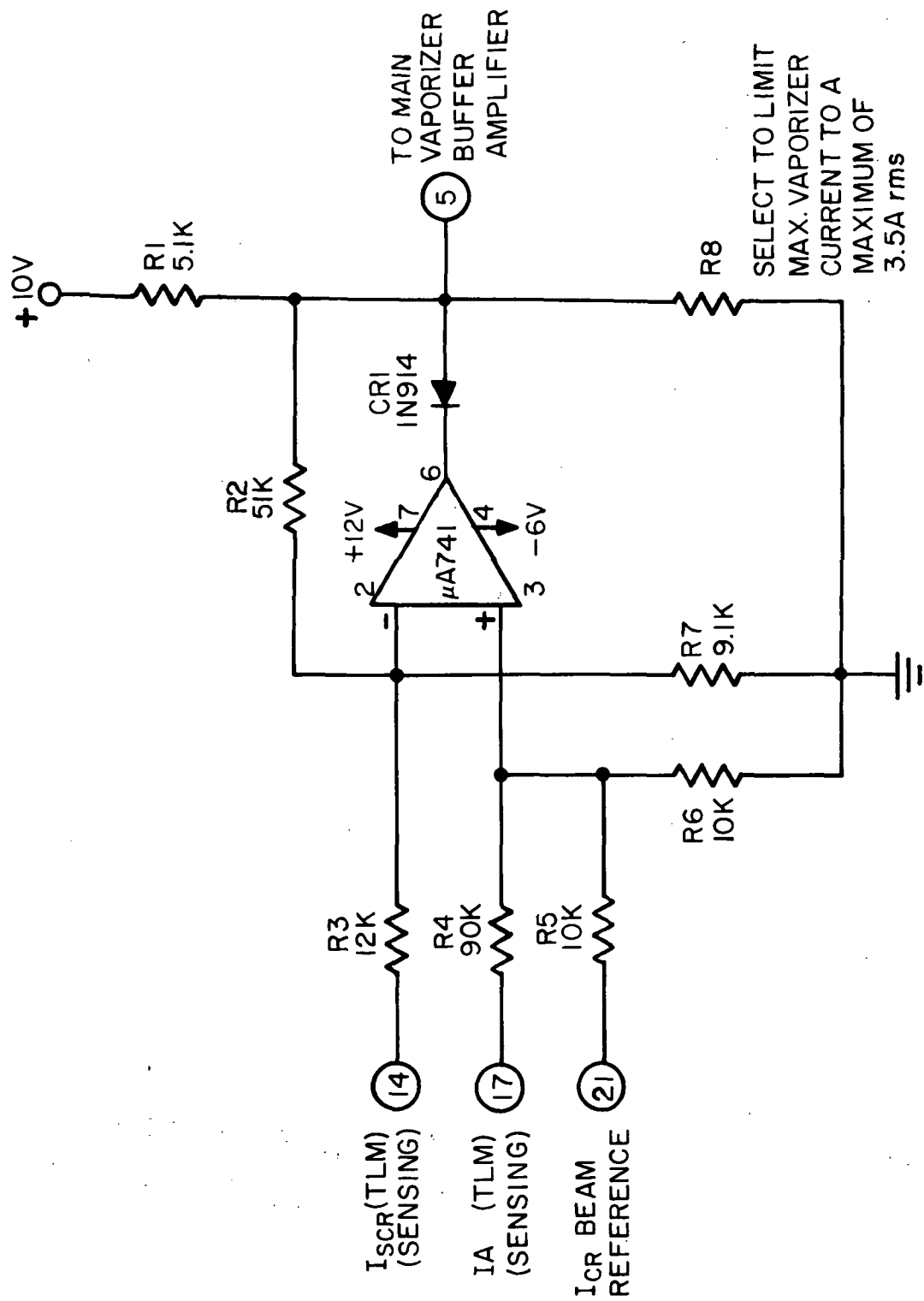


Fig. 51. Main Vaporizer-Beam Current Controller.

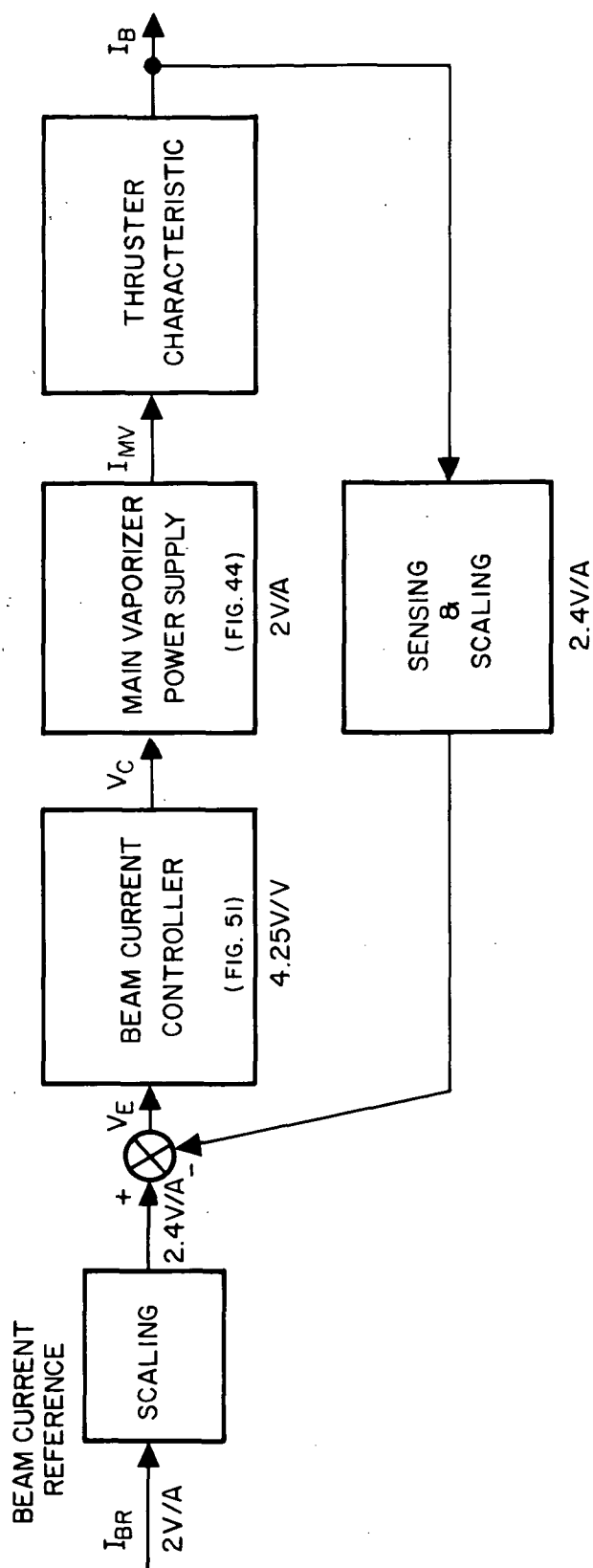


Fig. 52. Beam Current Closed Loop Control Block Diagram.

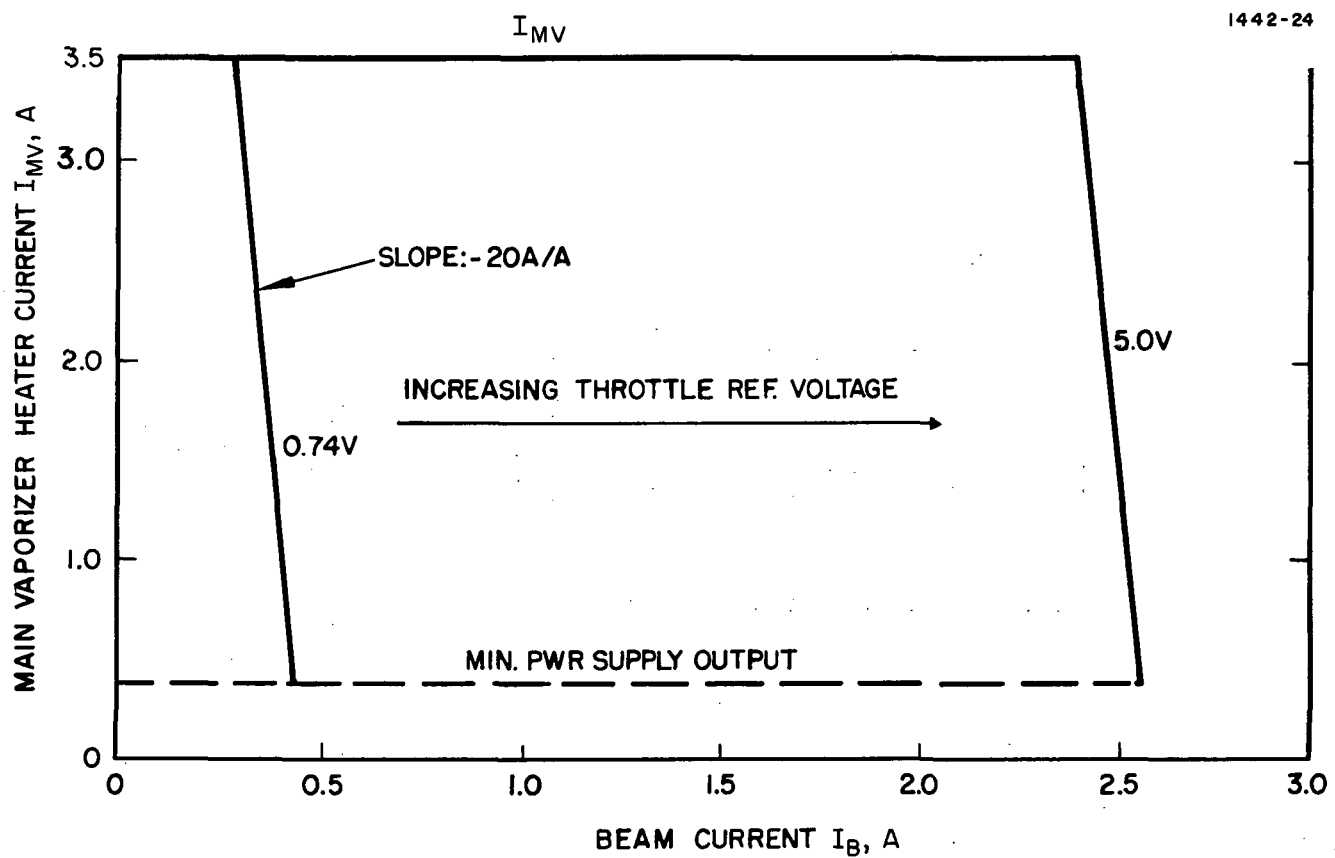


Fig. 53. Beam Current-Main Vaporizer Transfer Characteristic.

Performance of the beam current controller for perturbations in discharge voltage and discharge current at fixed operating points in the throttling range has been satisfactory, although room for improvement still exists. Representative values denoting the loops capability of offsetting external perturbations are $\Delta I_B / \Delta V_D = 0.2\%/V$ and $\Delta I_B / \Delta I_D = 0.3\%/A$ at a nominal beam current level of 1.0 A. As would be expected, each of the above terms is positive. Since for each I_B setting, a corresponding optimum value of V_D and I_B is held by other circuitry in the control system, and the resultant beam current inaccuracies due to these perturbations is insignificant during steady state operation.

Discharge Voltage Controller - When the control system is in closed loop operation, the discharge voltage is controlled to a fixed voltage level (nominally 40 V) by controlling the cathode vaporizer neutral flow which essentially sets the plasma impedance offered the discharge power supply.

The controller (amplifier) used is shown in Fig. 54. Lead compensation C_1 has been employed in the controller to separate its loop response from that of the slower beam current controller, producing improved recovery from HV overloads and more stable steady state thruster operation. The proportional controller compares sensed discharge voltage (from the discharge power supply) scaled at 0.1 V/V to a control panel discharge voltage setpoint of equal scaling. The resultant error signal is amplified and routed to the cathode vaporizer power supply through its buffer amplifier. Resistor R_1 establishes the minimum voltage to which the controller will respond, while the divider composed of R_2 and R_8 limits the maximum cathode vaporizer current to safe levels.

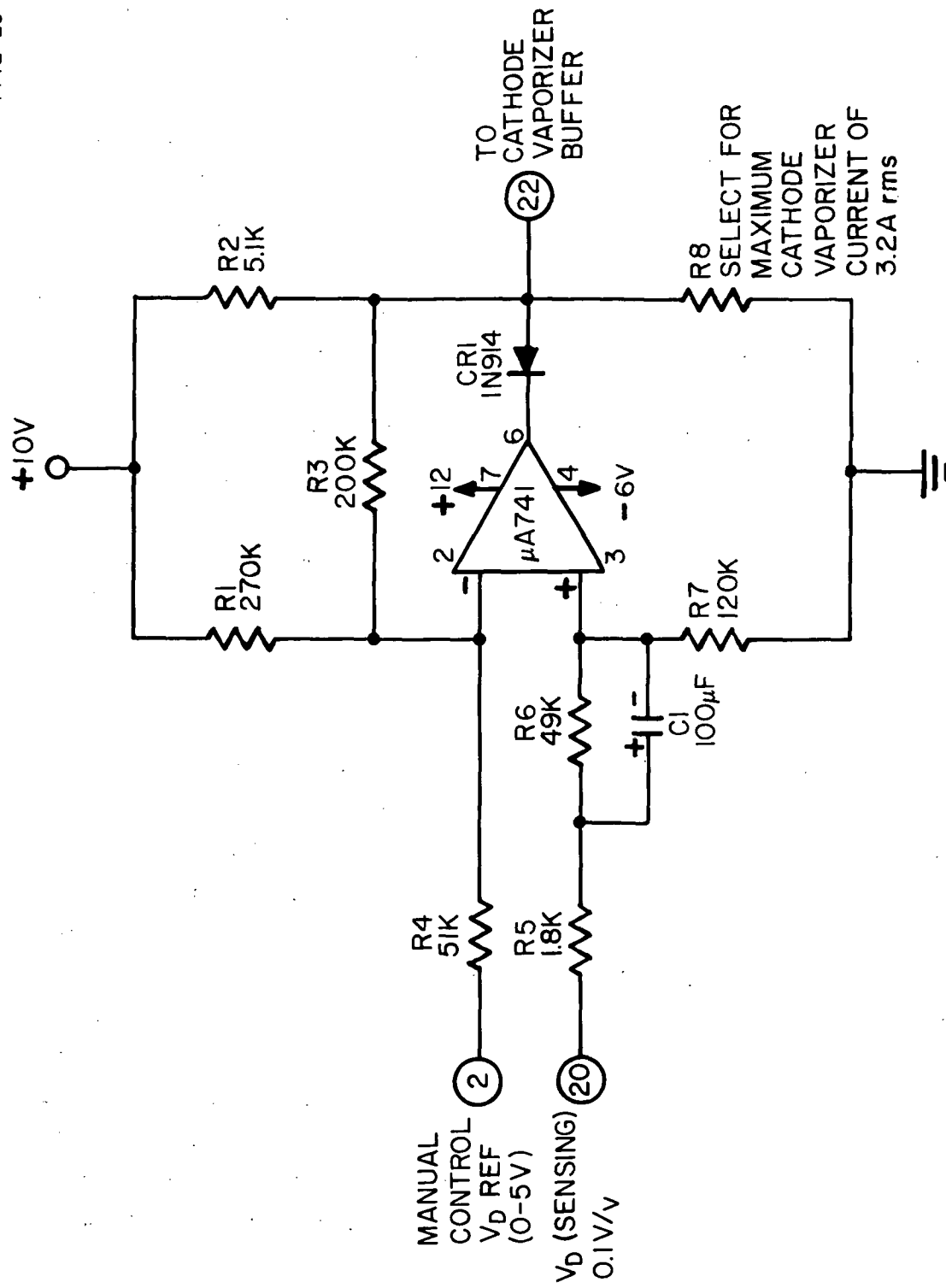


Fig. 54. Discharge Voltage Controller.

Figure 55 displays the closed loop block diagram, which indicates the relationship of the various units that contribute to the total configuration. The transfer characteristic indicating the open loop cathode vaporizer heater current as a function of discharge voltage is shown in Fig. 56.

An area which has had little in-depth investigation during this program is the open loop variation of discharge voltage V_D with varying cathode vaporizer current I_{KV} for fixed values of discharge current I_D . Those tests performed indicated that for a nominal operating V_D level of approximately 40 V, small signal $\Delta V_D / \Delta I_{KV}$ variations of 30 V/A to 50 V/A are typical over the throttling range of I_D values. From considerations of the known fixed gains of the remaining elements, a ΔV_D voltage variation of 1 V over the throttling range could be projected. During final throttle performance testing, an actual discharge voltage variation of 1.7 V was recorded. This represents a loop accuracy of approximately $\pm 2\%$ over the throttling range and is attributed to the accumulative factors of nonlinear cathode vaporizer power/neutral flow characteristics and of nonlinearities in the V_D sensing circuitry.

Neutralizer Controller - The principal function of the neutralizer is to provide a source of electrons neutralizing the ion beam. In space applications, if this function is not adequately accomplished, the spacecraft can change relative to the level space plasma and thrust will be affected. In a ground test configuration, where the thruster system common is allowed to float with respect to a beam current collector (or facility ground), an analogous measure of neutralization is the floating potential V_g .

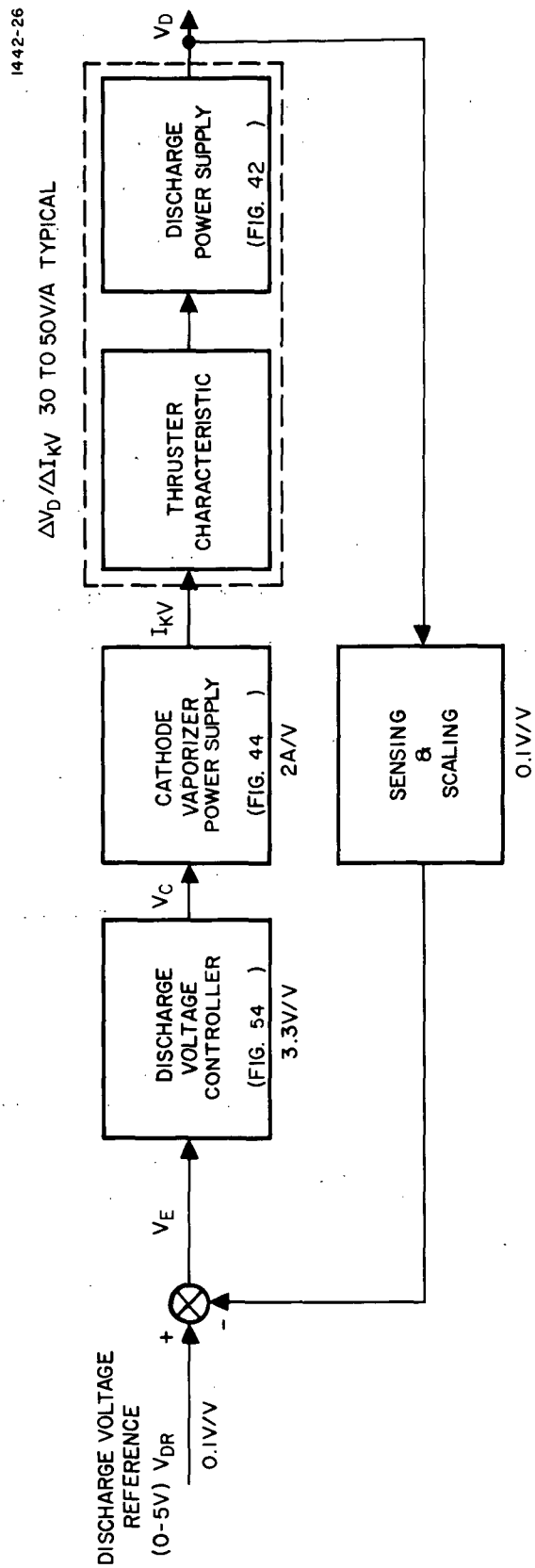


Fig. 55. Discharge Voltage Closed Loop Control Block Diagram.

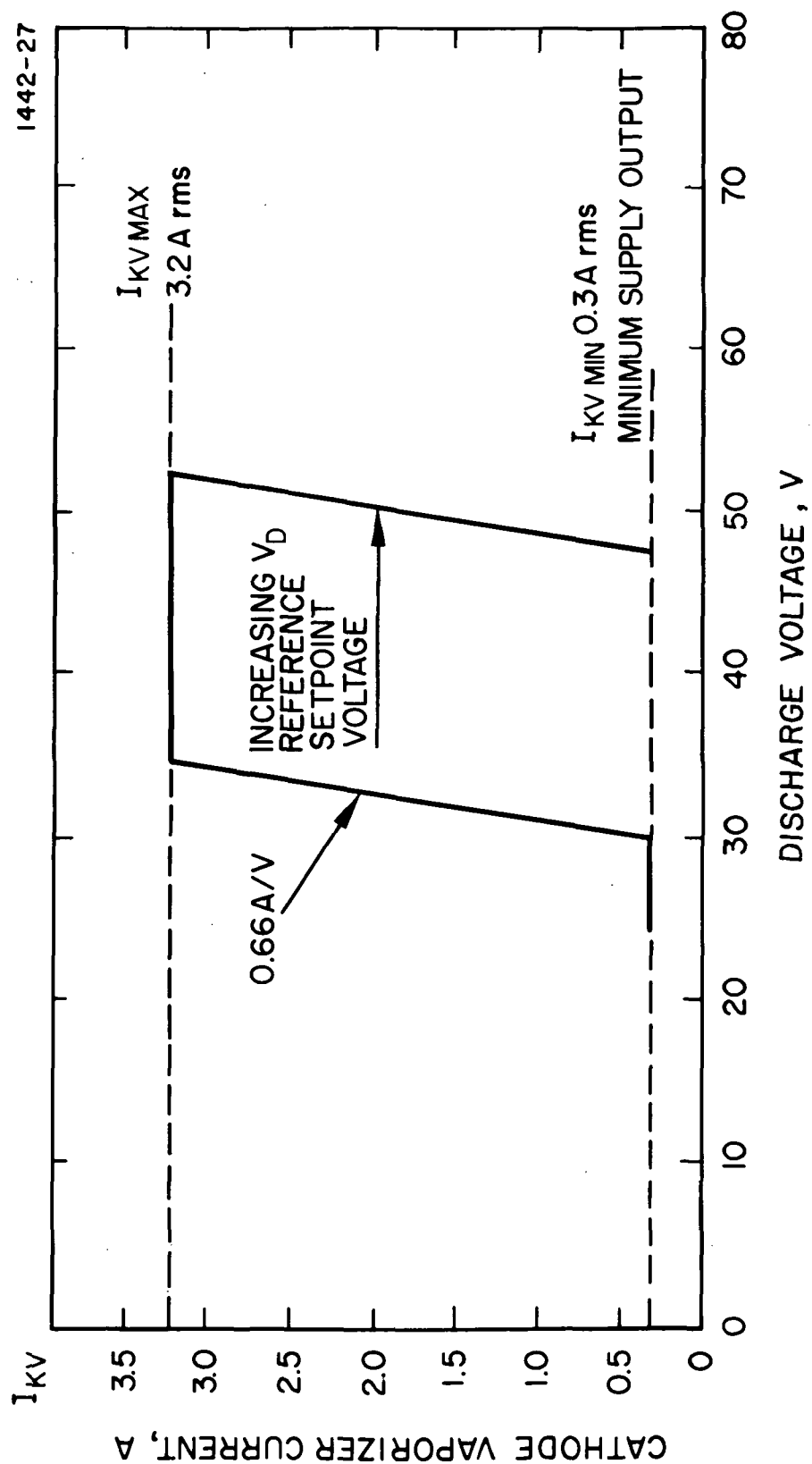


Fig. 56. Discharge Voltage-Cathode Vaporizer Transfer Characteristic.

While the neutralizer tip temperature and the keeper current and voltage must be preset, the active parameter in the neutralizer control loop is the neutral flow which is, in turn, a function of the neutralizer vaporizer heating power. Neutralization control becomes a problem of maintaining a neutral flow range, which assures stable efficient neutralizer operation at flow levels and does not adversely affect total propellant utilization. As previously discussed in Section II-C, it was initially difficult to achieve conditions of satisfactory stable neutralizer operation or to define an acceptable control criteria.

The neutralizer controller finally implemented requires a well defined relationship between neutralizer neutral flow $\dot{m}_N$ and neutralizer keeper voltage V_{NK} . The circuit configuration constructed shown in Fig. 57 can be easily reconfigured to operate on a parameter other than V_{NK} , if the parameter sensing is properly conditioned and scaled. The polarity of the controller wiring assures that V_{NK} will be held to its control panel setpoint value if there exists one or more flowrates allowing the value to be achieved. It is not necessary that the relationship between V_{NK} and $\dot{m}_N$ be single valued, only that all flowrates for which V_{NK} is less than or equal to the set V_{NK} lie in satisfactory range of system operation when judged on the basis of acceptable maximum propellant flow and maximum values of V_g .

Accelerator Voltage Throttling - Provisions have been included in the control system to vary the accelerator voltage automatically during single knob control beam current throttling. Figure 58 shows the transfer characteristic of accelerator supply voltage as a function of beam current. The characteristic is established with the accelerator voltage throttling circuit shown in Fig. 59, which automatically modifies the supply setpoint at the input to the buffer amplifier as a function of the beam current reference I_{BR} . Trimpot

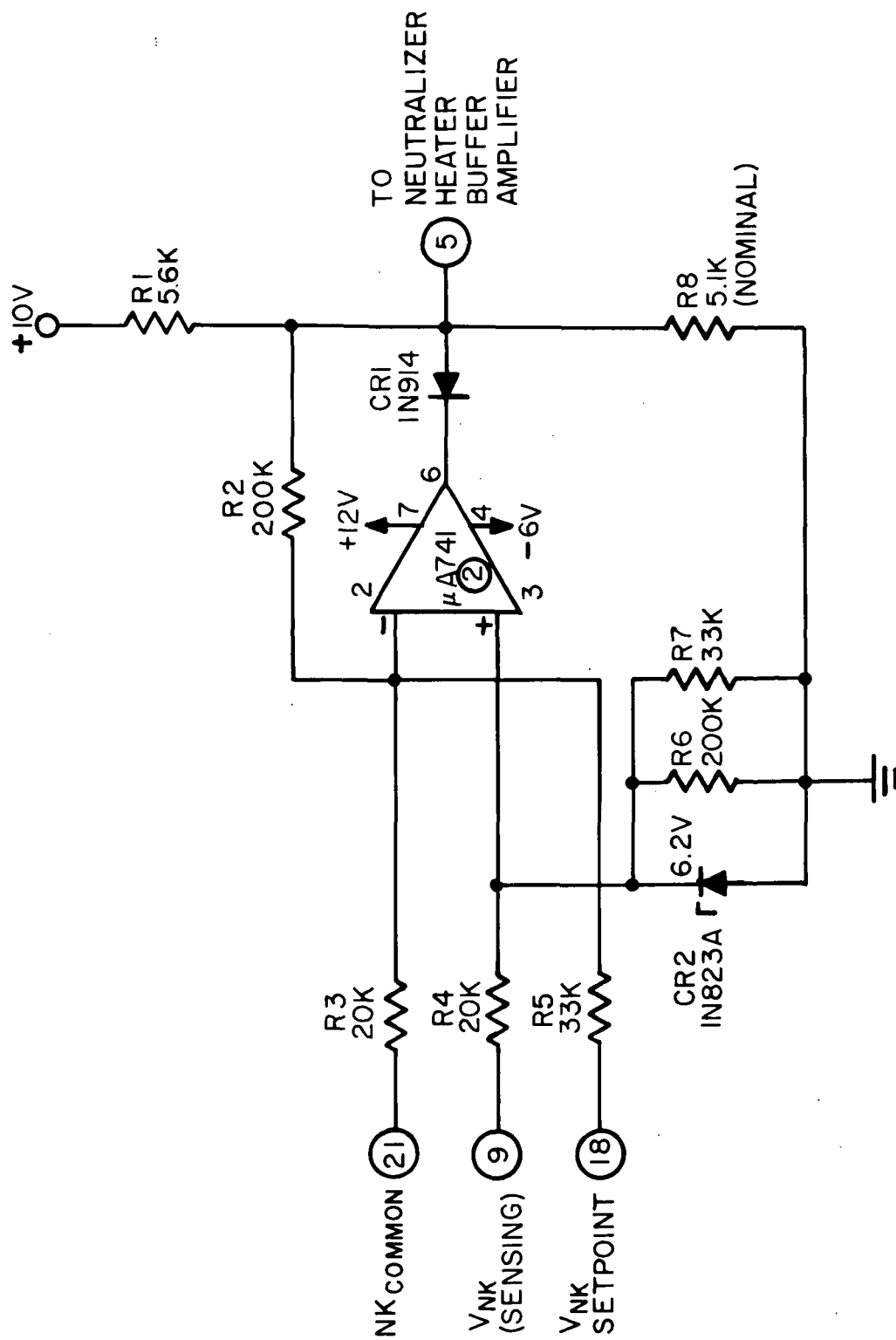


Fig. 57. Neutralizer Controller Circuit Configuration.

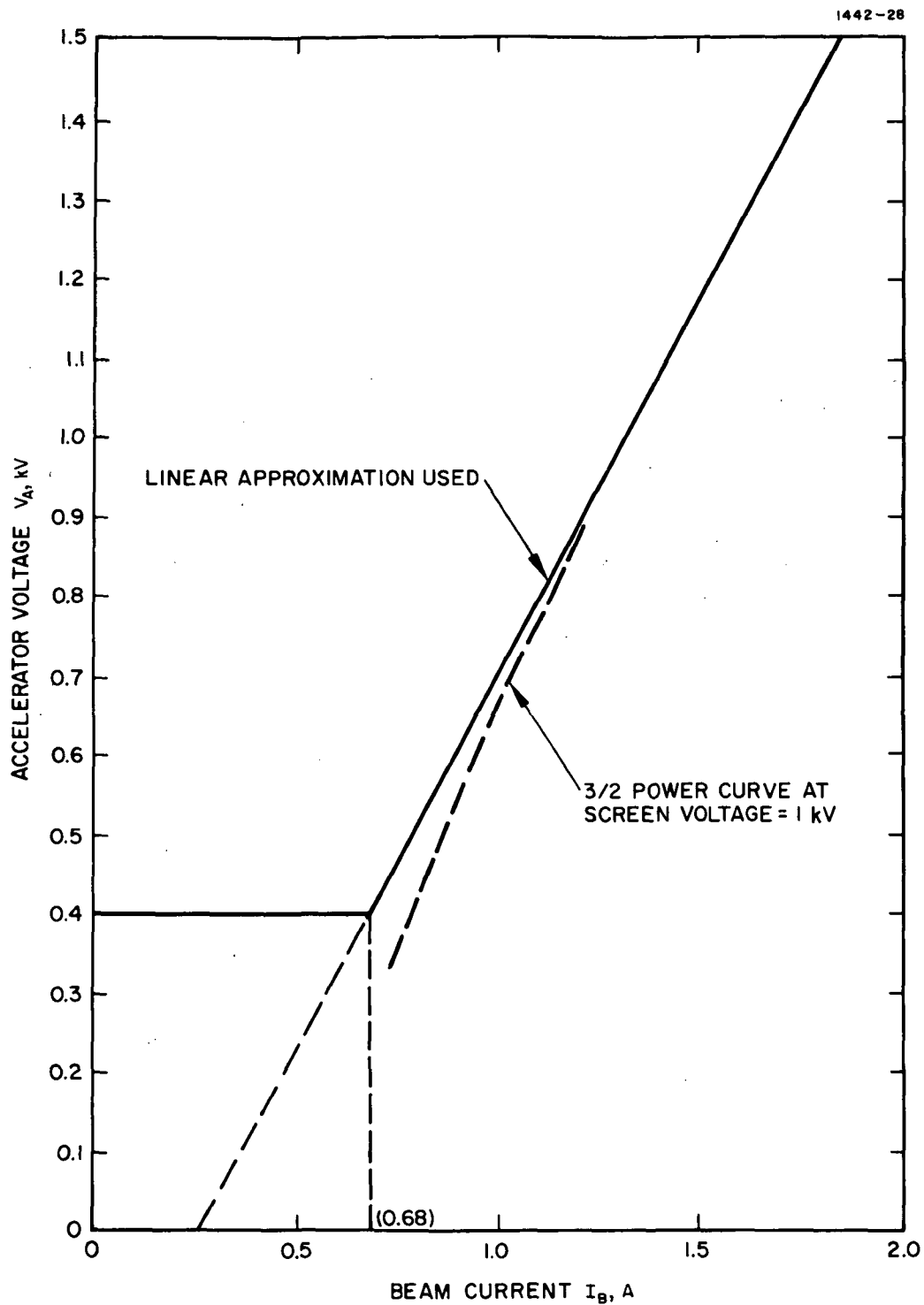


Fig. 58. Accelerator Voltage Throttling Characteristic.

Fig. 59. Accelerator Voltage Throttling Circuitry.

adjustments allow the minimum accelerator voltage level, the slope breakpoint, and the transfer gain to be independently adjusted.

The circuit, as adjusted, maintains a voltage of -400 V dc for I_{BR} value, corresponding to less than 0.68 A of beam current. Above 0.68 A produces a straight line approximation of the accelerator voltage requirement denoted by the thruster perveance, reaching -1500 V dc at a beam current level of 1.85 A for a fixed screen voltage of +1000 V dc.

Cathode Heater Power Throttling -- During thruster throttling, the thermal feedback from the discharge to the cathode can cause wide cathode temperature excursions if the cathode heater power is left at a setpoint level acceptable for low beam current operation. It is apparent that a decrease in fixed thruster losses can be achieved by reducing the cathode heater power input as power in the discharge is increased.

In the present system a very simple circuit approach is employed to accomplish cathode heater power throttling. The throttling transfer characteristic is shown in Fig. 60, and the circuit configuration used to implement the transfer characteristic is illustrated in Fig. 61. The input to the cathode throttling circuit is conditioned sensed discharge current scaled at 0.25 V/A. The output is routed to the cathode heater power supply via its buffer amplifier. The magnitude of R_3 establishes the maximum heater current at the lowest I_D value in the throttling range. R_2 determines the I_D level at which a power decrease is initiated, while R_1 allows selection of the rate of decrease.

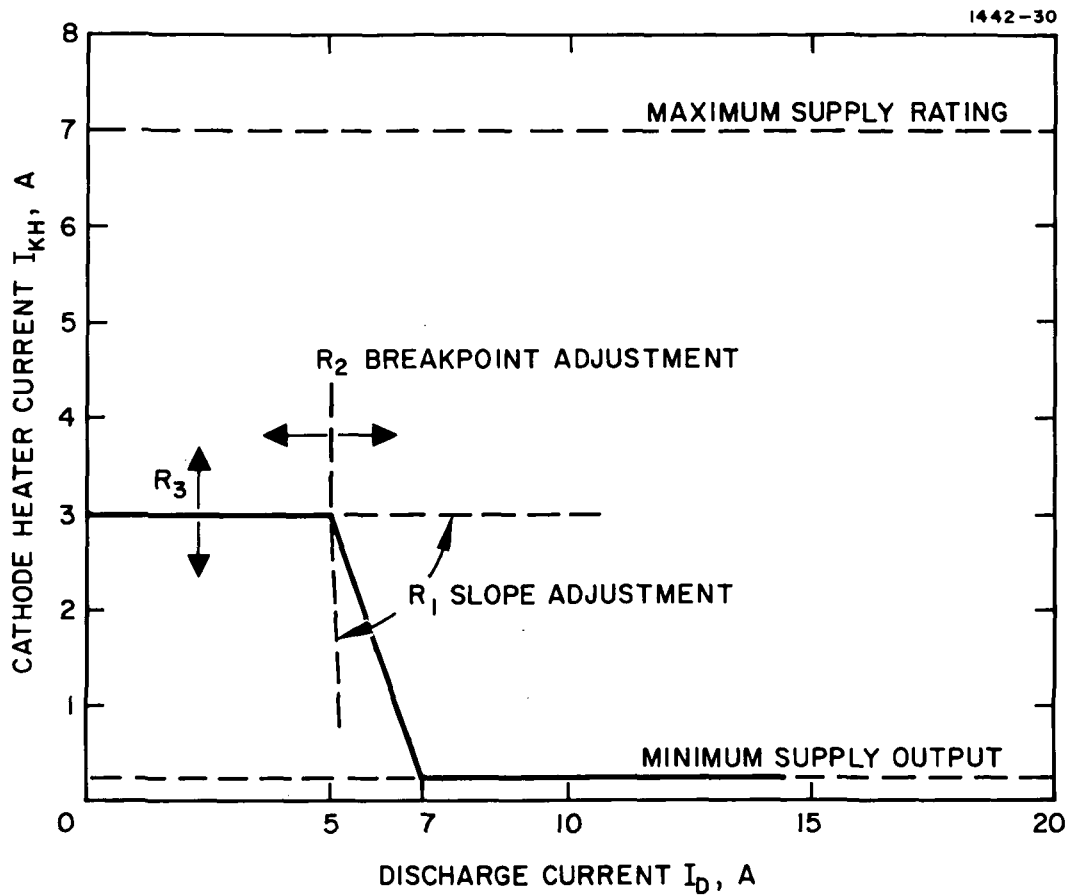


Fig. 60. Cathode Heater Throttling Transfer Characteristic (Shown for Adjustments used in Performance Testing).

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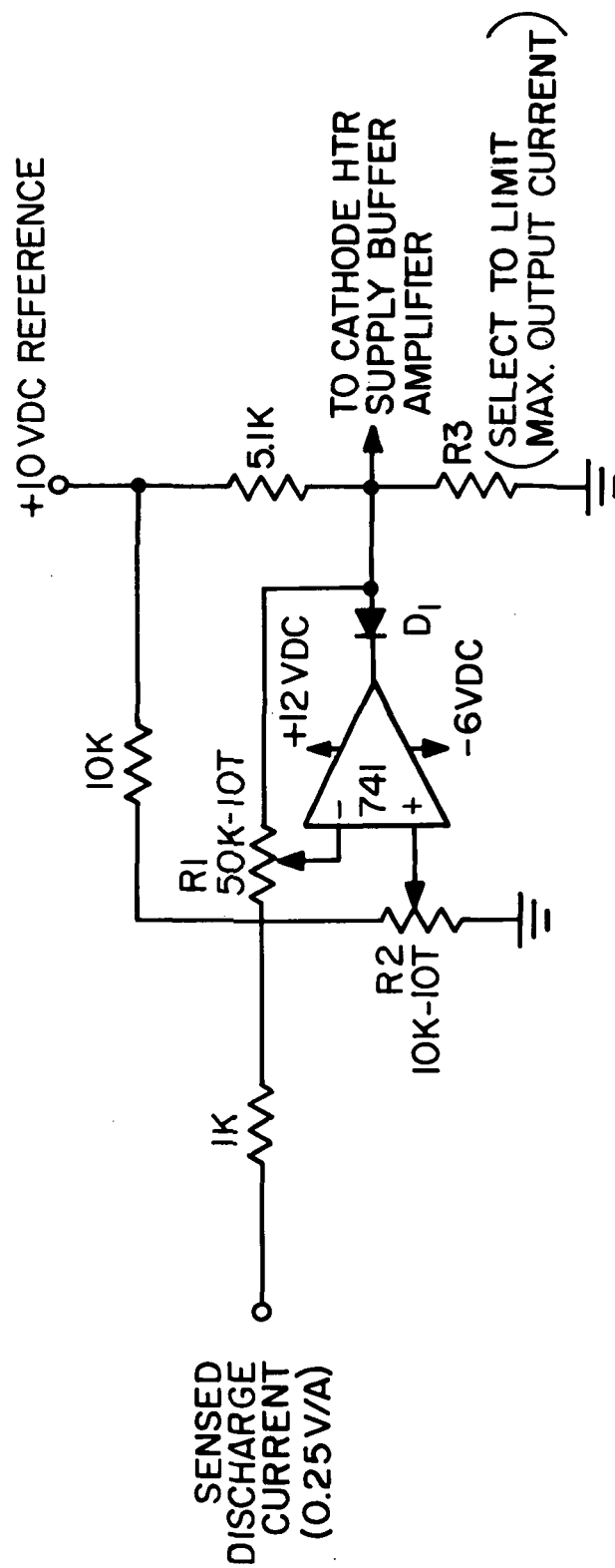


Fig. 61. Cathode Heater Throttling Circuitry.

Discharge Current Throttling - The mode of thruster discharge chamber operation chosen for throttling was to maintain discharge voltage constant (using the discharge voltage controller) and to vary the discharge current I_D as a function of beam current I_B . With the incorporation of the magnetic baffle, the functional relation deemed most satisfactory for thruster operation was determined to be linear, i.e., $I_D = KI_B$, K constant.

To implement the linear function, an adjustable gain amplifier was used to scale and convert the single beam current throttling reference I_{BR} to the desired magnitude to act as a variable discharge supply setpoint. For performance testing, the amplifier gain was adjusted to give an I_D/I_B ratio of 6:5.

Early difficulties encountered in maintaining the linear transfer characteristic over the full throttling range were determined to be due to nonlinear characteristics of the discharge power supply. The problem was overcome by reworking the mag-amp current sensing used in the feedback loop. The present maximum deviation from linear is better than $\pm 1\%$.

Control Mode and Scale Factor Summary - The specific control modes associated with each thruster voltage and current parameter are listed in Table XVIII, as a condensed reference to the way in which the thruster system is controlled during throttling. Table XIX presents a listing of the control and electrical parameter sensing scale factors germane to the power supply-control system interface.

Power Supply Spectral Measurements - Voltage and current frequency spectrum measurements of all dc power supplies in the power conditioning system were performed at two beam current levels, 1 and 1.85 A. Figure 62 shows block diagrams

TABLE XVIII
Thruster Parametric Control Modes

Parameter	Control Mode
Beam Voltage	Constant (manual setpoint)
Beam Current	Closed loop controlled with main vaporizer. Level established by variable setpoint from throttling circuitry.
Discharge Voltage	Closed loop controlled with cathode vaporizer (manual setpoint).
Discharge Current	Controlled in proportion to beam current. Level established by variable setpoint from throttling circuit.
Accelerator Voltage	Controlled in proportion to beam current over range of 0.68 to 2.0 A. Level established by variable setpoint from throttling circuit.
Accelerator Current	Limited by overload detection circuitry.
Cathode Keeper Voltage	Regulates to provide constant current.
Cathode Keeper Current	Constant (manual setpoint).
Cathode Vaporizer Current*	Closed loop controlled to maintain discharge voltage proportional to manual setpoint.
Main Vaporizer Current	Closed loop controlled to maintain beam current proportional to variable setpoint from throttling circuit.
Main Isolator Current*	Constant (manual setpoint).
Cathode Tip Heater Current*	Controlled in proportion to discharge current by variable setpoint from throttling circuit.
Neutralizer Tip and Vaporizer Heater	Closed loop controlled to maintain keeper voltage proportional to setpoint.
Neutralizer Keeper Voltage	Closed loop controlled with neutralizer tip and vaporizer heater current (manual setpoint).
Neutralizer Keeper Current	Resultant of keeper supply level adjustment.
Magnetic Baffle Coil	Carries discharge current.
*Internally current-regulated power supplies.	

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TABLE XIX
Control and Electrical Parameter Sensing
Scale Factors

Power Supply	Control Scaling (output/control voltage)	Sensed Parameter Scaling (sensed voltage/ output)
Screen	200 V/V	2.4 V/A
Accelerator	300 V/V	18 V/A
Discharge	3 A/V	0.1 V/V
Main Vaporizer	2.0 A/V	*
Cathode Vaporizer	2.0 A/V	*
Neutralizer Heater	0.6 A/V	*
Cathode Heater	0.6 A/V	*
Main Isolator	0.6 A/V	*
Neutralizer Keeper	**	0.25 V/V
Cathode Keeper	**	*
*Sensed supply TLM not a factor in closed loop or sequential control. **Supply does not participate in closed loop control or throttling.		

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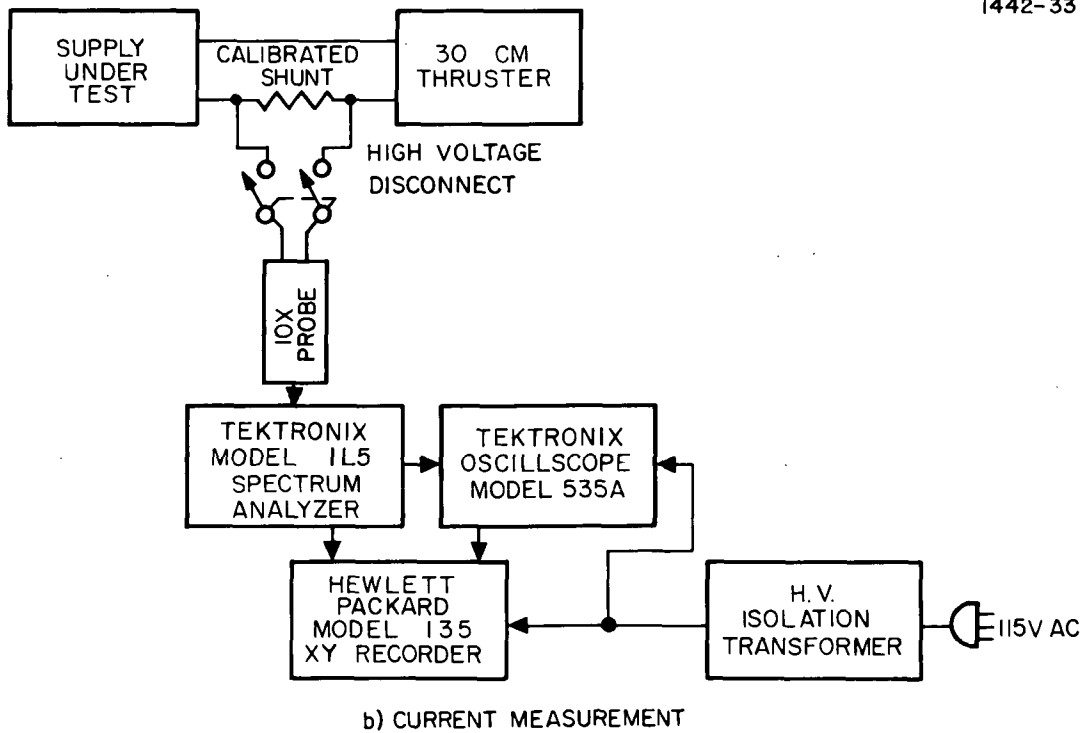
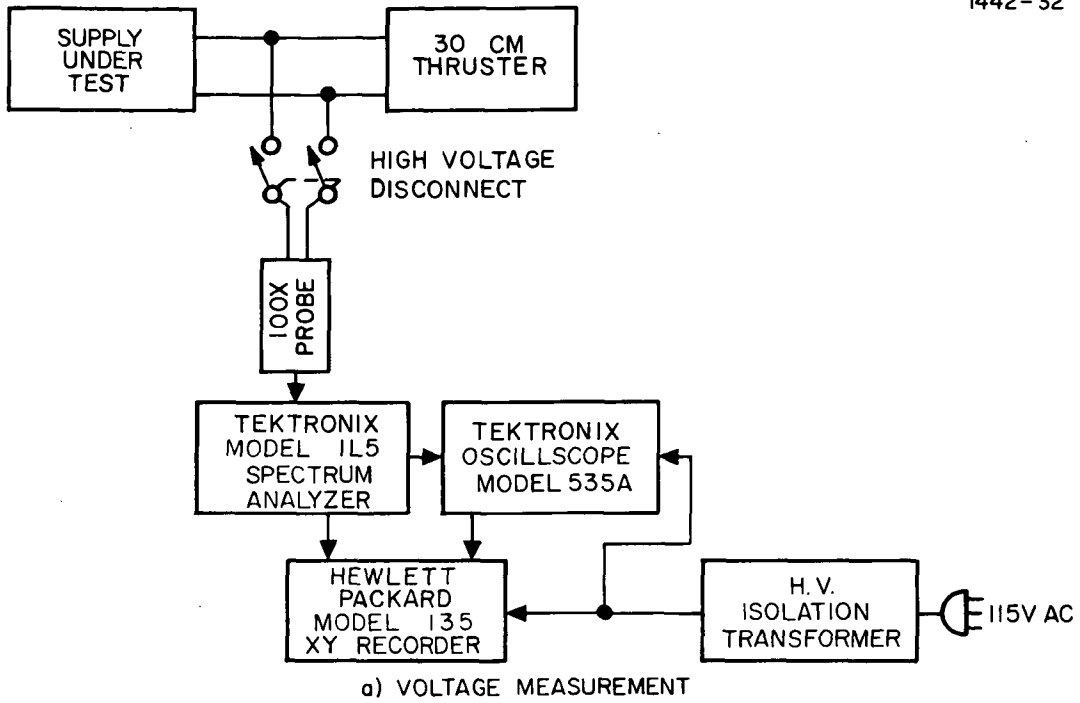


Fig. 62. Test Setups.

of the test setups and identifies the instrumentation employed. Measurements were taken near the vacuum chamber bulkhead where the leads from the power conditioning terminate prior to entering the chamber. In total, more than 200 recordings were made of the voltage and current spectrum for the screen, accelerator, discharge, cathode keeper, and neutralizer keeper supplies at the two thruster operating levels. Copies of these recordings were submitted to LeRC at an interim point in the program.

In general, the spectral characteristics display the various power supply frequencies and a very large number of harmonics, rather than any inherent frequencies that can be associated with the plasma processes of the thrusters. To a first order, the spectrum was not changed significantly by the beam current operating level. In addition, the beam supply and discharge supply have essentially the same spectra when loaded by a load simulator as during thruster operation. The characteristics of the neutralizer keeper supply spectra however, were considerably different.

Representative spectral recordings for the screen and neutralizer keeper supplies are presented in Figs. 63 through 65. These traces have been grouped to allow some comparisons to be made of voltage and current characteristics and characteristics at different operating levels. The recordings have been aligned in the frequency axis to remove the typical $\pm 5\%$ instrumentation center frequency drift encountered during testing. The apparent 5 kHz fundamental in the 60 Hz neutralizer keeper power supply (120 Hz ripple) is as yet unexplained, but may be due to the 5 kHz pulsewidth modulated neutralizer heater power.

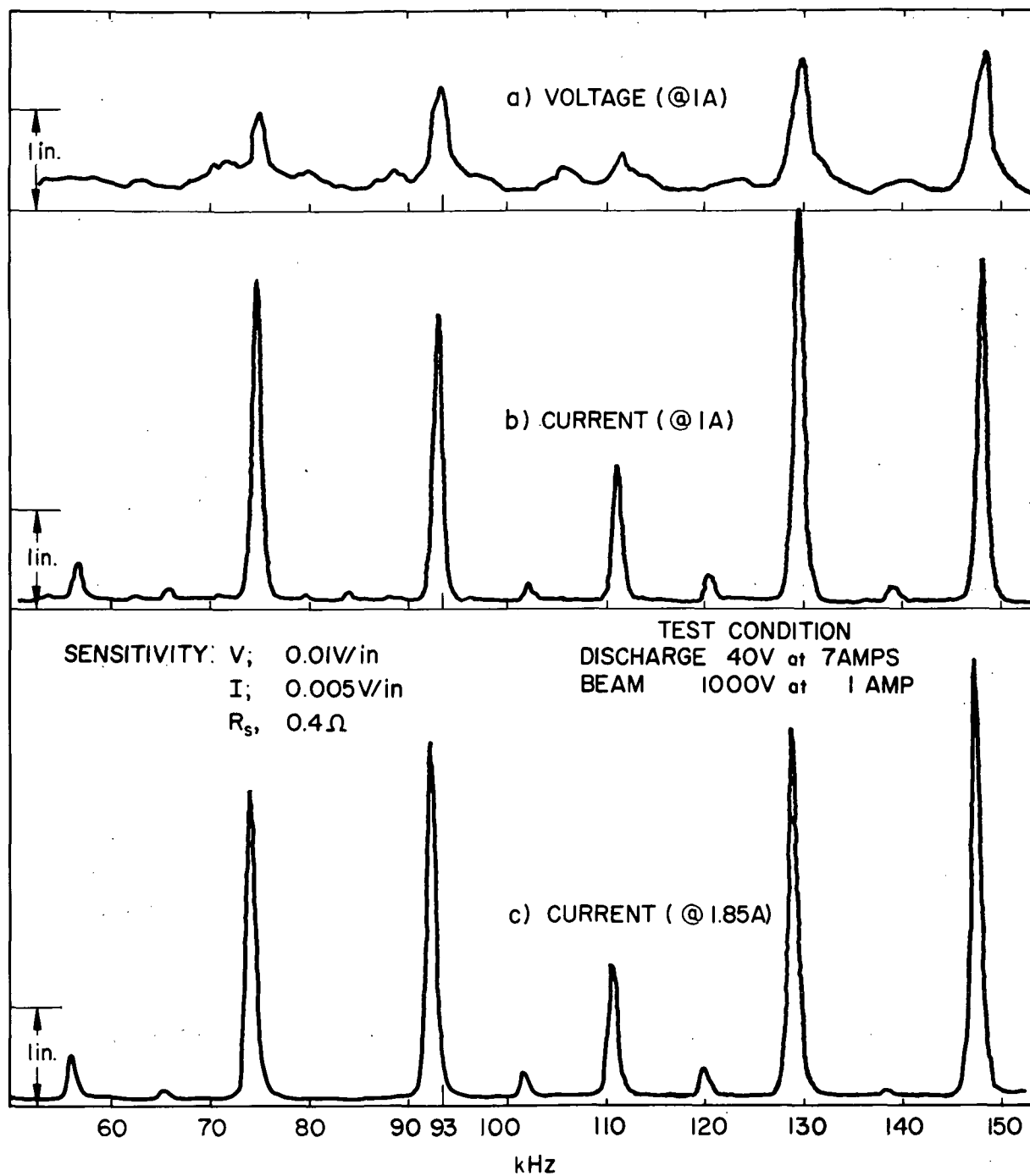


Fig. 63. Screen Power Supply Spectra.

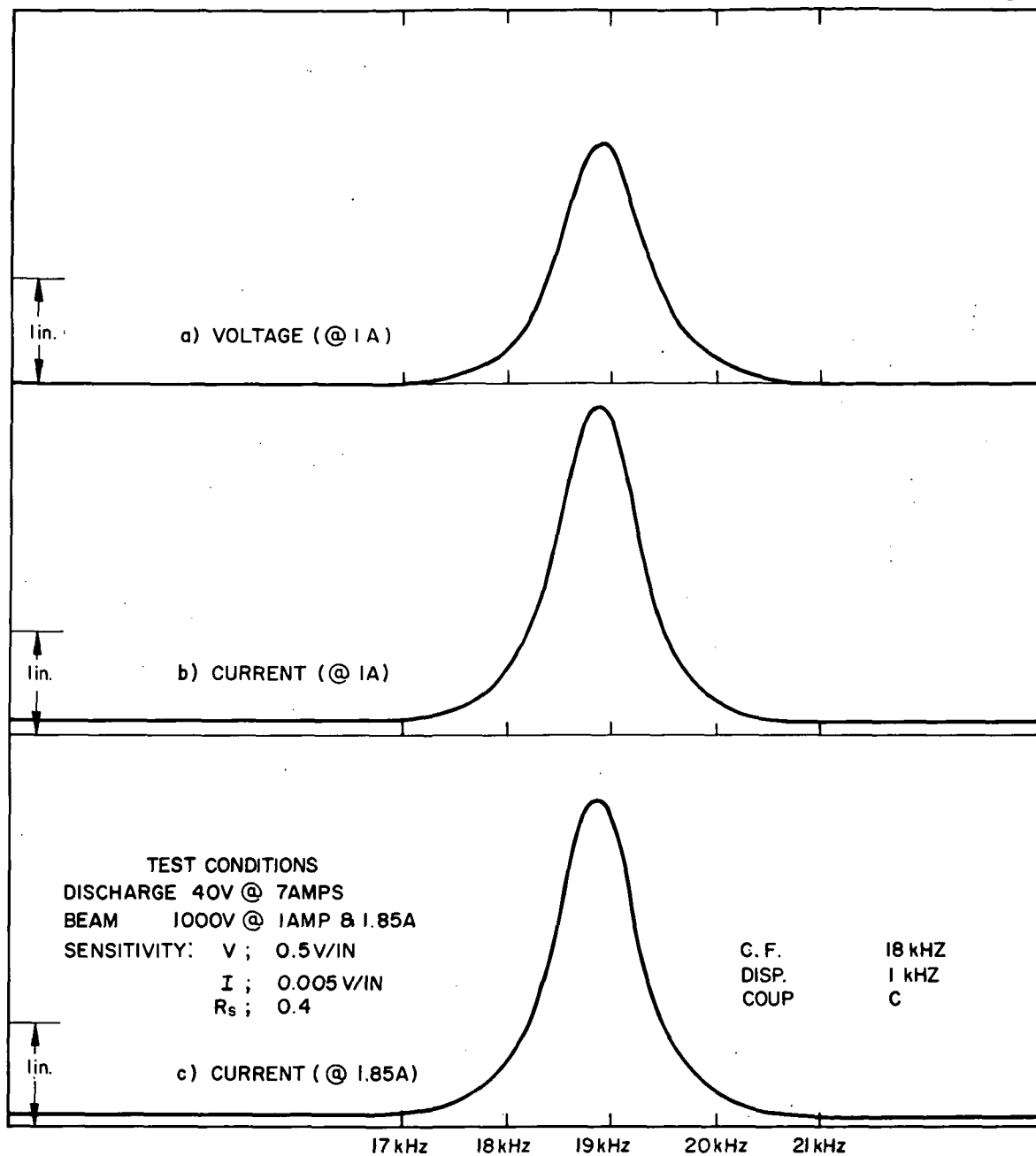


Fig. 64. Screen Power Supply Spectra.

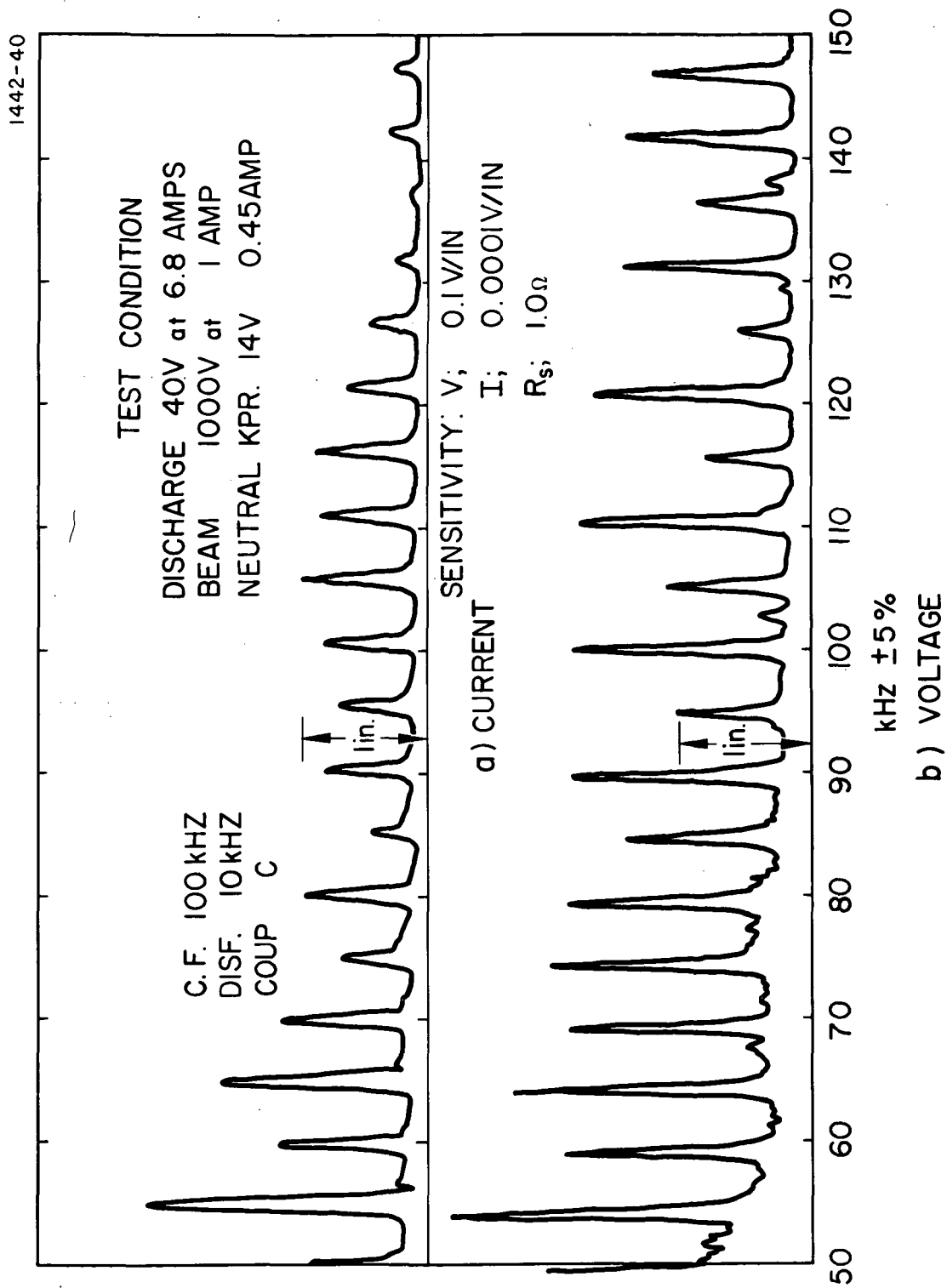


Fig. 65. Neutralizer Keeper Power Supply Spectra.

d. System Integration with Thruster

When the control system is placed in automatic single knob control, the propulsion system, composed of the thruster, power conditioning, and control system, is capable of being throttled over a wide dynamic operating range. In addition, the HV overload detection and recycle circuitry provides the system with the capability to automatically recover from arc overloads to any preset level in the range.

The circuitry that accomplishes the sequential and set-point control has been discussed in previous sections in terms of circuit configurations, loop gains, and various transfer characteristic. However, one of the better ways of giving a physical feel for the dynamic behavior of the system while being throttled is to observe recorded traces of various thruster voltage and current parameters as the single throttling reference command is adjusted to discrete levels in the throttling range.

The response of the system to changes in the throttling references is shown in the excerpt from the multichannel recorder that is presented in Fig. 66. These data, which were recorded during the 50 hour throttling demonstration test, show a series of throttling steps from a beam current of 0.65 up to 1.85 A and back down to 0.36 A. As shown by the recording, the stability of the discharge voltage over this wide beam current variation was very good.

The transient and interrelated behavior of the various parameters is very evident from the traces. Of particular interest are the differences in the system response, depending on whether it is throttled up or down.

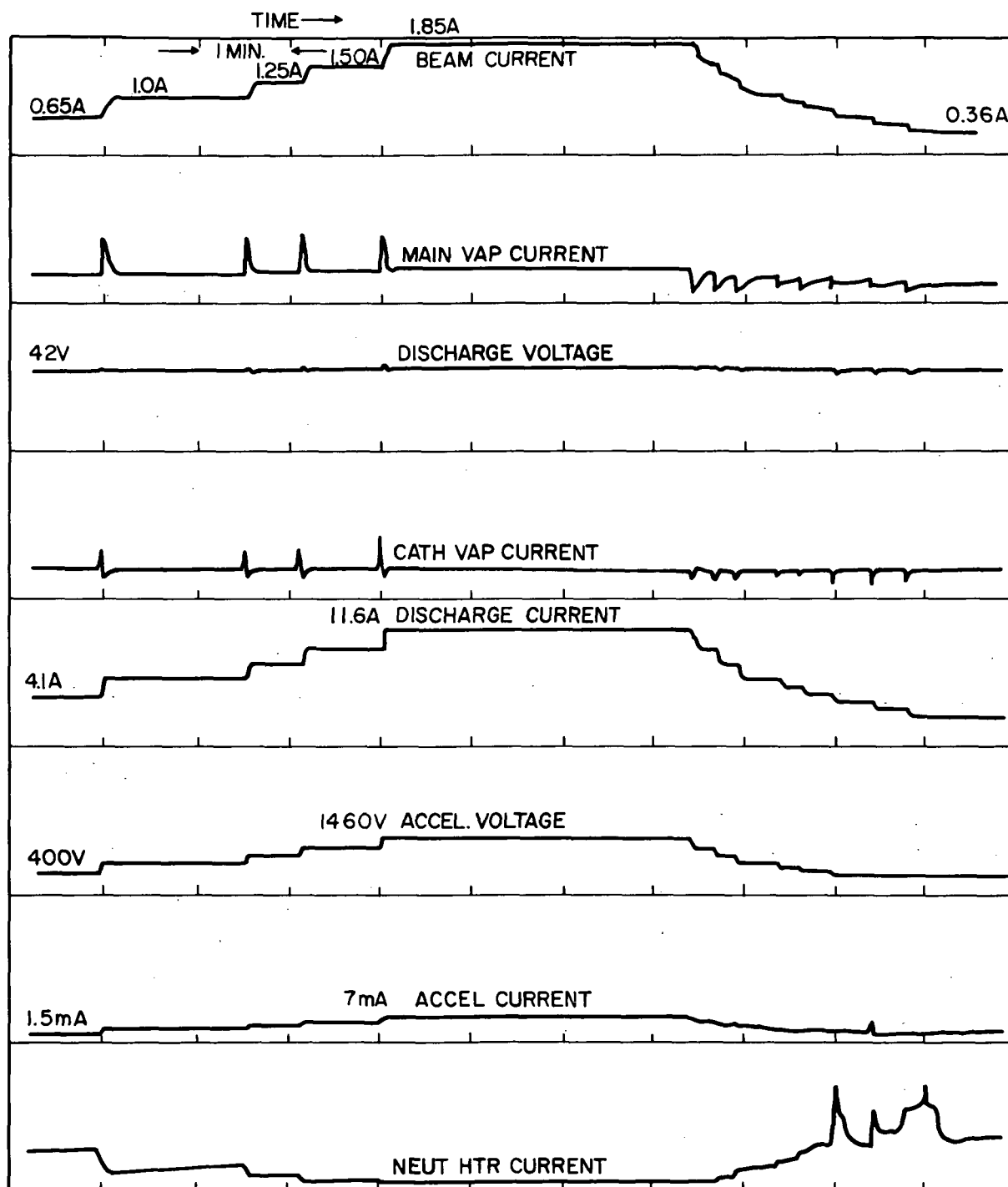


Fig. 66. Recorder Chart from Throttling Test.
 $V_{\text{Beam}} = 1000 \text{ V.}$

The beam current and main vaporizer current traces show the action of the beam current controller. When throttling up, the beam current rises sharply to a steady state level in response to a throttling reference step, since the main vaporizer power supply can quickly drive the vaporizer temperature upward. When throttling down the main vaporizer current undershoots, but acquisition of the new steady state level is impacted by the relatively slow thermal time constant of the vaporizer.

As the discharge current setpoint is automatically stepped with the throttling reference, perturbations in discharge voltage appear. When this occurs, note that the control system responds, as a result of the discharge voltage controller action, by applying more or less cathode vaporizer current depending on throttling direction.

The accel voltage trace corresponds to the throttling transfer characteristic controlling its setpoint as a function of the throttling reference magnitude. The number of voltage steps during throttling is seen to be less than the number of reference steps since the accel voltage is fixed at -400 V dc for beam currents less than 0.68 A. The accel current obtained a maximum value of 7 mA at a beam current level of 1.85 A.

The neutralizer heater current (used in this configuration to control neutralizer flowrate as a function of neutralizer keeper voltage) had wide excursions as the beam current level was changed. The extreme variations during the throttle down are attributed to the early neutralizer configuration which transitioned between the plume and spot modes. At beam current levels above approximately 1.25 A, the neutralizer cathode self-heated to the extent that the neutralizer controller was driven to its off state (minimum heater current of approximately 0.3 A), and the vaporizer continued

to heat above the required temperature causing the neutralizer keeper voltage to fall below its setpoint level.

With the exception of the neutralizer, system behavior over the contract specified beam current range of 0.37 A to 1.85 (5:1 throttling) was as expected and stable. Operation over an expanded 12:1 range (0.17 to 2.0 A) produced no control problem except for a slight sloppiness in the beam current and discharge voltage controllers at the extreme low end of the beam current range where small signal vaporizer flow/power gains fall off. Throughout the throttling range, recovery to new steady state levels of operation was extremely smooth, well defined, and fast, following each step in the throttling reference. This same control system has been successfully used during recent neutralizer tests at high keeper currents, as described in Section II-C.

SECTION III

SYSTEM INTEGRATION AND PERFORMANCE TESTING

The initial GFE thruster was equipped with a single insulated electrode system and was operated with conventional 60 cycle power supplies. The final, deliverable hardware included a high perveance, dual grid electrode system, magnetic baffle, and was operated with flight-type, high frequency power conditioning with closed loop single knob controls. This section of the report describes the major tests and system integration procedures used to implement these modifications.

A. ION OPTICAL SYSTEM ENDURANCE TEST

The 450 hour test, conducted at the end of Task 0, was designed to verify the endurance of the ion optical system that was chosen for use during the remainder of the program. The test was conducted on a 24 hour a day basis, using the 3 m diameter high vacuum facility and the same conventional power conditioning system used for the previous contract.

The propellant flowrate was monitored by measuring the volumetric flow to each of the three vaporizers every hour using glass pipettes. The total weight of mercury consumed during the test was measured and compared to the short term flowrates. Cathode and neutralizer vaporizer temperatures were stabilized by proportioning thermocouple controllers. The main vaporizer heater was controlled by a circuit which adjusted the neutral mercury flow to maintain a fixed beam current. Safety circuitry was provided to shut off the discharge supply in the event of continued excessive accelerator drain current.

The 30 cm thruster, as GFE under the terms of the contract, was used for the test. As a result of earlier experience with a conventional dual grid system, the thruster (which had been designed for a single insulated grid) was modified by the addition of a support ring to stabilize the mounting plane of the electrodes. The electrodes were spaced to 0.21 ± 0.02 cm at the periphery and then pulled together by the center support to a face-to-face spacing of 0.05 ± 0.01 cm, thus placing the center support under tension and dishing the electrodes toward each other.

The screen electrode was 0.045 cm thick and the accelerator 0.125 cm. Both were matched drilled from arc cast molybdenum. The screen apertures were 0.230 cm diameter and those in the accelerator 0.175 cm. The screen electrode had been used previously in earlier tests, but the accelerator was new, thus providing a uniform, undamaged surface from which to measure any erosion which might occur during the test. As discussed previously, a series of thin tantalum strips were spot welded to the accelerator shield ring to aid in quantitative measurement of any sputtering that might occur on the accelerator adjacent to the neutralizer. A 0.075 cm diameter wire was spot welded between the apertures on the accelerator in the same vicinity to further this same purpose.

The neutralizer position was modified prior to the start of the test to make an angle of 30° with respect to the beam axis. It was located 3.8 cm downstream of the accelerator electrode and 2.5 cm outside the peripheral row of beam apertures. The neutralizer performance was discussed in Section II-C.

The test was run in two segments due to a failure of the main cathode heater which ultimately caused the discharge to extinguish after 427 hours of test time. The thruster was removed from the facility, the heater repaired, and the test continued to complete the 450 hours. While the thruster

was out of the chamber, all loose sputtered material was removed from the thruster with a vacuum cleaner without disassembly of the grids. The only other test interruption was caused by a brief power failure which necessitated a restart at 176 hours after an off period of approximately 5 min.

While the beam current was stabilized with a closed loop to the main vaporizer, other test parameters varied slightly during the test. Table XX lists the nominal operating parameters and their operating bands during the test.

B. SYSTEM INTEGRATION - Task I

The initial integration of thruster, power conditioner and control system occurred near the conclusion of Task I. The two primary goals associated with this task were to define a thruster design and operating procedure that would maximize the thruster efficiency over a 5:1 throttling range and to define control circuits that would hold the thruster to the desired operating parameters over this throttling range. The original work plan for this task defined a procedure under which no closed loop control was to be used. A series of electrical parameters were to be measured at each of a number of fixed propellant flow conditions. This plan was found to be impractical because of drift in the neutral flow-rates as the electrical (and hence thermal) characteristics were varied. After several unsuccessful attempts at this method of operation, it was apparent that some type of closed loop vaporizer control was necessary to stabilize thruster operation. Since the prototype control circuitry was nearing completion, it was possible to revise the test procedure and fix some of the electrical parameters by means of the control system and to measure flows in a manner similar to that which would be actually used in a final system.

TABLE XX
Test Operating Bands and Parameters

Operating Conditions		Power, W
Tank Pressure, Torr	$(1.0 \pm 0.2) \times 10^{-6}$	1870.0
Beam Current	1.87 A	
Beam Voltage	1.0 kV	
Accelerator Current	9 ± 1 mA	23.0
Accelerator Voltage	-1.5 kV	
Discharge Current	11.2 ± 0.7 A	470.0
Discharge Voltage	42.0 ± 1 V	
Cathode and Isolator Heater Power		35.0
Cathode Keeper Voltage	10 V	2.5
Cathode Keeper Current	250 mA	
Neutralizer Tip Heater Power		12.0
Neutralizer Keeper Voltage	15 ± 5 V	4.5
Neutralizer Keeper Current	300 ± 50 mA	
Floating Potential	20 ± 4 V	37.0
Main Vaporizer Power		10.0
Main Vaporizer Temperature	$283 \pm 2^{\circ}\text{C}$	
Cathode Vaporizer Power		4.0
Cathode Vaporizer Temperature	$251 \pm 2^{\circ}\text{C}$	
Neutralizer Vaporizer Power		2.0
Neutralizer Vaporizer Temperature	$200 \pm 5^{\circ}\text{C}$	
Main Neutral Flowrate	1.930 ± 0.050 A	
Cathode Neutral Flowrate	0.080 ± 0.003 A	
Neutralizer Neutral Flowrate	0.090 ± 0.005 A	
Total Neutral Flowrate	2.10 ± 0.05 A	
Specific power in Discharge, eV/ion		252
Total eV/ion		320
Mass Utilization in Discharge, %		93
Mass Utilization Total, %		89.5
Power Efficiency, %		76
Total Efficiency, %		68

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Specifically, the main vaporizer flow was directly controlled to hold the beam current constant and the discharge voltage held to a preselected value by controlling the cathode flow. The discharge current was preset and held constant by the constant current discharge supply.

The first loop to be closed was the main vaporizer-beam current control function. This improved the thruster stability dramatically, so that it was possible to obtain performance data over a beam current range from 0.6 to 1.5 A as a function of I_I/I_B and discharge voltage.

The above performance mapping was done with a fixed baffle (6.2 cm diameter located 0.38 cm downstream of the pole tip). With this baffle the discharge tended to become either unstable or very inefficient for cathode flow rates outside a range of 100 to 200 mA. In addition, the discharge tended to extinguish when the extraction voltages were re-applied after an arc-out, and discharge reignition required a cathode neutral flow of the order of 500 mA (with 60 V discharge voltage applied). Because of the "hard restarting" condition and the other considerations discussed in Section II-B, a magnetic baffle (5.4 cm diameter 0.076 cm thick) was installed and evaluated. The magnetic baffle was operated, by passing the discharge current through the baffle control coil. Data points were obtained for 1, 2, and 3 turns in the control coil. Data points were held for a period of approximately one hour, using both the main and cathode vaporizer control loops. Propellant reservoir readings were recorded at 10 min intervals to obtain flow data. Within the experimental accuracy of these measurements, there was no significant difference in the performance (from an efficiency standpoint) between 1, 2, and 3 turns in the magnetic baffle control coil. From the standpoint of stability of operation, the cathode propellant flowrate and its permissible

range of variation with discharge voltage was a prime consideration. Figure 11 showed that on the basis of cathode propellant flow, 2 turns was most suitable. With 2 turns in the magnetic baffle control coil, the cathode propellant flow remained within 100 to 160 mA equivalent flowrate range over the throttling range and provided sufficient variation with discharge voltage to present satisfactory control characteristics (minimum variation of 15 mA for 38 to 42 V discharge voltage variation). The thruster system and control loops operated very stably and permitted throttling over the desired range.

C. DESIGN VERIFICATION TESTS - TASK V

Task V integrated the thruster, power conditioning, and control systems that had resulted from the performance optimization and design studies described in the preceding sections of this report. In order to assure the best possible performance for the resulting system the following steps were taken:

1. Preliminary system integration was performed to assure a functional system and optimize system performance over the desired operating range.
2. A 50 hour design verification test was conducted to document the performance of the system and demonstrate the thrust throttling capability when operated from a single control signal.
3. Extensive performance mapping was conducted to quantitatively define the system performance as a function of input power and specific impulse.

Significant features of this test thruster were:

- 30 cm dual grid optics system consisting of a 61% open area screen grid with 0.208 cm apertures and accelerator grid with 0.193 cm apertures in a hexagonal array with 0.254 cm center-to-center spacing. The electrodes were spaced 0.051 cm apart at the center
- A hollow cathode with a 0.076 cm orifice
- A variable magnetic field baffle
- A hollow cathode neutralizer with a 0.038 cm orifice mounted 9 cm downstream of the accelerator grid and 9 cm outboard of the peripheral apertures of the accelerator grid
- Electrical isolators in the feedlines downstream of the main and cathode vaporizers.

The feed system used during Task V was a laboratory-type glass pipette system. The mercury for each of the three vaporizers, main cathode, and neutralizer, was stored in a separate graduated glass pipette mounted on the bulkhead external to the vacuum chamber. The mercury was gravity fed to the vaporizers. Mercury flowrates were obtained by periodically (nominally every 10 min) reading the level of the mercury in the pipettes.

The thruster control system used during this test was that discussed previously and shown in Fig. 45. This control system was used to control a 250 V line, high frequency, flight-type power conditioner. Switches on the front panel of the controller permitted the selection of control options varying from manual control of each power supply to single knob throttling. In the single knob throttling mode the discharge current, accel voltage, cathode tip heater, and main vaporizer current are all varied when a change in beam

current is commanded. The control mode for each thruster operating parameters was listed in Table XVIII. In addition to the operating level control functions the control system contains sensing and sequencing circuitry which detects high voltage overloads, initiates shutdown of the high voltage supplies and cutback holding control of various supplies and control loops, and provides automatic recycling to reestablish system operation at the pre-overload level. Table XXI sequentially describes the startup procedure used during these tests.

The vacuum test facility used for all Task V testing was the same chamber used for all previous testing under this program. The chamber is 3 m in diameter and 6 m long. This chamber has a LN_2 cooled cryowall and a 2.4 m diameter water cooled stainless steel collector mounted approximately 4.3 m from the thruster. The background pressure in the vicinity of the thruster was typically 1 to 2×10^{-6} Torr. Two flat disk probes were used for taking beam profiles. One probe was mounted so that it sampled the beam approximately 2.5 cm downstream of the accel electrode. The other probe crossed the beam approximately 2.1 m from the thruster.

The operating parameters that are used to calculate thruster performance (i.e., V_S , J_S , V_I , J_I) were measured on direct sensing meters, which are periodically calibrated by the Hughes Calibration Laboratory. All other power conditioner parameters were obtained from meters mounted on the power conditioner console that monitors the telemetry outputs of the various supplies. Continuous monitoring of performance data was provided by a multichannel strip chart recorder on which was recorded beam current, beam voltage, accel current, accel voltage, discharge current, discharge voltage, main vaporizer heater current, and cathode vaporizer heater current.

TABLE XXI
Startup Procedure

1. Measure main isolator and cathode isolator leakage.
2. Apply main isolator heater power.
3. Apply cathode heater power (heats cathode tip and cathode isolator).
4. Apply neutralizer tip heater power.
5. When main and cathode isolator temperatures are greater than 150°C, measure isolator leakage current.
6. Apply main vaporizer, cathode vaporizer, and neutralizer vaporizer heater power.
7. Apply cathode keeper and neutralizer keeper voltages.
8. When cathode keeper and neutralizer keeper have lit, apply discharge voltage.
9. When discharge is lit, start filling of cryowall.
10. When cryowall is full and pressure is less than 1×10^{-6} , set all parameters to run condition and apply screen and accel voltages to extract beam.

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Testing under Task V was conducted in three phases:
(1) integration of the Task III thruster, flight-type power conditioner, and the control system that was developed under Task IV, (2) a 50 hour design verification test to demonstrate the throttling capability, and (3) steady state performance mapping tests.

As a result of these integration tests, several changes were made in the thruster - namely the number of turns on the magnetic baffle was increased from two to three, the baffle diameter was increased from 5.40 cm to 5.62 cm, and additional heat sinking was added to the neutralizer to improve control characteristics. The cathode neutral flowrate measured for 40 V discharge chamber operation after the above changes was shown in Fig. 11.

During the integration test phase, several minor electrical modifications and adjustments were made to the power conditioning and control system in preparation for the 50 hour throttling demonstration test. These resulted in improved electrical sensor linearity and offset adjustments and gain to align the tracking of the power supplies and control loop setpoints in the single knob throttling mode.

The second test phase under Task V was a 50 hour throttling demonstration test. During this test, the thruster was operated in the single knob control mode over a beam current range of 0.17 to 2.0 A (12:1 throttling). The test plan followed was to throttle up from 0.35 A to 1.85 A in a series of five steps. The thruster was operated at each of the six beam current levels for three hours to obtain flow data for efficiency calculations. It was then throttled back down to 0.35 A over the same steps in a period of one hour. The original throttling up sequence was repeated. The thruster was then operated at 0.17 A for two hours, raised to 2.0 A, and operated there for 80 min.

Control system and power conditioning operation over the contract beam current range of 0.37 to 1.85 A (throttling range of 5:1) was stable. Operation over the expanded range of 0.17 to 2.0 A (throttling range of 12:1) produced no control system problems except those previously discussed and a slight sloppiness in the beam current and discharge voltage controllers at the extreme low end of the beam current range. The linearity of the throttling control is illustrated in Fig. 67. During this test, the total efficiency of 66% at 1.85 A exceeded the contract goal of 64%. The mass utilization efficiency penalty of the neutralizer was more than compensated for by a high electrical efficiency. A plot of total efficiency versus total input power is presented in Fig. 68. The performance data accumulated during the throttling test is summarized in Table XXII. The response of the system to throttling changes in the single knob control mode is shown in the excerpt from the multichannel recorder presented earlier in Section II-F-3, Fig. 66.

The final test run under Task V, was designed to establish the performance of the discharge chamber, ion extraction system, and neutralizer over the full power range. At each of four beam currents the discharge losses (eV/ion) were measured as a function of η_m by varying the ratio of discharge to beam current ($V_D = 40$ V); the ion optical system perveance was measured by changing the total voltage; the input power was varied by adjusting V_B ($V_T = \text{const}$); and the neutralizer controller was exercised by adjusting the neutralizer keeper voltage set point. In each case the data point was established by setting the electrical parameters into the control loops and measuring the mass flowrate for approximately one hour to establish η_m .

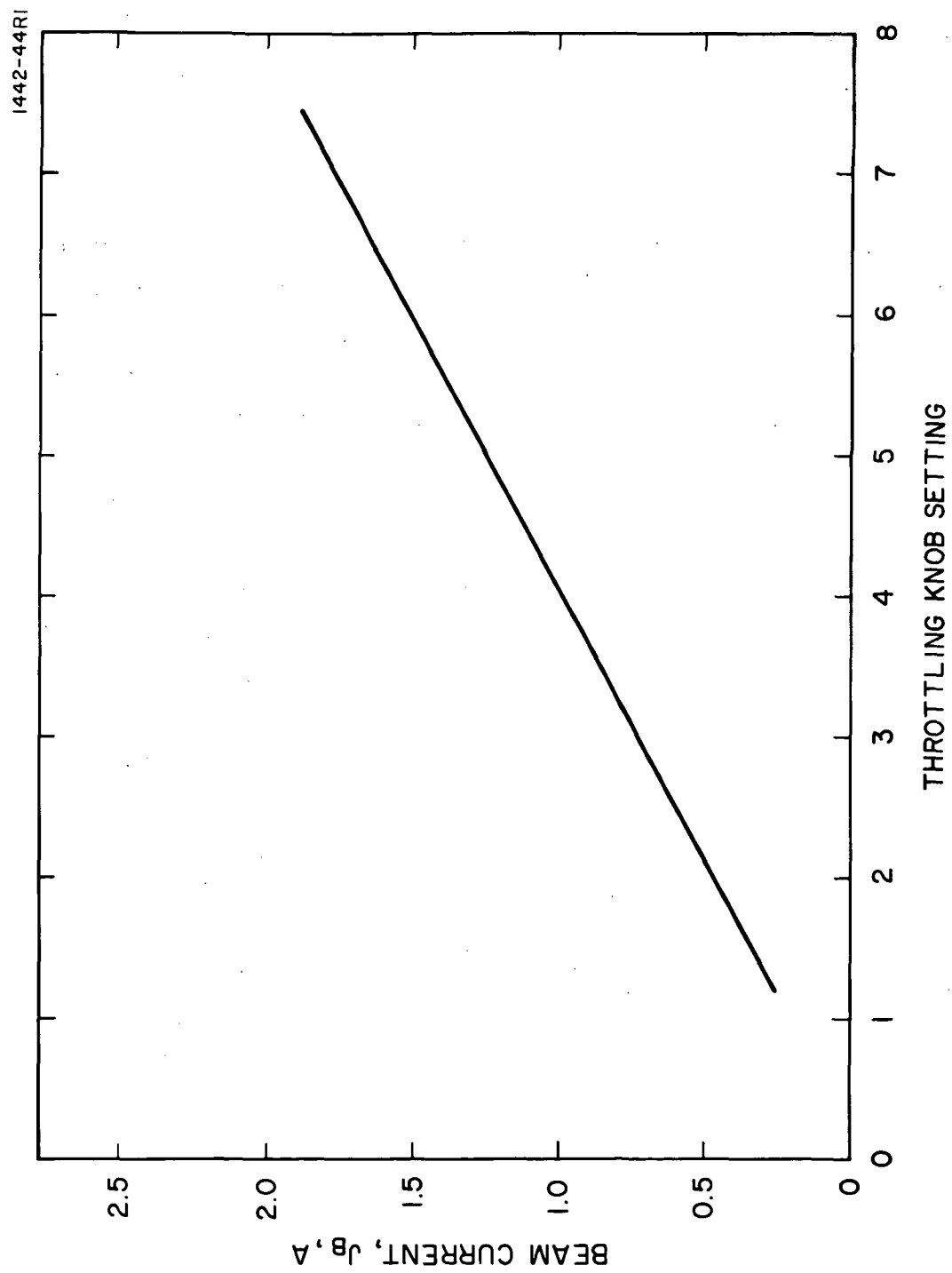


Fig. 67. Beam Current Versus Throttling Control Setting.

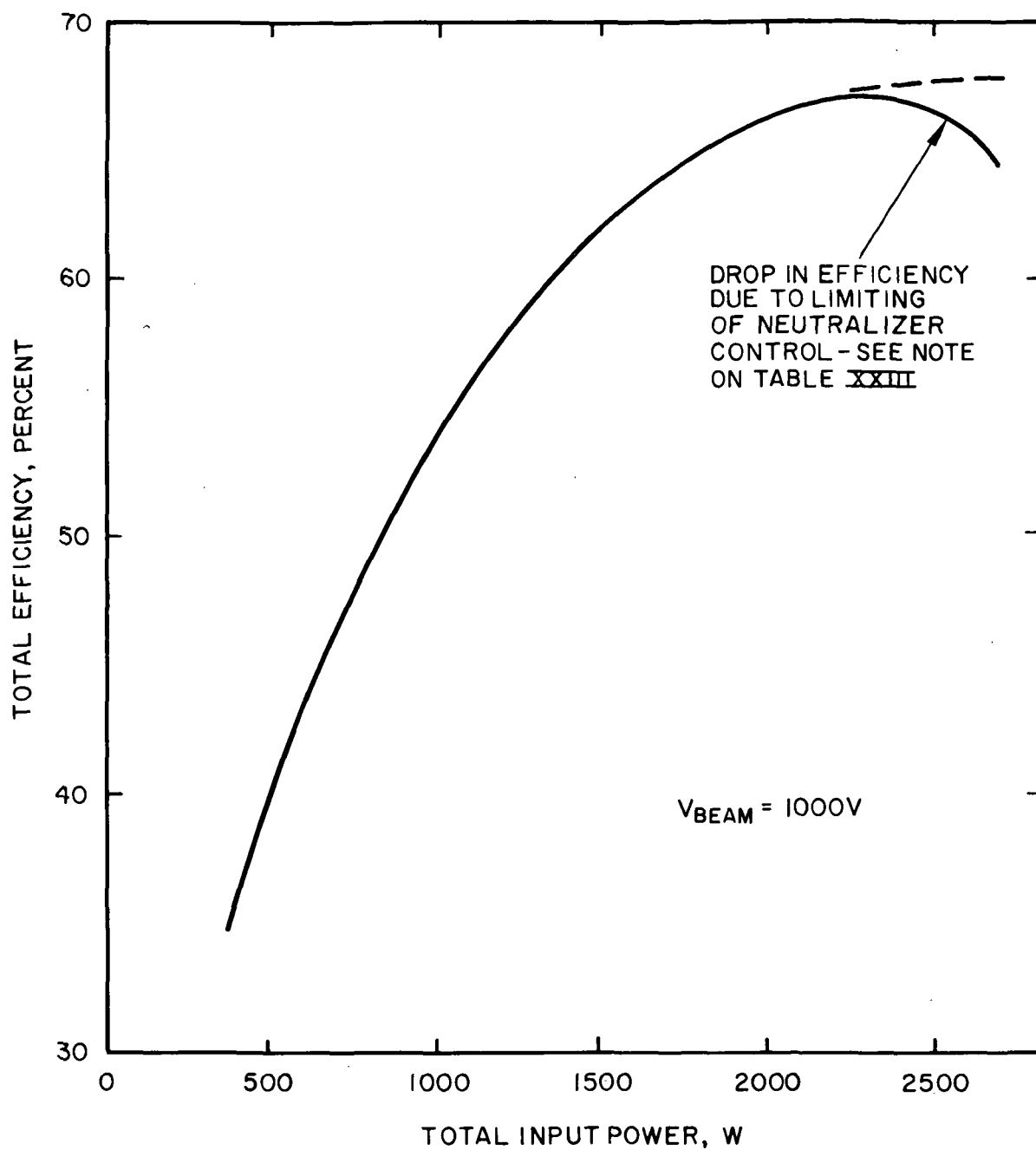


Fig. 68. Total Efficiency Versus Input Power.

During a similar test the ion beam current profiles were measured immediately downstream of the thruster and at a point 2.8 m downstream. These data are shown in Fig. 69. For the particular profiles shown the beam current was 1.5 A; the beam voltage 1.33 kV and the accelerator -0.8 kV. Varying the accelerator voltage produced the additional data presented in Table XXII.

Table XXII

Beam Divergence Measured as a Function
of Accelerator Voltage

Beam		Accel Voltage	Beam Half-Angle	
Current	Voltage		at 50% Intensity	at 10% Intensity
Amps	Kilovolts	Kilovolts	Degrees	Degrees
1.5	1.33	1.0	8.2	15.9
1.5	1.33	0.8	6.9	14.1
1.5	1.33	0.6	5.8	12.5

A summary of the test results is presented in Table XXIV. Figures 70 through 73 illustrate several features of interest. Figure 70 shows the different shape of the eV/ion versus η_m curves when the data is taken by setting the electrical parameters and measuring flow as compared to the curves obtained by setting the mass flowrates through the main and cathode vaporizers and rapidly varying the discharge parameters (both voltage and current must vary with fixed flow rate). Holding the discharge voltage constant and varying the current generates a set of curves that drop sharply toward the zero eV/ion limit rather than approaching it asymptotically. These should not be extrapolated beyond

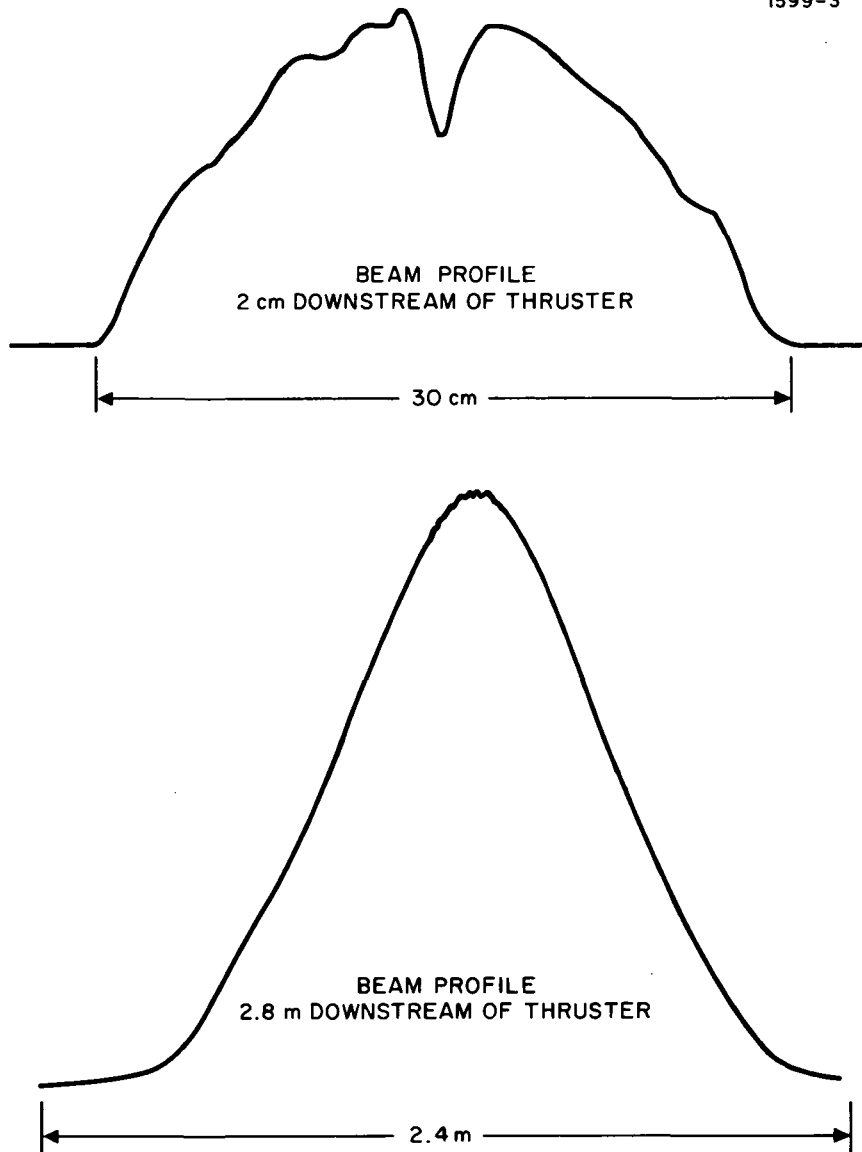


Fig. 69. Ion Beam Profiles Measured at
2 cm and 2.8 cm from the Thruster.

TABLE XXIII
Summary of Throttling Test Results

Constants: $V_{\text{BEAM}} = 1000 \text{ V}$
 $V_{\text{DISCHG}} = 40 \text{ to } 42 \text{ V}$

Neut. Flows			$I_{\text{DISCHG}},$ A	$\frac{\text{eV}}{\text{Ion}}$	$\eta_{\text{mass}},^*$ %	$\eta_{\text{pwr}},$ %	$\eta_{\text{total}},^*$ %	$P_{\text{total}},$ W
Main	Cath.	Neut.,*						
A (Equiv.)								
$I_{\text{BEAM}} = 2.0$								
1.99	0.161	0.264	13.0	259	83	78	65	2577
$I_{\text{BEAM}} = 1.85 \text{ A}$								
1.90	0.156	0.163	11.6	251	84	78	66	2384
1.89	0.148	0.157	11.5	250	84	78	66	2371
$I_{\text{BEAM}} = 1.55 \text{ A}$								
1.63	0.124	0.078	9.6	247	85	78	66	1984
1.60	0.124	0.084	9.5	255	84.5	78	66	1969
$I_{\text{BEAM}} = 1.25 \text{ A}$								
1.34	0.122	0.068	7.7	246	82	78	62	1600
1.30	0.118	0.064	7.75	259	83	77	64	1590
$I_{\text{BEAM}} = 0.95$								
1.04	0.119	0.090	6.1	260	76	77	58	1231
0.99	0.131	0.068	6.3	276	79	76	60	1233
1.18	0.129	0.047	6.4	271	70	76	53	1258
$I_{\text{BEAM}} = 0.65$								
0.725	0.136	0.122	4.6	281	68	76	51	884
0.740	0.117	0.097	4.4	285	68	75	51	862
0.705	0.141	0.036	4.4	277	75	75	51	876
$I_{\text{BEAM}} = 0.35$								
0.361	0.143	0.213	2.6	312	49	73	36	478
0.416	0.131	0.149	2.4	281	52	75	39	481
$I_{\text{BEAM}} = 0.17$								
0.272	0.045	0.199	1.2	290	33	75	25	277

* This data was taken prior to improving neutralizer performance. Extrapolation of the data shown in Fig. 18, page 42 improves the total efficiency at both high and low power levels.

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TABLE XXIV

Task V Performance Map

Date	Time	J_{ϕ}° Å	V_S° V	V_A° V _K	V_{ϕ}° V _K	V_I° V		J_I° A		m_C° A (equiv.)	m_N° A (equiv.)	η_M° %	$\epsilon_{I,}^{\circ}$ eV/Ion	η_I° %
						Plan	Actual	Plan	Actual					
9-22	1350	1.85	1000	-1500	8.3	40	40	13.0	12.9	0.201	0.255	93.9	279	63.6
9-22	1220	1.85	1000	-1500	8.3	40	40	12.0	11.9	0.166	0.237	90.1	258	62.8
9-22	1530	1.85	1000	-1500	8.2	40	40	11.1	11.1	0.154	0.204	88.9	239	64.0
9-23	1134	1.85	1000	-1500	9.5	40	40	10.2	10.2	0.116	0.260	88.4	220	63.0
9-23	1302	1.85	1150	-1350	9.6	40	40	12.0	12.0	0.165	0.286	91.3	260	64.3
9-23	1424	1.85	900	-1600	9.6	40	40	12.0	12.0	0.170	0.297	92.6	260	61.2
9-23	1630	1.85	1300	-1200	9.6	40	40	12.0	12.0	0.174	0.302	91.0	260	65.0
9-20	1920	1.41	1000	-1100	10.9	40	40.0	11.2	11.1	0.185	0.135	94.0	315	64.0
9-20	1850	1.4	1000	-1100	9.0	40	40.0	9.8	9.8	0.148	0.118	87.7	280	62.0
9-20	1050	1.4	1000	-1100	9.0	40	40.2	9.1	9.1	0.158	0.136	82.6	260	59.0
9-20	2050	1.37	1000	-1100	9.0	40	40	8.4	8.4	0.128	0.128	86.2	242	55.2
9-20	2250	1.4	1150	-950	9.0	40	40	9.1	9.1	0.136	0.117	86.5	260	63.9
9-20	2320	1.4	800	-1300	9.0	40	40	9.1	9.2	0.137	0.138	89.4	263	59.3
9-21	0030	1.4	1300	-800	9.0	40	40	9.1	9.1	0.1467	0.162	87.4	260	64.8
9-21	1906	0.90	1000	-600	9.9	40	39.8	7.2	7.2	0.147	0.106	85.6	315	57.8
9-21	2020	0.90	1000	-600	10.0	40	40.1	6.3	6.3	0.139	0.114	80.6	281	55.8
9-21	2130	0.90	1000	-600	10.0	40	40.1	5.8	5.8	0.132	0.105	79.9	259	56.8
9-21	2240	0.90	1000	-600	10.0	40	40.1	5.4	5.4	0.130	0.109	78.6	241	56.8
9-22	0000	0.91	1150	-450	10.0	40	40.0	5.8	5.7	0.136	0.107	74.5	251	55.0
9-22	0100	0.90	800	-800	10.0	40	40.0	5.8	5.8	0.130	0.100	78.7	258	53.4
9-22	0200	0.90	600	-1000	10.0	40	40.2	5.8	5.7	0.130	0.107	75.8	255	46.7
9-22	0300	0.90	1300	-400	10.0	40	40.1	5.8	5.8	0.134	0.092	86.7	258	65.2
9-22	0510	0.90	1000	-600	8.2	40	40.0	5.8	5.8	0.130	0.610	74.0	258	24.8
9-22	0410	0.90	1000	-600	11.7	40	39.8	5.8	5.8	0.123	0.058	74.5	256	54.2
9-21	0350	0.40	1000	-400	10.1	40	40.0	3.2	3.4	0.168	0.235	71.8	340	36.3
9-21	0240	0.40	1000	-400	10.1	40	40.1	2.8	2.8	0.398	0.215	73.6	286	39.5
9-21	0140	0.41	1000	-400	10.1	40	40.3	2.6	2.6	0.353	0.181	81.5	256	40.2
9-21	0510	0.40	1000	-400	10.0	40	40.5	2.4	2.4	0.425	0.242	71.2	243	38.6
9-21	0630	0.40	1150	-400	10.1	40	40.2	2.6	2.3	0.470	0.219	65.4	231	38.8
9-21	0752	0.40	800	-400	10.4	40	40.0	2.6	2.6	0.434	0.183	70.2	260	38.5
9-21	0750	0.40	600	-500	10.3	40	40.6	2.6	2.6	0.488	0.195	64.9	264	31.7
9-21	1110	0.40	1300	-400	10.5	40	40.1	2.6	2.6	0.434	0.176	68.9	261	42.8
9-21	1353	0.40	1000	-400	12.4	40	39.7	2.6	2.7	0.434	0.156	67.8	268	41.3
9-21	1410	0.40	1000	-400	14.0	40	40.0	2.6	2.6	0.461	0.139	66.5	260	41.6
9-21	1600	0.40	1000	-400	16.2	40	40.0	2.6	2.7	0.461	0.044	66.0	270	45.9

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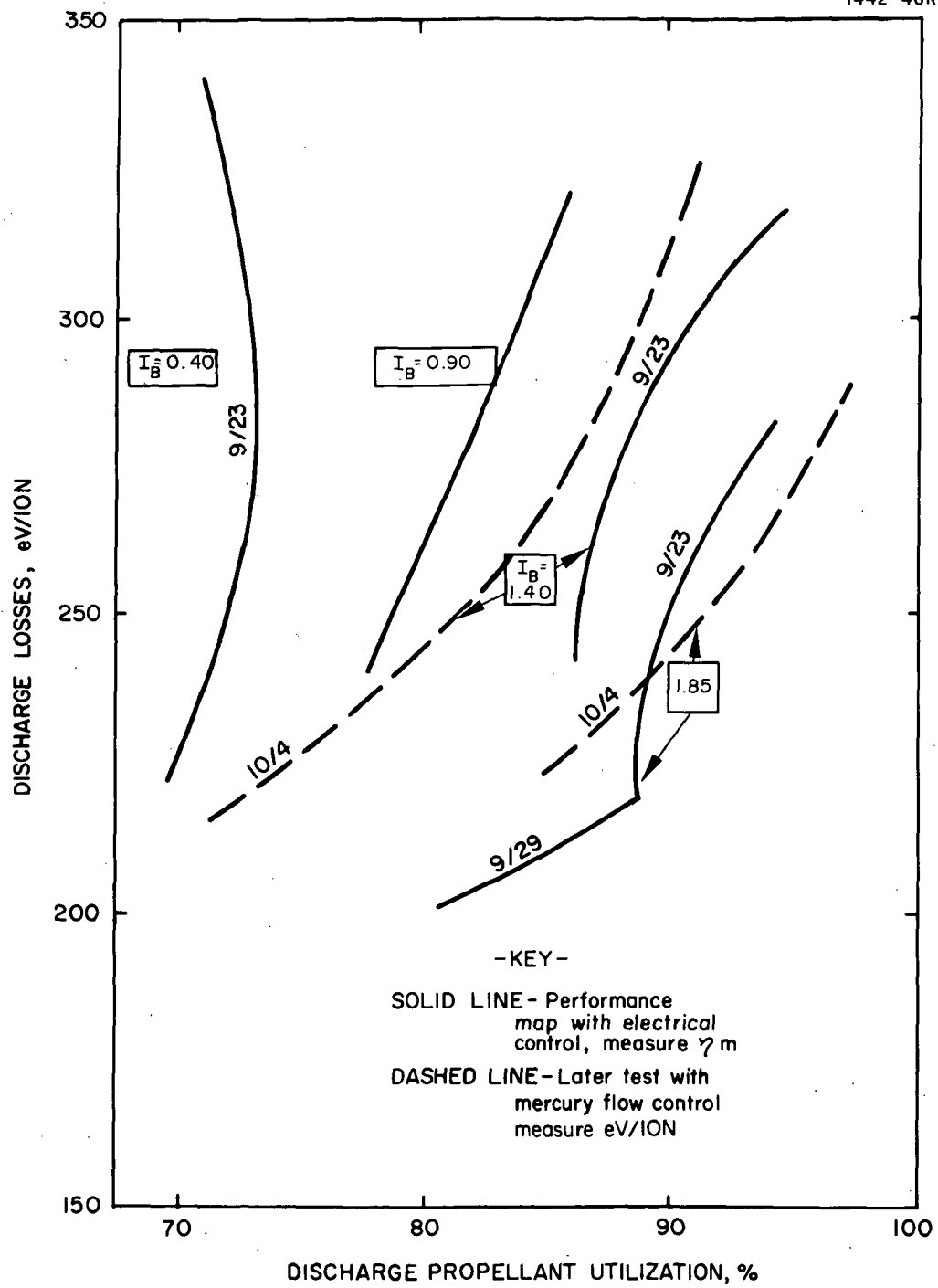


Fig. 70. Discharge Losses Versus Mass Efficiency.

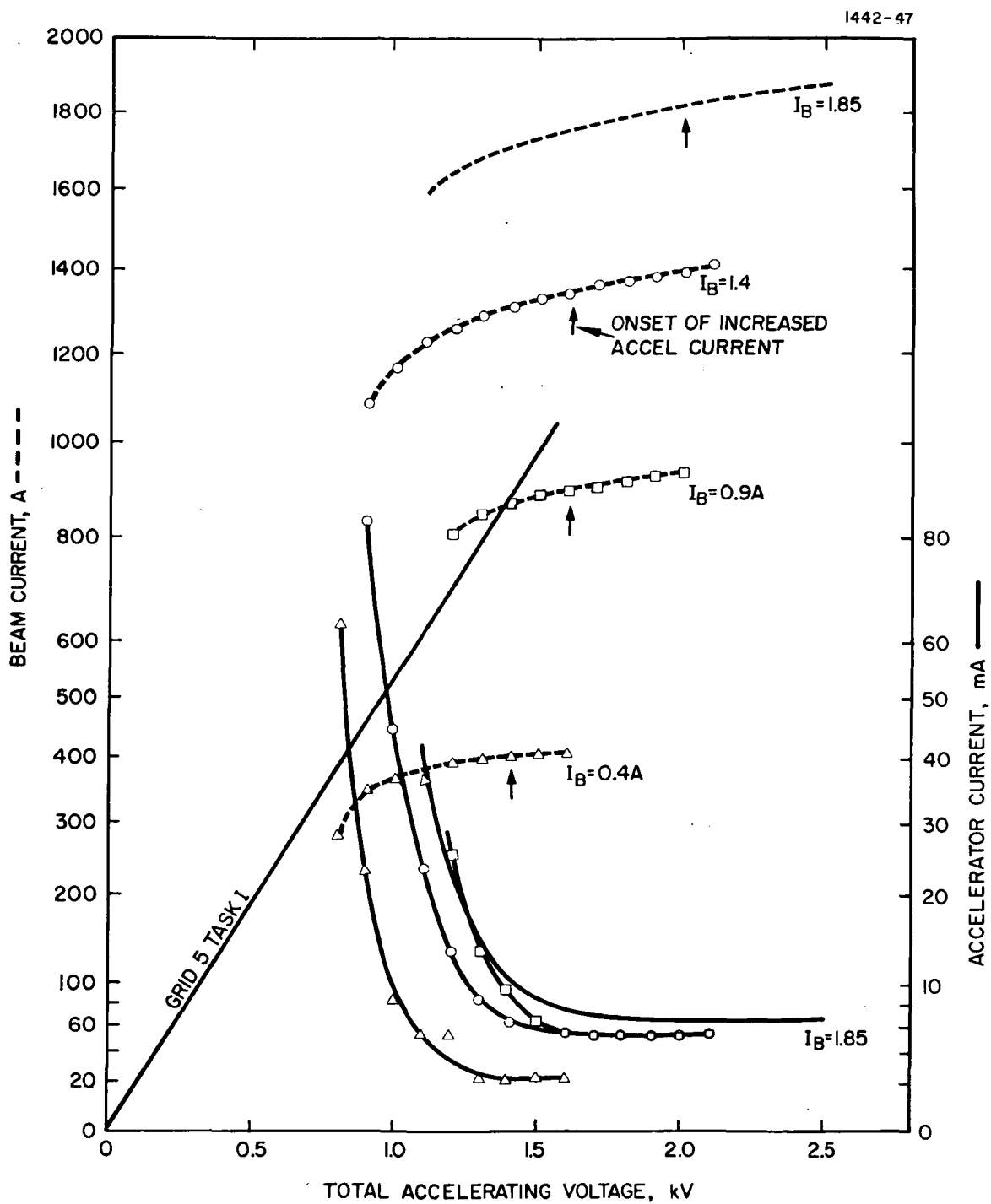


Fig. 71. Electrode Perveance for Task V Thruster.

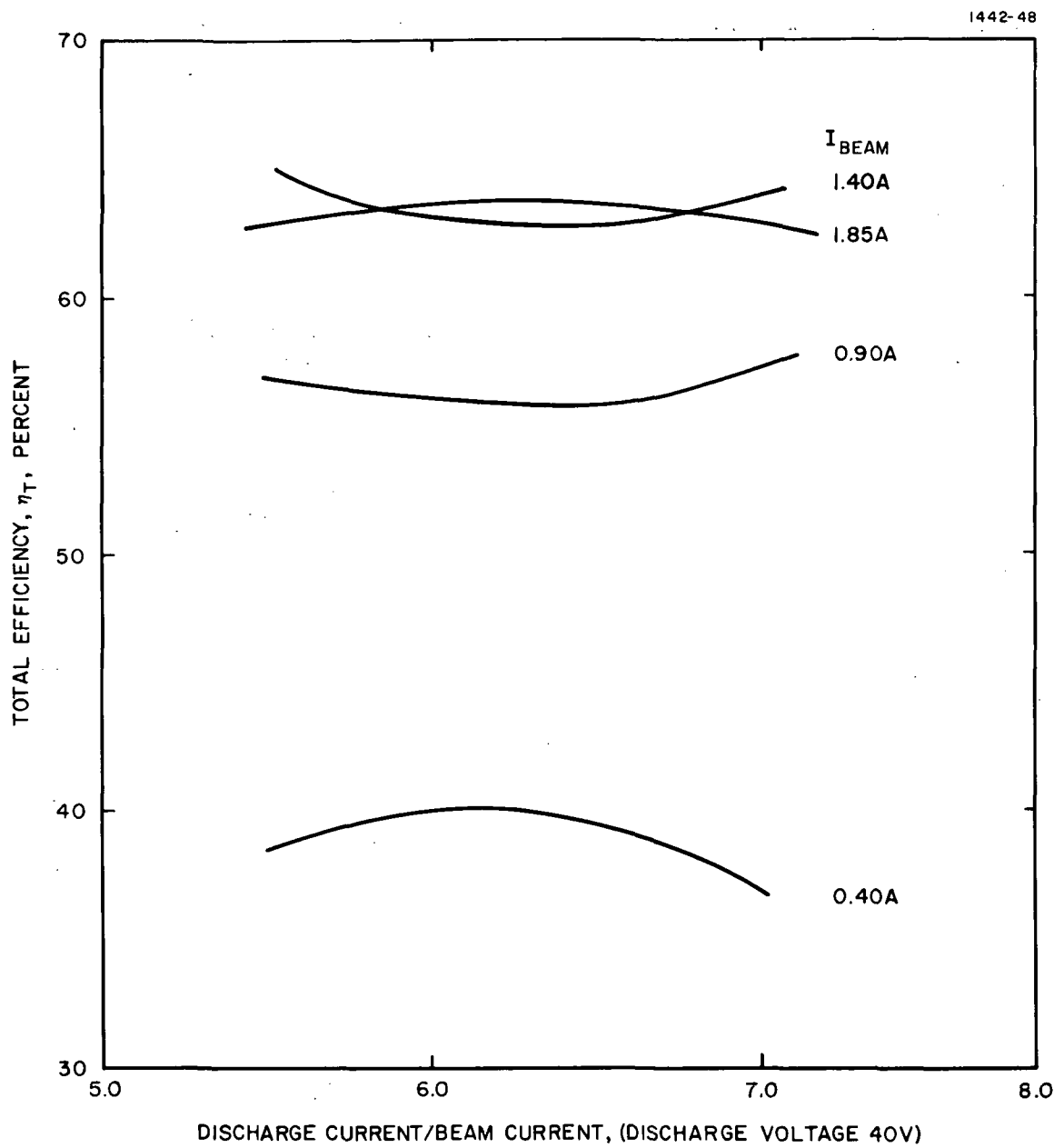


Fig. 72. Total Efficiency Versus Discharge Current to Beam Current Ratio.

the last point because at a point near 200 eV/ion, the discharge becomes unstable and will extinguish (possibly as a result of the very low cathode neutral flow demanded by the controller to maintain the 40 V discharge at the low discharge current). Figure 71 shows the electrode system perveance attained with this grid set. No serious arcing or irregular behavior was observed with this grid set during either of the last two tests. Figure 72 shows that a total efficiency is not a strong function of the ratio of discharge current to beam current over the range from 5.5 to 7.0 (220 to 280 eV/ion). The total efficiency is illustrated in Fig. 73. The efficiency measured here is somewhat less than observed during the earlier 50 hour throttling test. This difference is due to higher neutralizer mass flow during this last test. Even with the high neutralizer mass flow, the total efficiency goal of the contract at 1000 V beam voltage and 1.85 A beam current was achieved. When the thruster was operated at a 0.9 A beam current and 1000 V beam voltage, the total efficiency dropped to 57%. However, when the beam voltage was raised to 1300 V, which is the kind of adjustment that must be made to maintain the effective specific impulse at ~ 2750 sec, the total efficiency exceeded the contract goal. These results are summarized in Table XXV.

The tests conducted under Task V of contract NAS 3-14140 demonstrated two important facts: (1) the thruster and control system which have been developed provide a thruster system that can be throttled over a range of greater than 5:1 and (2) the goal of a total efficiency of 64% at a beam current of 1.85 A and beam voltage of 1000 V was achieved.

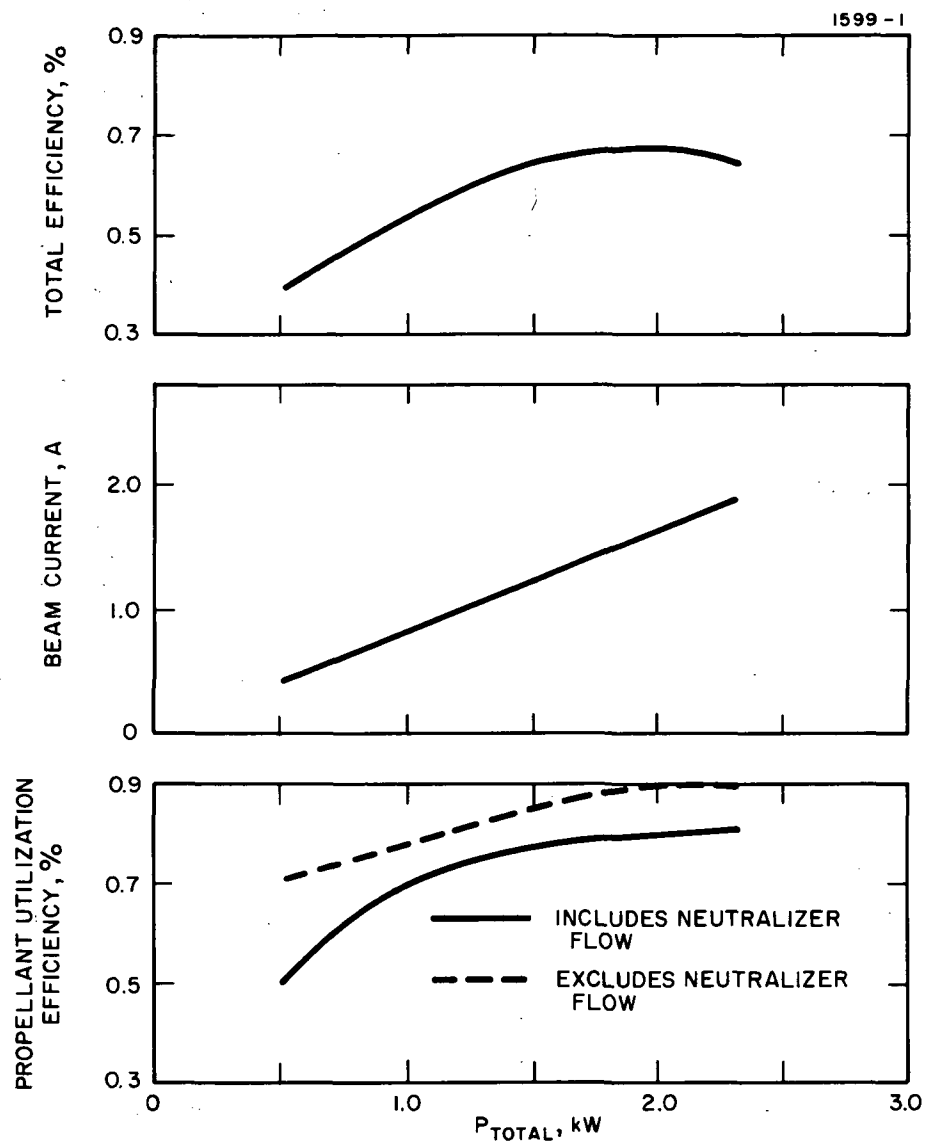


Fig. 73. Total Efficiency Versus Total Power.

TABLE XXV

Comparison of Contract Goals and Test Results
at Full and Half Power

	A Contract Goals	B Test Results	C Test Results	D Calculated V_B Required for $I_{sp} = 2630$	E Test Results
I_B	1.85	1.85	0.90	0.90	0.90
V_B	1000	1000	1000	1300	1300
η_E	74	77	78	82	82
η_M	87	83	73	73 (assumed)	80
η_T	64	64	57	60	65
I_{sp}	2750	2630	2310	2630 (assumed)	2870
• All measured data taken at $\epsilon_I = 260$ eV/ion • In column D, η_E was calculated assuming same losses as in column C.					

T419

SECTION IV

DELIVERABLE HARDWARE

As the final task under this contract, a complete thruster system and two sets of spare parts were fabricated, tested, and delivered to NASA LeRC along with reproducible working drawings, equipment logs, and test results. A photograph of this thruster is shown in Fig. 74. These short term test results duplicated those taken in the more extensive performance map of the prototype thruster presented in Table XXIV. The final thruster system weighed 6.95 kg, as shown in the detailed weight breakdown of Table XXVI.

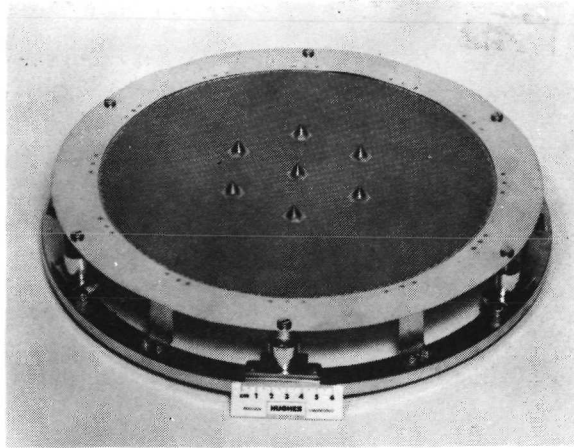
The thruster shown in Fig. 74 employs an ion extraction system with a single flexible central interelectrode support of the type used to take the preceeding data. Two other ion extraction systems were delivered to LeRC as part of the final hardware package. Both optics used still interelectrode supports capable of sustaining compression as well as tensile loads and of withstanding some lateral force as well. The set with seven such supports is shown in Fig. 75. The other is identical except that it has only a single central support. Performance evaluation tests will be conducted at LeRC.

M8374



Fig. 74. Thruster System Assembly.

M8498



M8499

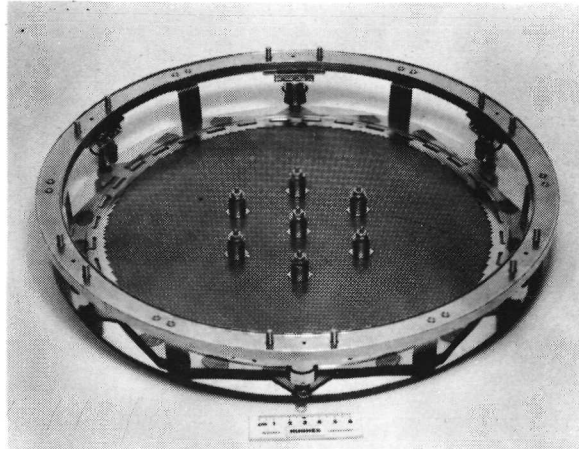


Fig. 75.
30 cm Electrode With Multiple
Interelectrode Supports

TABLE XXVI

30 cm Thruster Weights

Thruster Shell Including Mounting Hardware for Optics and Axial Magnets	1.120 kg
Backplate Assembly Including CIV and MIV Mounting Interfaces and Radial Magnets	0.680
Optics Subassembly	1.620
CIV Subassembly	0.300
MIV Subassembly	0.140
Main Propellant Distributor	0.340
Baffle Assembly	0.200
Anode	0.225
Ground Screen, Mask, and Rear Shield	1.285
Electrical Terminal Blocks and Insulators	0.540
Neutralizer Subassembly	0.500
Total	6.950 kg (15.2 lb)

T351

SECTION V

CONCLUSIONS

The over-all objective of this program was to develop a 30 cm mercury ion thruster module with high efficiency and long lifetime capabilities. The thruster power level must be controlled by a single 0 to 5 V signal, which can be used to select any desired operating point within a 500 to 2500 W operating range. These objectives were accomplished during this program.

During the course of this work the following observations were made:

- Test data indicated that the required 10^4 hr useful lifetime could not be predicted for single, insulated electrode systems. As a result, the conventional dual grid design was chosen for this application and redesigned to improve performance.
- Satisfactory discharge chamber efficiency and stability could not be achieved over the required 5:1 power range with a fixed discharge chamber configuration. A magnetic baffle that automatically varies the discharge chamber impedance as a function of discharge current was installed. This permitted easy startup and extended the stable beam current operating range from 0.16 to at least 2.0 A.
- Three control loops were required for stable operation. The beam current was controlled by the main mercury flow and the discharge voltage by the mercury flow through the cathode, with the discharge current preset at the power supply. The neutralizer mercury flow, which proved the most difficult to control, was regulated by the neutralizer keeper voltage while maintaining a constant neutralizer keeper current.

- The mass utilization in the discharge chamber was found to decrease as the beam current decreased over the throttling range. This, coupled with the fact that the mercury mass flow required by the neutralizer does not decrease as the beam current decreases, causes the total mass utilization to fall as beam current is reduced.

While the thruster produced under this contract represents the state-of-the-art for this type of primary electric propulsion module, there are several areas that require further attention:

- Verification of the mechanical design of the thruster under simulated launch conditions.
- Improvement of discharge chamber performance, particularly at the low end of the power range.
- Improvement in the ion optical system design to increase the screen electrode open area, and if possible, eliminate the need for the central interelectrode support.
- Improvement in neutralizer performance to reduce the mass flow required for stable operation.
- Verification of over-all system performance and durability by a long duration test of the combined thruster, control system, and power conditioner.

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