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RETROFIT AND VERIFICATION TEST OF 30 cm ION THRUSTER

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16. Abstract

Endurance testing of the 900-series, 30-cm mercury ion thruster disclosed several design deficiencies, and this program was initiated to modify the thruster design to correct these deficiencies. Twenty modifications were found to be necessary and were approved by design review. These design modifications were incorporated in the thruster documents (drawings and procedures) to define the J-series thruster. Sixteen of the design revisions were implemented in a 900-series thruster by retrofit modification. A standardized set of test procedures was formulated, and the retrofit J-series thruster design was verified by test. Some difficulty was observed with the modification to the ion optics assembly, but the overall effect of the design modification satisfies the design objectives. The thruster was tested over a wide range of operating parameters to demonstrate its capabilities.

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FOREWORD

The work described in this report was carried out at Hughes Research Laboratories, primarily during 1978, but finally completed in 1980. During this period, personnel of both NASA's Lewis Research Center and Hughes Research Laboratories were replaced as a consequence of reorganizations. Initially, the program was conducted by the Ion Physics Department and was managed by Dr. R.L. Poeschel, assisted by Mr. S. Kami. In May of 1978, the fabrication of thruster hardware, and the work remaining on this program, was transferred to the High Voltage Technology Department. Mr. D.E. Schnelker then served as program manager until leaving HRL. Dr. C.R. Dulgeroff assumed the role of program manager to complete the work.

SUMMARY

The major objectives of this program were to modify the design of the 900-series 30-cm thruster to correct deficiencies that had been discovered in recent life tests and to verify the modified thruster design. Initially, the deficiencies in design were reviewed by Hughes personnel and modifications were formulated to correct those deficiencies (based primarily on results and recommendations determined under other NASA projects). A design review was conducted, and the design modifications were submitted to NASA for approval. Twenty design changes were approved for incorporation into the 900-series design to form the J-series, and 16 of these were approved for retrofit. Thruster SN 901 was modified accordingly to become thruster SN J1, and tests were performed in accordance with a standardized acceptance test format (formulated under this program). Unanticipated difficulties were encountered during this test, and the thruster was delivered to NASA's Lewis Research Center without the planned extended "characterization" of thruster performance over a wide range of operating parameters having been completed. It was later discovered that the modifications to the ion optics design had produced a thermally driven dimensional instability of the electrode mounting structure. Further design modification was necessary, and work under this program was suspended until a "representative" J-series thruster could be supplied. Several other component failures (heaters and vaporizers) delayed completion of the retrofit of the remaining 900-series thrusters (under NASA contract NASA 3-21357) and the subsequent completion of the characterization tests under this program (using thruster SN J3). Through the work performed on this program and other NASA technology developments, the 30-cm J-series mercury ion thruster now meets the design goals of 130-mN thrust at 3000-sec specific impulse and 2.68-kW maximum power input with a projected lifetime of 15,000 hr (at full power).

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

At the outset of this program, development of the 900-series mercury ion thruster was considered to be essentially complete since the thruster had demonstrated the performance goals, and the only major deficiency was the projected wearout lifetime. On the basis of endurance test results, the projected lifetime of the screen grid electrode (ion optics assembly) of the 900-series thruster was only 10,000 hr, far less than the 15,000-hr design goal. The major objective of this program was to re-examine all features of the thruster's design with respect to endurance test results and any other evidence of failures or potential failures reported in the technology programs conducted by NASA's Lewis Research Center (either in-house or by contract). A set of design modifications was formulated and presented for NASA review and approval. Some of these modifications were proposed as corrections to specific failures (already observed), and others were offered as preventative measures against potential failures or fabrication difficulties. Of the 22 design modifications proposed, 20 were approved for incorporation into the 900-series design to form the J series, and 16 were approved for retrofit into the government-furnished 900-series thruster (SN 901). The thruster was modified and a "standardized" acceptance test was formulated and performed to verify that the J-series thruster design provided the required performance characteristics. The retrofit modification of the thruster was not as straightforward as anticipated, and difficulties were encountered in applying the formalized set of preconceived test procedures on a new thruster. Consequently, the initial retrofit thruster, SNJ1, was delivered to NASA's Lewis Research Center where extensive testing was performed. Ultimately, additional design modifications were identified and incorporated in retrofitting the remaining six 900-series thrusters under NASA contract NAS 3-21357. The acceptance test procedures were also revised several times. After it was apparent that all of the essential design features had been verified and the test procedures had been validated, thruster SNJ3 was furnished to this program for conducting an extended "characterization" of thruster performance over a wide range of operating parameters. In retrospect, this characterization was premature since subsequently it was discovered that the time required to establish equilibrium conditions (for propellant measurement) is longer than had been allotted under the characterization test plan. Consequently, the data obtained can only be used for examining major trends, not fine details.

The work described above is discussed in detail in the following sections; however, the work performed under this program represents only the first step of the work that was eventually required to obtain the J-series thruster design and fabrication documentation. The major portion of the work had to be completed under NASA contract NAS 3-21357. Consequently, a complete description of the J-series design, in its final form, has not been attempted here. This report is intended as an accounting of the portion of the work performed under this program, and the final report for contract NAS 3-21357 should be referred to for a complete description of the current J-series thruster design.

SECTION 2

DOCUMENTATION REVIEW AND RECOMMENDED DESIGN MODIFICATIONS

The initial phase of this program was devoted to reviewing the design documentation for manufacturing 30-cm ion thrusters and to identifying thruster modifications considered necessary to eliminate potential failures. The review served to incorporate corrective measures that were approved and carried out under other programs. This amounted to revising or deleting existing drawings and procedures to reflect changes already being followed in fabrication and assembly. The identification of proposed modifications resulted from endurance tests, structural tests, and performance characterization tests.

There were 22 modifications recommended; of these, 20 were accepted by the NASA project manager. These 20 are discussed below, with the major modifications discussed first.

Screen Grid

Based on the erosion rate of the screen grid during a 4000-hr endurance test, the projected lifetime of the screen grid was estimated to be less than 10,000 hr. Since the design goal for the thruster lifetime is 15,000 hr, corrective action was imperative. The action taken was to alter the accelerator grid design. Lewis Research Center (LeRC) and Hughes Research Laboratories (HRL) technology programs showed that a low transmission (less than 30%) accelerator grid permits discharge chamber voltage to be lowered without a loss in thruster efficiency. A lower discharge voltage reduces the fraction of doubly charged ions that are produced in the chamber; the lower energy and fewer doubly charged ions combine to reduce screen grid wear. The recommended change was to decrease the diameter of the apertures in the accelerator grid from 0.152 cm (0.060 in.) to 0.114 cm (0.045 in.). The modification to the accelerator support necessitated by this change is discussed later on.

Insulation of Wire near Cathode Polepiece

Teflon/Kapton insulated leads connected to the cathode heater, magnetic baffle coil, and cathode keeper passed through the region around the cathode polepiece. Operating temperatures of ∿300°C caused the insulation to loosen; this could permit a short between the leads and surfaces at different potentials. This did in fact happen to the cathode keeper lead during the endurance test after 4000 hr of operation. To preclude this from happening, a change in the insulation in the hot region was proposed. Ceramic beads were suggested as replacements as shown in Figure 1. In the cooler regions, no change in insulation was proposed.

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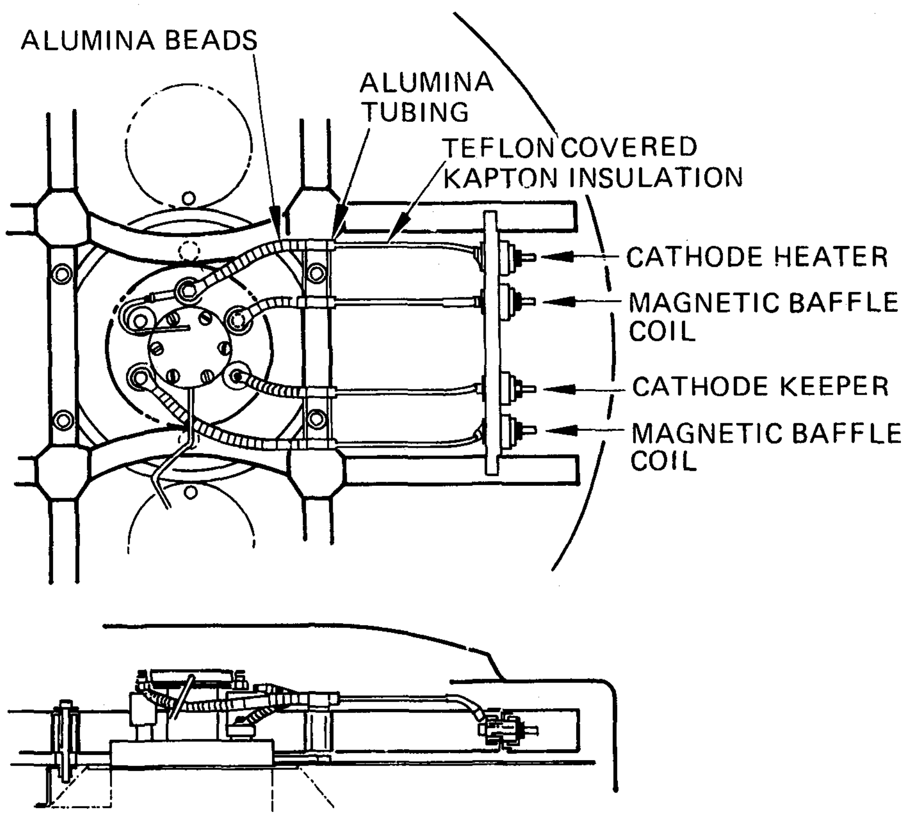

Figure 1. Modification in wiring to eliminate Teflon/Kapton insulation in proximity to the cathode polepiece.

Cathode Polepiece Wire Mesh Covering

Wire mesh is used to cover surfaces where sputter deposition is anticipated. The mesh inhibits spalling by providing an irregular curved surface for the deposition. In spite of this, large flakes were observed in the interior of the cathode polepiece during an examination following 4000 hr of testing. Tests at LeRC showed that a better choice for mesh size would be a 0.018-cm (0.007-in.) spacing between 0.009-cm (0.0035-in.) diameter wire. This wire size and spacing were proposed as a replacement for the original mesh.

Gimbal Bracket Insulators

Two gimbal pads are used to support the thruster. These pads are diametrically opposite on the outer cylinderical surface of the thruster. The gimbal pads were supported by ceramic insulators. But during a vibration test some of these insulators fractured. For this reason, a modification was suggested to replace them with insulators made of Vespel. The Vespel insulator design included threaded steel inserts. The temperature limit of 300° for Vespel was acceptable since the insulator temperature is not expected to exceed 200°C.

Lesser modifications proposed and accepted are discussed next.

Anode

Stainless-steel wire mesh was attached to the inner surface of the anode in several places; its purpose was to minimize the formation of flakes. Unfortunately, the method of attachment permitted the mesh to lift away from the anode surface. The proposed modification was to use anode material that had the mesh bonded to it.

Baffle Support and Magnetic Coil

The end of the tubular baffle support has openings that permit electrons to pass from the cathode past the baffle into the discharge chamber. The material next to these openings is covered with tantalum foil. This foil interfered with the magnetic coil when it was installed on the support tube. The proposed design increased the magnetic coil diameter and the diameter of the part of the baffle support used to mount the coil. The dimensions of the openings in the end of the baffle support remained the same.

Cathode Inserts

Tantalum wires were used to attach the porous tungsten inserts to the cathode tube. These wires frequently became brittle and broke during assembly. Rhenium wire was suggested as a replacement to decrease the chance of failure.

Neutralizer Erosion Shields

Examination after the 4000-hr test revealed erosion in the neutralizer assembly. An extension of the neutralizer erosion shield was suggested to protect this area.

Wiring Harness

An increase of the harness wire length (to 3.65 m) was proposed to accommodate the interface requirements for thruster testing. A Hughes specification for lead wire was also proposed for wire purchases.

Anode Insulator

Since Lucalox is no longer available, HRL proposed that the anode support insulator be changed to alumina (AL 300).

Vaporizer

Several variations in vaporizer behavior were observed. To obtain more uniform vaporizer material, a new specification was proposed. Detailed fabrication instructions were also suggested to be incorporated into the design package.

Neutralizer Fasteners

Neutralizer fasteners were located in places that were close to insulated wire leads. Using torqueing tools on these fasteners sometimes caused damage to the insulation. This damage was difficult to prevent and detect. The relocation of these fasteners was proposed to avoid the problem.

Wire Harness Clamp

The Mycroy harness clamp broke several times during assembly. The design change proposed that the material be changed to machinable ceramic.

Insulator Shield

Cup shields are used to protect insulators from material deposits. Misalignment of the shields could easily occur, creating a short. A self-centering design for the shields was proposed.

Gimbal Pad

Tolerance buildup could create an extremely small clearance between the gimbal pad (at spacecreaft potential) and the accelerator grid mounting (at screen potential). This required a custom fit to avoid arcing. A change in the pad dimension was suggested to eliminate this special handling during assembly.

Backplate Structural Brace

The backplate was fitted to the backplate structural brace with shims. This procedure was time consuming and inaccurate. The design proposed incorporated spacers on the brace, and these spacers were custom machined for a good fit.

Cathode Isolator Heater

Identical main and cathode isolator heaters were fabricated, but the heater used on the cathode isolator had to be partially uncoiled when assembled. This bending of an active part of the heater was undesirable. A request was made to change the final design configuration of the cathode isolator heater coils.

Ground Screen

Once a thruster was mounted by attaching to the gimbal pads, access to the wiring terminals or inspection of some thruster components required that the thruster be removed from the mount and the neutralizer assembly detached from the ground screen. The proposed design altered the ground screen so that it could be removed without disturbing the neutralizer or the mount.

Propellant Manifold

Performance testing requires individual monitoring of mercury flow to the three vaporizers. This meant that propellant line connectors had to be made within the ground screen and were subjected to undesirable flexing. A proposed manifold at the rear of the thruster for feed lines to the three vaporizers could be used for either single or multiple mercury lines.

Coaxial Heater Terminal

Coaxial heaters are used on the vaporizers and cathodes. The terminals were complex, fragile, and difficult to fabricate. It was proposed to use the simpler terminal used on the 8-cm thruster.

This completes the discussion of the modifications accepted by the NASA project manager. Two additional modifications were proposed and rejected. They dealt with the backplate wire mesh specification and the isolator heaters. It was determined at the design review that there was not a good justification for the proposed changes and they were dropped.

Only 15 of the design modifications listed and described above were made on thruster SN 901. Those modifications incorporated were those affecting the following components or subassemblies:

(1) Ion optics electrodes (accelerator aperture diameter)

(2) Cathode polepiece subassembly (wire mesh coverings)

(3) Anode (bonded wire mesh)

(4) Gimbal pad mounting insulators (Vespel)

(5) Porous tungsten cathode inserts (lead attachment)

(6) Neutralizer erosion shields (change in area)

(7) Wiring harness (wire size and lengths)

(8) Anode insulators (alumina)

(9) Neutralizer housing subassembly (dimensions)

(10) Wire harness clamp (material)

(11) Insulator shields (self-centering)

(12) Ion optics assembly mounting ring (fastener recess)

(13) Backplate structural brace (custom spacers)

(14) Outer ground screen (improve fit)

(15) Propellant line manifold (test interface).

Most of these modifications were straightforward with the only difficulties encountered typically from having to disassemble the thruster parts to a greater degree than has been common practice (for example, to replace insulator shields where the fastening hardware was safety wired and partially enclosed by welded structures). In several such cases, special tools and/or procedures had to be devised to perform the retrofit. Consequently, the retrofit modifications that had been estimated as requiring six weeks to perform eventually required four months (paced to some extent by the delivery of materials).

Although it was relatively straightforward to revise the drawings and documents to account for the changes listed above, a careful review of the drawings and inspection and process documents (IPD) revealed that considerably more work than had been budgeted was required to make the package accurate and self-consistent. Consequently, the document package (drawings and IPDs) was only revised to correct major discrepancies and changes instituted under this program and recommendations were made for further corrections and refinements. Subsequent drawing revisions and design changes were performed under contract NAS 3-21357 that further modified Items 1, 2, 3, 10, 12, and 14 listed above.

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SECTION 3

ACCEPTANCE TEST OF THRUSTER SNJ1

Under this program, several key procedural documents (identified by the numbers IPD-PR-138 through IPD-PR-143) were written related to preparing and testing 30-cm thrusters. These documents are as follows:

- IPD-PR-138, 30-cm Thruster Acceptance Procedure, provides detailed instructions for taking and reducing data.
- IPD-PR-139, Thruster Test Facility, specifies the vacuum facility and thruster interface requirements.
- IPD-PR-140, Power Processor, specifies the power supply requirements and characteristics needed for thruster testing.
- IPD-PR-141, Instrumentation and Calibration, describes the test equipment and methods used for calibration.
- IPD-PR-142, Preliminary Thruster Preparation, describes the measurements and procedures required in installing a thruster in a test facility.
- IPD-PR-143, Data Formats for Thruster Testing, contains the data formats for recording the data in acceptance and performance evaluation tests.

The documents above (in their first version) were used for the testing of thruster SN J1. Some of the documents have been revised; however, the first acceptance test of J1 contained the following major elements:

- Initial cathode conditioning
- Thruster start-up by a prescribed algorithm
- Determination of the minimum baffle current for stable operation
- Measurement of neutralizer-keeper-voltage vaporizer-temperature characteristics

- Determination of the minimum emission current for selected operating points
- Measurement of thruster efficiencies for 10 operating points
- Documentation of oscillation thruster parameter
- Documentation of thruster high voltage overload recycle characteristics
- Documentation of the ion optics system for selected operating points.

These test elements were initially described by NASA and furnished to the Hughes program manager. They were then written in the format of Hughes IPDs in the form reproduced in Appendix A of this report. One goal in formulating a standardized acceptance test under this program was to define test procedures that could be performed at any facility where ion thrusters can be tested, and by personnel having only limited ion propulsion background. Consequently, the form of the IPD included in Appendix A is more tutorial than could be accommodated while attempting to carry out the steps of the test sequence. Several revisions have resulted as a consequence, and the test is now relatively straightforward to perform, but does require an automated power processor and an experienced operator of ion thrusters.

Adhering to these initial procedures during the initial startup of thruster SN J1 led to several difficulties. The first four attempts were unsuccessful in establishing a beam as a result of: (1) wiring error, (2) insufficient cathode vaporizer power, or (3) recycle logic. After these problems were eliminated, an unstable beam was obtained with much arcing. Eventually, the recycle logic problem recurred and the test was terminated. The sixth start was unsuccessful: the arcing diminished and the testing begain. All the major elements of the acceptance test were completed for thruster J1 and the test results submitted in the Acceptance Test Document.

The operating and performance data for the acceptance test are summarized in Table 1. (The symbols are defined and explained in Appendix A, pages 11 through 14 of IPD-PR-138.) The total power for the principal throttling points (1, 4, 6, 7, and 9) of Table 1 is plotted versus efficiency in Figure 2 for comparison with data for the 900-series EMT. The efficiency of the retrofit thruster as measured under this program is slightly better than for a typical 900-series thruster operated at 36-V discharge voltage. Hence, the combined modifications to thruster design and thruster operation (i.e., the small hole accelerator grid and a lower (32 V) discharge voltage) should increase the thruster wearout lifetime with equal or better efficiency than the 900-series thruster (which will be verified by endurance testing under other programs). Table 2 lists the typical operating parameters for thruster SN J1 for the principal throttling points.

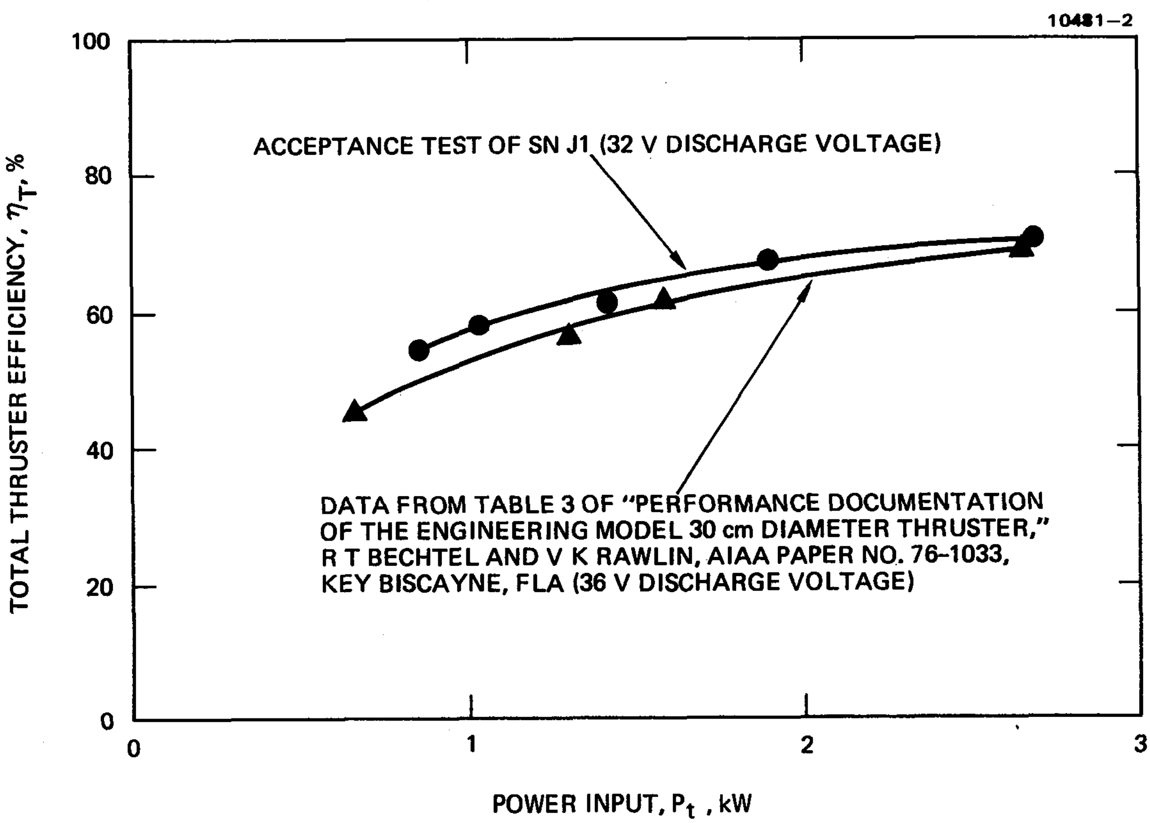

Figure 2. Comparison of performance data for the retrofit thruster, SN J1, and a typical 900-series EMT.

Table 1. Acceptance Test Summary for Thruster SNJ1

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THRUSTER PROPERTY	TEST POINT									
	1	2	3	4	5	6	7	8	9	10
J_b, A	2.022	2.005	1.999	1.598	1.295	1.295	1.013	0.750	0.750	0.750
V_b, V	1100.0	1100.0	1100.8	940.0	1100.7	820.5	699.8	1103.0	600.0	601.2
V_D, V	32.1	31.0	32.0	32.1	32.0	32.0	32.0	32.0	32.0	31.0
J_E, A	12.0	12.0	11.4	10.0	8.5	8.5	7.0	5.75	5.75	5.75
J_{MB}, A	2.2	2.2	2.2	2.2	2.5	2.5	2.5	2.7	2.7	2.7
V_{NK}, V	14.6	14.5	14.6	14.8	14.6	14.6	15.5	15.5	15.5	15.5
P_t, W	2677.6	2648.2	2635.1	1889.5	1763.7	1406.3	1015.2	1079.0	852.0	842.0
η_e	0.830	0.833	0.835	0.796	0.808	0.755	0.698	0.767	0.705	0.713
$\dot{m}_{MV}$, A[a]	1.997	2.073	2.017	1.578	1.264	1.292	1.006	0.649	0.710	0.693
$\dot{m}_{CV}$, A[a]	0.120	0.124	0.097	0.116	0.127	0.124	0.117	0.177	0.168	0.178
$\dot{m}_{NV}$, A[a]	0.032	0.031	0.045	0.026	0.056	0.037	0.031	0.056	0.043	0.049
$\dot{m}_t$, A[a]	2.149	2.228	2.159	1.720	1.447	1.453	1.154	0.882	0.921	0.920
η_D, %	91.3	87.8	90.7	90.6	89.7	88.3	88.2	89.1	84.2	84.9
η_t (UNC)	0.940	0.900	0.926	0.927	0.895	0.891	0.859	0.850	0.814	0.815
F_T	0.9765	0.9776	0.9775	0.9776	0.9773	0.9759	0.9833	0.9839	0.9829	0.9784
γ	0.9512	0.9565	0.9543	0.9546	0.9563	0.9560	0.9871	0.9732	0.9748	0.9705
η_T, %	70.6	68.6	70.4	67.4	66.1	61.5	56.4	61.8	54.6	54.8
I_{SP}, sec	2968	2858	2933	2715	2842	2442	2245	2750	1946	1941
F, mN	130.0	129.0	129.0	95.4	83.8	72.3	53.9	49.4	36.5	36.3
$J_{E_{min}}$, A	10.6	–	–	8.2	–	6.5	5.0	–	3.75	–

[a] EQUIVALENT AMPERES NEUTRAL FLOW

ALL POINTS HAVE V_A = -300, J_{NK} = 1.8 A, J_{CK} = 1.0 A

Table 2. Typical Operating Parameters for the Principal Throttling Points Plotted in Figure 2

10481–3

THRUSTER PROPERTY	UNIT	TEST POINT				
		1	4	6	7	9
BEAM VOLTAGE (V_b)	V	1100	940	820	700	600
BEAM CURRENT (J_b)	A	2.0	1.6	1.3	1.0	0.75
ACCEL VOLTAGE (V_{ACCEL})	V	300	300	300	300	300
ACCEL CURRENT (J_{ACCEL})	mA	4.1	3.0	2.4	2.0	1.4
DISCHARGE VOLTAGE (V_D)	V	32	32	32	32	32
EMISSION CURRENT (J_E)	A	12	10	8.5	7.0	5.75
CATH KEEPER VOLTAGE (V_{CK})	V	4.5	5.0	5.4	5.9	6.9
CATH KEEPER CURRENT (J_{CK})	A	1.0	1.0	1.0	1.0	1.0
MAG BAFFLE VOLTAGE (V_{MB})	V	0.5	0.5	0.5	0.5	0.5
MAG BAFFLE CURRENT (J_{MB})	A	2.2	2.2	2.5	2.5	2.7
MAIN VAPORIZER VOLTAGE (V_{MV})	V (rms)	6.2	6.2	6.0	6.2	5.9
MAIN VAPORIZER CURRENT (J_{MV})	A (rms)	1.1	1.0	0.9	1.0	0.9
CATH VAPORIZER VOLTAGE (V_{CV})	V (rms)	5.3	6.0	6.4	6.8	7.4
CATH VAPORIZER CURRENT (J_{CV})	A (rms)	1.0	1.3	1.4	1.4	1.6
NEUT VAPORIZER VOLTAGE (V_{NV})	V (rms)	4.7	5.0	5.2	5.6	5.7
NEUT VAPORIZER CURRENT (J_{NV})	A (rms)	0.5	0.9	0.9	0.9	1.0
NEUT KEEPER VOLTAGE (V_{NK})	V	14.6	14.6	14.6	15.5	15.5
NEUT KEEPER CURRENT (J_{NK})	A	1.8	1.8	1.8	1.8	1.8
NEUT COUPLING VOLTAGE (V_g)	V	10.7	10.7	10.7	10.4	10.6
NEUT COUPLING CURRENT (J_g)	A	0	0	0	0	0
MAIN VAPORIZER TEMP (T_{MV})	°C	337	329	319	308	292
CATH VAPORIZER TEMP (T_{CV})	°C	352	352	353	349	364
NEUT VAPORIZER TEMP (T_{NV})	°C	303	309	311	306	311

We found that some of the details of the acceptance test procedure were not adequate to ensure that the tests could be performed without difficulty. The major difficulties experienced were procedural in nature and are listed below:

- The value of magnetic baffle current to provide stable operation at the initial high voltage application is 2.7 A; the value of 1.5 A that was specified originally was observed to be very unstable.

- Specifications for neutralizer keeper voltage and current were not adequate to prevent the neutralizer keeper discharge from being extinguished under recycle conditions or other marginally stable thruster operating conditions.

It was also believed that the time (8 min) between discharge ignition and application of the beam voltage for operation in the Hughes chamber was too short; however, subsequent tests have not shown this to be the case.

At the conclusion of the test, the Hughes and NASA project managers agreed to delay the characterization tests until one or two of the J-series retrofit thrusters had been tested.

SECTION 4

EVOLUTION OF THE J-SERIES THRUSTER DESIGN

After the anomalies observed in testing thruster SN J1, and similar difficultes observed in the performance evaluation of several more of the retrofit ion optics assemblies prepared under contract NAS 3-21357 for the remaining six thrusters, an intensive investigation of the ion optics mounting structure was undertaken. This work was divided among two NASA contracts and internal studies at NASA LeRC. Under contract NAS 3-21040, a three-dimensional finite element analysis was performed to model the ion optics mount and electrode deformation under thermally induced stress. These computations supported those performed at LeRC (two-dimensional) and showed that the stiff grid mount caused distortion of the screen grid electrode that could either increase or decrease the interelectrode spacing, depending on the point of buckling and the temperature distribution. Temperature measurements were performed under contract NAS 3-21357 to provide input data for the analytic models, and a revised grid mounting structure was designed and verified analytically. The revised mounting, shown in Figure 3, relies on stiffening rings made of molybdenum to support the molybdenum grids without inducing stresses that arise from differential expansion. The titanium mounting is still a very "stiff" member with respect to axial displacement or torsion but is relatively "soft" (flexible) with respect to radial forces. Consequently, the spacing between the grid-stiffening rings can be maintained without introducing bending moments or radial stresses from the mount. The success of this assembly enabled retrofit and testing to proceed; however, only limited success was achieved in reworking the grid sets distorted from operation with the mountings of the previous design. On some assemblies, several iterations of stress relieving fixtures and procedures had to be made to achieve the desired results.

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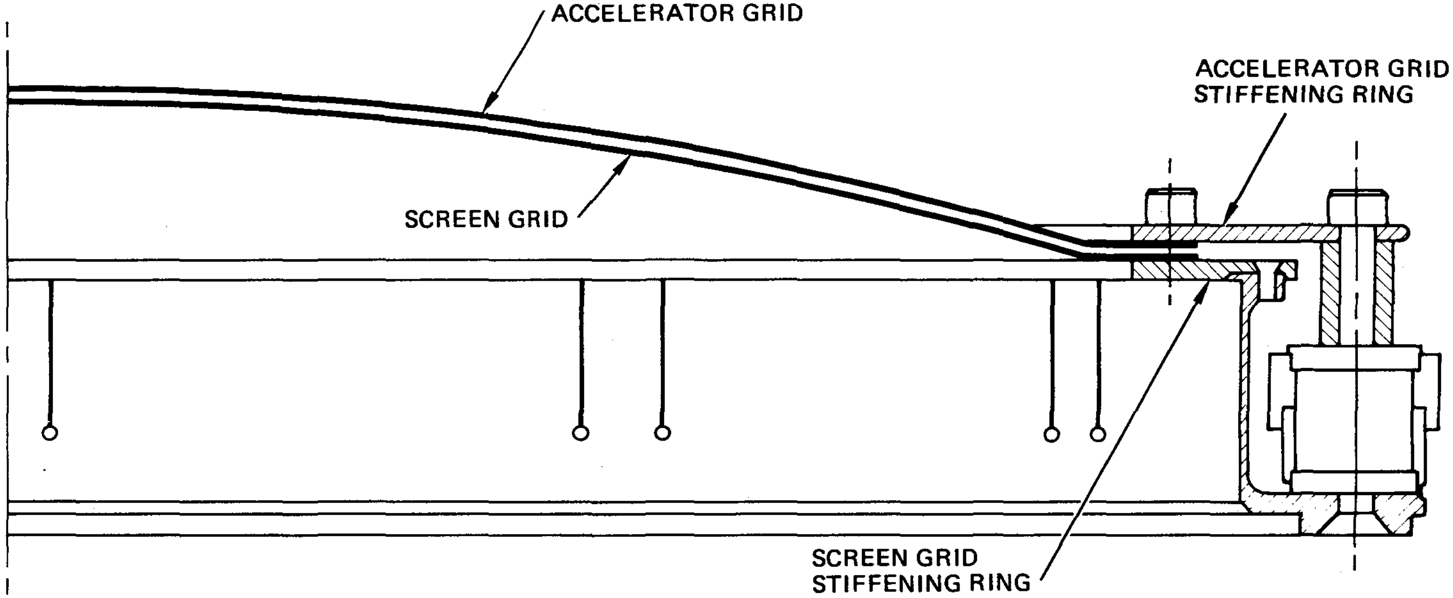

Figure 3. Cross section of the ion accelerator grid assembly for the J-series 30-cm thruster.

The replacement of isolator-vaporizer (I-V) assemblies was not considered an item for retrofit under this program. However, testing of the existing I-V assemblies under contract NAS 3-21357 disclosed marginal performance of several assemblies. Consequently, a complete redesign of all I-V assemblies and revision of fabrication procedures was undertaken under NAS 3-21357.

Several cathode heaters failed during cathode conditioning; these failures were traced to the use of poor-quality tantalum by the heater vendor. Heater specifications were revised and made more restrictive, with the result that the vendor was unable to fabricate satisfactory heaters for a period of more than a year (severely delaying the retrofit program).

Having overcome these obstacles, retrofit modification of several thrusters was completed; acceptance tests were performed on these thrusters. By April 1980, the design and test specifications were considered to be stabilized, and thruster SN J3 was transferred to this program as a "representative" thruster for "characterization" testing over an extended range of operating parameters. Although this thruster should be representative of performance capabilities, the I-V assemblies are not of the J-series design (as described in the final documentation package). The test results for this thruster are described in Section 5.

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SECTION 5

CHARACTERIZATION TESTING OF THRUSTER SNJ3

After acceptance testing of thruster SNJ3 under contract NAS 3-21357, the thruster was transferred to this program for testing over an extended range of operating parameters. As discussed above, the acceptance test provides data for defining some of the thruster control settings as functions of beam current. Consequently, the acceptance test results will be discussed here briefly before presenting the characterization test data.

The performance data for the acceptance test of thruster SNJ3 are summarized in Table 3. The format of this table is different from that of Table 1, which summarizes the acceptance test data for thruster SNJ1. This difference is a consequence of the changes to the acceptance testing and reporting procedures that have evolved since the procedures listed in Appendix A were formulated. Two of the test procedures that are required for defining the control set-points for operating the thruster over its range of capability are the measurement of the magnetic-baffle-current/cathode-keeper-voltage characteristic and the neutralizer-keeper-voltage/neutralizer-vaporizer-temperature characteristic (as functions of ion beam current). From these characteristics, the so-called "standard" reference values for the magnetic baffle current and the neutralizer keeper voltage were defined; these are plotted as functions of ion beam current in Figures 4 and 5.

To measure propellant flow requires a relatively long period; the acceptance test data were used to define a "calibration" of propellant flow rate as a function of vaporizer temperature. The relationships shown in Figures 6 through 8 were used to determine the propellant flows for the characterization test. This permitted collecting a relatively large number of data without logging an excessive amount of time on the thruster (which results in the deposition of back-sputtered collector material on the thruster).

Table 3. Acceptance Test Data/Performance Summary for Thruster SNJ3

10481-4

			TEST POINT											
			1	2	3	4	5	6	7	8	9	10		
OPERATING PARAMETERS	V_b	V	1101	1100	1100	940	1099	817	698	1099	597	596		
	J_b	A	2.007	2.002	2.003	1.600	1.300	1.297	0.997	0.751	0.750	0.750		
	V_D	V	32.0	31.0	32.0	32.0	32.0	32.0	32.0	32.0	32.0	31.0		
	J_D	A	14.0	14.0	13.4	11.6	9.8	9.8	8.0	6.49	6.49	6.49		
	J_E	A	12.0	12.0	11.4	10.0	8.5	8.50	7.0	5.74	5.74	5.74		
	J_{MB}	A	2.1	2.10	2.10	2.5	2.70	2.70	2.90	3.00	3.00	3.00		
	V_{CK}	V	4.30	4.22	4.30	4.80	5.31	5.34	5.99	6.72	6.75	6.88		
	J_{CK}	A	0.957	0.957	0.958	0.967	0.957	0.967	0.954	0.956	0.967	0.953		
	V_{ACCEL}	V	-340	-340	-340	-336	-341	-334	-331	-339	-328	-327		
	J_{ACCEL}	mA	4.14	4.11	3.90	3.96	1.93	2.27	1.75	1.10	1.25	1.52		
	V_{NK}	V	15.08	14.70	14.72	14.99	15.34	15.28	15.71	15.73	15.72	15.80		
	J_{NK}	A	1.81	2.10	2.10	1.81	1.81	1.81	1.81	1.81	1.81	1.80		
	V_G	V	10.55	10.61	10.61	10.84	10.96	11.09	11.14	11.40	10.90	11.16		
FLOWS	T_{MV}	°C	314	313	311	304	297	296	287	276	275	274		
	T_{CV}	°C	326	330	321	336	340	338	338	344	344	357		
	T_{NV}	°C	298	306	304	304	306	306	309	316	311	316		
	$\dot{m}_{MV}$	eq A	1.971	2.016	2.002	1.593	1.287	1.294	1.006	0.754	0.755	0.716		
	$\dot{m}_{CV}$	eq A	0.073	0.078	0.065	0.084	0.097	0.090	0.095	0.103	0.103	0.144		
	$\dot{m}_{NV}$	eq A	0.026	0.027	0.030	0.028	0.029	0.030	0.034	0.039	0.036	0.038		
	$\dot{m}_t$	eq A	2.070	2.121	2.097	1.705	1.413	1.414	1.135	0.896	0.894	0.898		
	η_{mD} (UNC)	%	98.2	95.6	96.9	95.4	93.9	93.7	90.6	87.6	87.4	87.2		
	η_{mD}	%	92.5	91.1	91.8	91.3	91.5	90.3	88.1	86.2	85.9	85.6		
	η_m (UNC)	%	97.0	94.4	95.5	93.8	92.0	91.7	87.8	83.8	83.9	83.5		
POWER	P_b	W	2210	2202	2203	1504	1429	1060	696	825	448	447		
	P_V	W	8.35	11.42	8.41	9.70	11.3	10.9	12.0	13.5	13.2	15.4		
	P_t	W	2661	2648	2638	1887	1763	1394	980	1069	691	687		
	η_e	%	83.1	83.2	83.5	79.7	81.1	76.0	71.0	77.2	64.8	65.1		
BEAM	α		0.9657	0.9721	0.9689	0.9747	0.9785	0.9785	0.9838	0.9909	0.9898	0.9893		
	F_T		0.9860	0.9877	0.9874	0.9874	0.9877	0.9857	0.9841	0.9851	0.9816	0.9867		
	γ		0.9522	0.9601	0.9567	0.9624	0.9665	0.9645	0.9682	0.9761	0.9716	0.9761		
	β		0.9416	0.9525	0.9470	0.9569	0.9634	0.9634	0.9724	0.9844	0.9825	0.9817		
	J_b^{++}/J_b^{+}		0.1324	0.1051	0.1186	0.0944	0.0790	0.0790	0.0585	0.0322	0.0362	0.0379		
MISC	η_T	%	73.1	72.4	73.0	69.2	69.7	64.8	58.4	61.6	51.3	51.8		
	F	mN	129.3	130.0	129.6	96.3	84.9	72.9	52.0	49.6	36.3	36.4		
	I_{SP}	sec	3066	3008	3033	2771	2950	2531	2249	2714	1993	1992		
	P_{tank}	Pa	2.9^{-4}	1.2^{-4}	1.3^{-4}	2^{-4}	1.6^{-4}	2^{-5}	7.5^{-5}	1.2^{-4}	1.9^{-4}	8.7^{-5}		

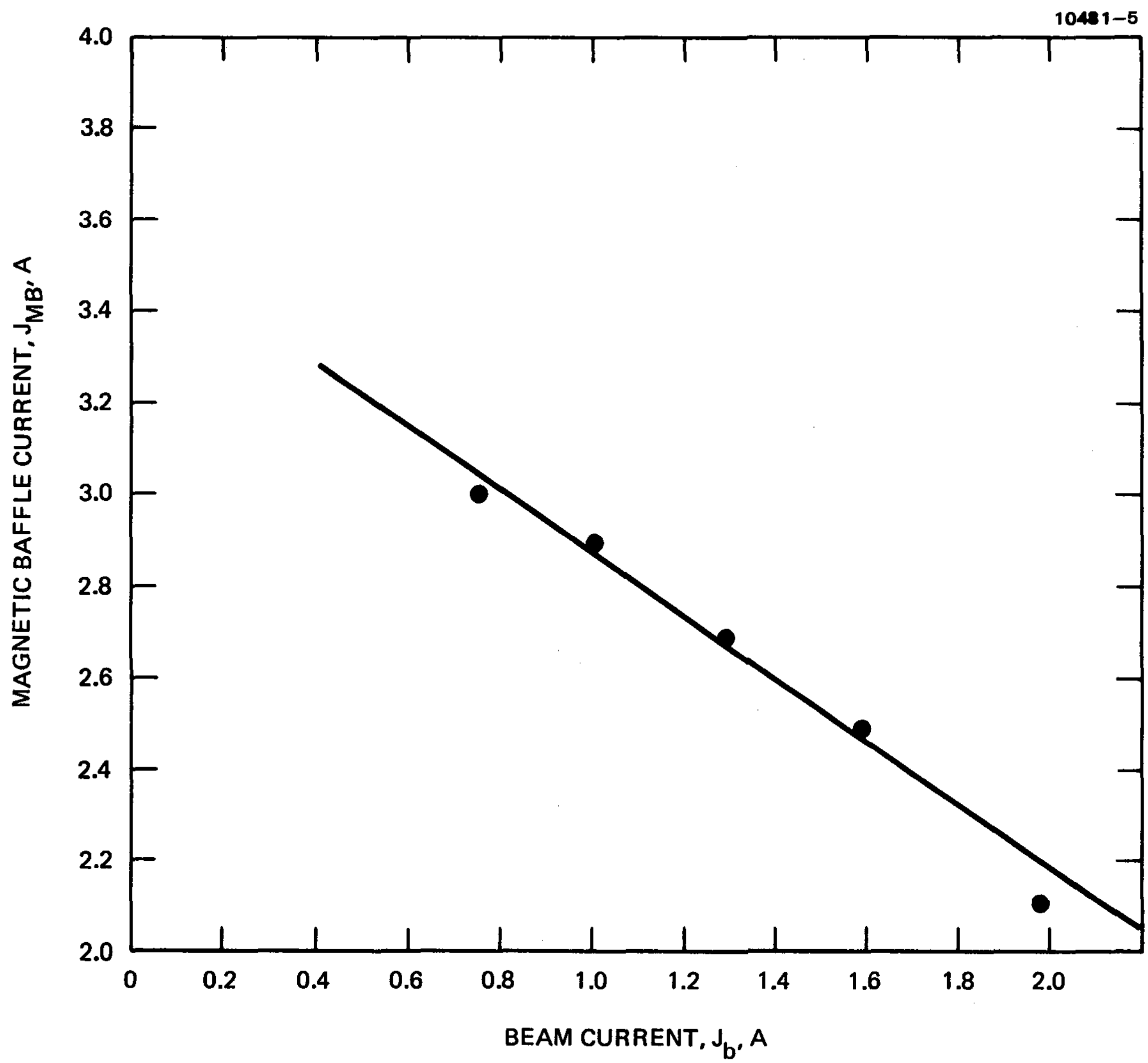

Figure 4. Magnetic baffle current selection for thruster SNJ3.

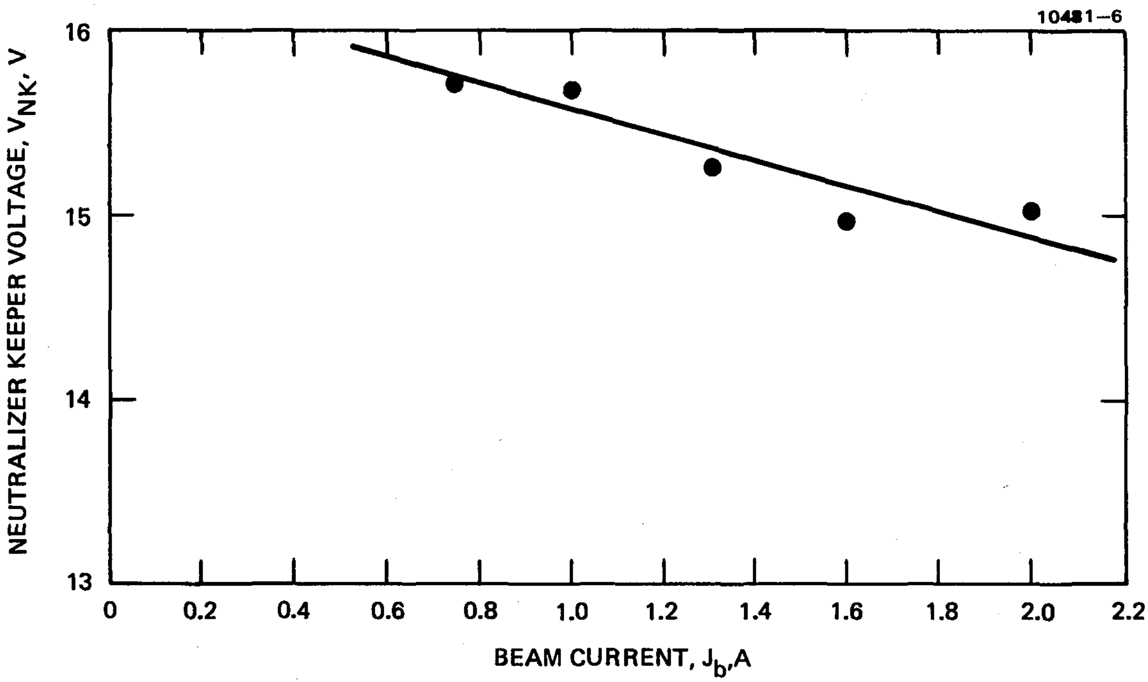

Figure 5. Neutralizer keeper reference voltages selected for thruster SNJ3.

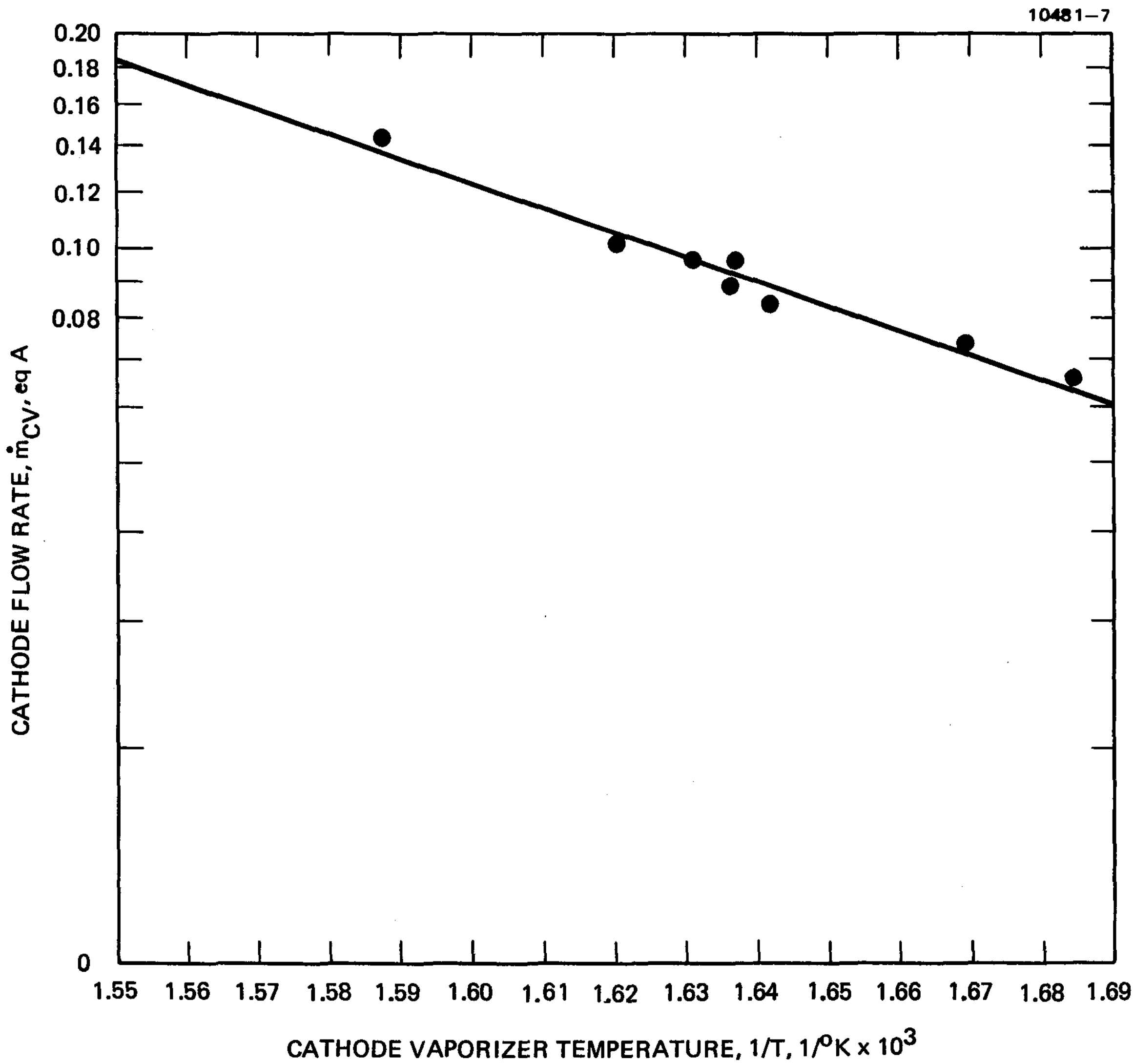

Figure 6. J-3 cathode vaporizer flow rate as a function of T_{VAP}^{-1}.

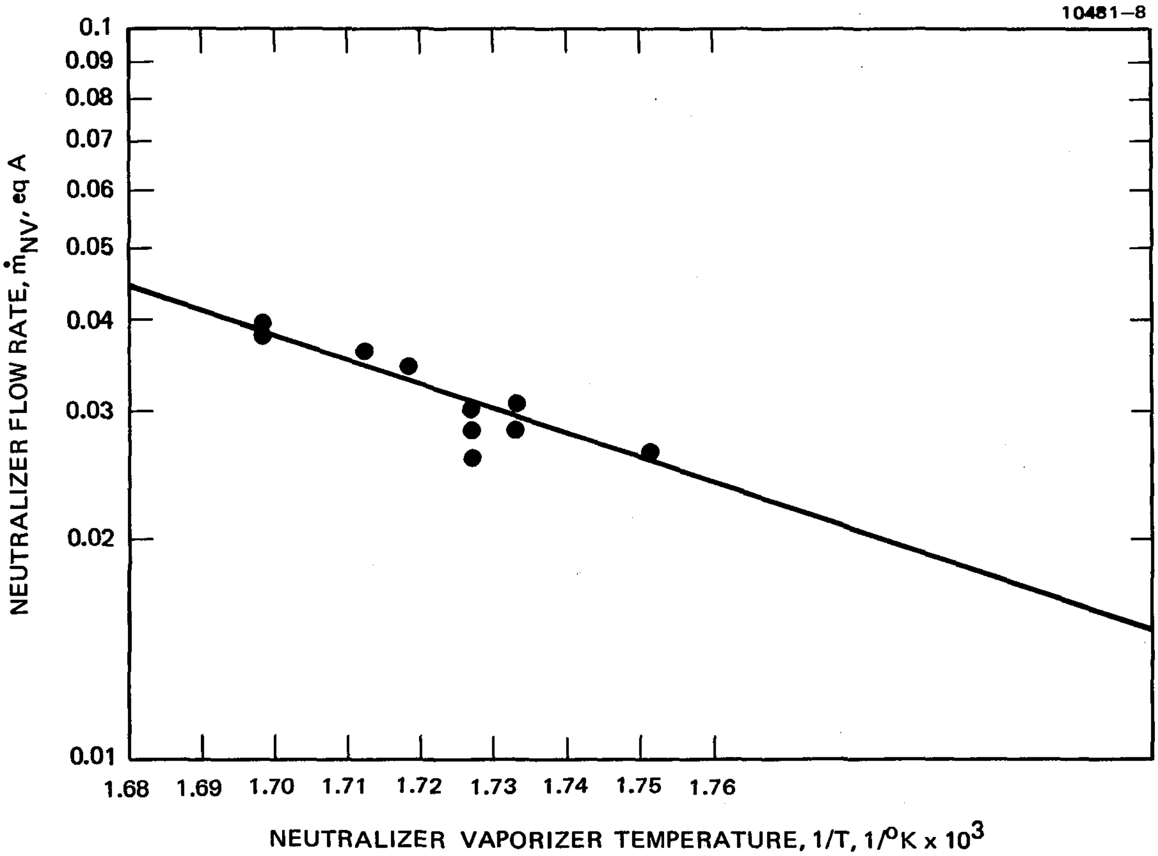

Figure 7. J-3 neutralizer vaporizer flow rate as a function of T_{VAP}^{-1}.

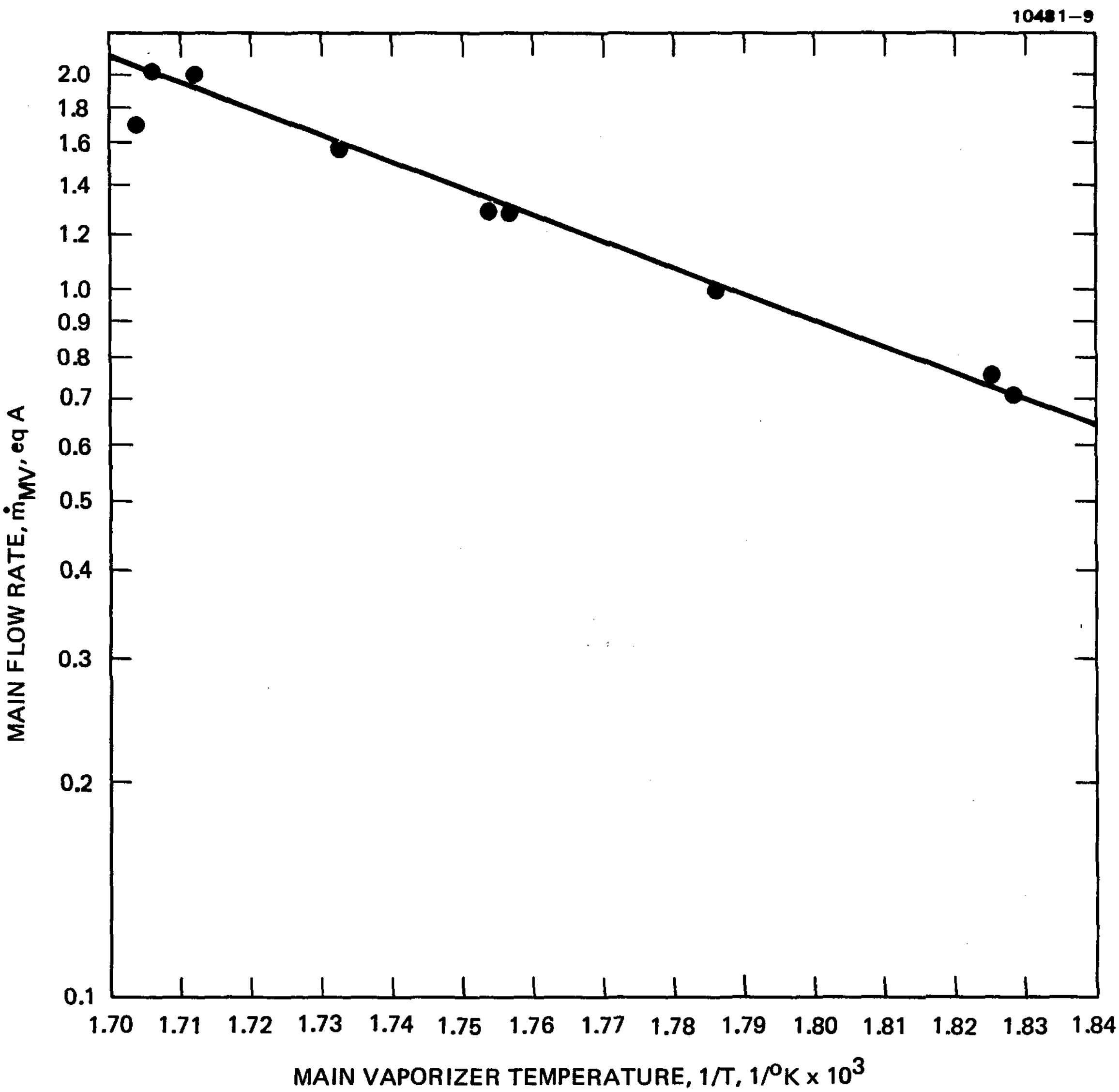

Figure 8. J-3 main vaporizer flow rate as a function of T_{VAP}^{-1}.

The characterization tests consisted of operating the thruster over the range from 0.75 A to 2.0 A at control set-points other than the 10 points of the operating envelope defined in the acceptance test. Table 4 shows the 47 tests that were performed (and also includes the set-point values for the standard acceptance test set-points, which are designated by TP).

Data for five beam current levels (J_b = 2.0, 1.6, 1.3, 1.0, and 0.75 A) are shown in Table 5. All are standard throttling points for the thruster. Discharge chamber voltage and current plus magnetic baffle current variations were investigated for J_b = 2.0, 1.3, and 0.75 A. Slight variations in V_b and V_{accel} were made for all beam levels.

Correction factors for doubly charged ions and beam divergence were measured for each test number. Vaporizer temperatures were recorded, but flow rates were not measured. An approximate flow value was obtained by using temperatures that corresponded to flow values generated from the acceptance test. The relationships between vaporizer temperature and flow value (from the acceptance test) are shown in Figures 6, 7, and 8. At the time the data in Table 5 were being collected, the time required for achieving thermal equilibrium was thought to be less than 1 hr. But now we know that equilibrium temperatures and propellant flow conditions are not reached until about 3 hr after changing operating points (resulting in a change in beam current or discharge power). Consequently, the data in Table 5 represent some operating points that were not yet at thermal equilibrium and, therefore, any use of this data to cross-plot and examine specific behavioral patterns should be approached with the precaution that apparent trends may be incorrect or contradictory. After exploring several possibilities for interpreting and drawing conclusions from these data, it was determined that the most significant results can be obtained from analyzing the thrust correction factors for beam divergence and doubly charged ions in the extraction ion beam.

Table 4. Thruster Operating Parameters for Characterization Test Points

10481-10A

BEAM CURRENT	V_b, V	V_D, V	TEST POINT	J_E, A	J_{MB}, A	ACCEL, -V	TEST NUMBER
J_b = 2.0 A	1100	32	1	12.0	STD 2.1	300	TP1 Ⓐ
	900	32		12.0	↓	300	1
	1100	32		12.0	2.0	300	2
					2.3		3
					2.4		4
	↓	↓		↓	2.6	↓	5
	1100	31 V	2	12.0	STD 2.1	300	TP2 Ⓐ
	1100 V	34		12.0		300	6
	1100 V	36		12.0	↓	300	7
	1100	32		12.0	STD 2.1	500	8
	↓	↓		↓	↓	400	9
	1100	32		11.75	STD 2.1	300	10
			3	11.5			TP3 Ⓐ
↓	↓	↓		11.25	↓	↓	11
J_b = 1.6 A	1100	32		10.0	STD 2.5	300	12
	940	32	4	10.0		300	TP4 Ⓐ
↓	MIN	32		10.0	↓	300	13
J_b = 1.3 A	1100	32	5	8.5	STD 2.7	300	TP5 Ⓐ
	820	32	6	8.5		300	TP6 Ⓐ
	MIN	32		8.5	↓	300	14
	820	32		8.5	STD 2.7	500	15
	↓	↓		↓	↓	400	16
	1100	32		8.5	STD 2.7	500	17
	↓	↓			↓	400	18
	820	34		8.5	STD 2.7	300	19
	820	36		8.5	↓	300	20
	820	32		8.5	2.2	300	21
					2.4		22
					3.2		23
↓	↓	↓		↓	3.4	↓	24

Ⓐ STANDARD THRUSTER ACCEPTANCE TEST POINT

Table 4. Continued

10481-10B

BEAM CURRENT	V_b, V	V_D, V	TEST POINT	J_E, A	J_{MB}, A	V_{ACCEL}, -V	TEST NUMBER
J_b = 1.3 A	820	32		9.0	STD 2.7	300	25
				8.0		300	26
↓	↓	↓		9.5	↓	300	27
J_b = 1.0 A	1100	32		7.0	STD 2.9	300	28
	900			7.0			29
	700		7	7.0			TP7 (A)
↓	MIN	↓		7.0	↓	↓	30
J_b = 0.75 A	1100	32	8	5.75	STD 3.0	300	TP8 (A)
	900						31
	600	↓	9	↓	↓	↓	TP9 (A)
	1100	32		5.75	STD 3.0	500	32
	↓	↓		↓	↓	400	33
	600	32		5.75	STD 3.0	500	34
	↓	↓		↓	↓	400	35
	600	32		5.75	2.4	300	36
					2.8		37
					3.2		38
	↓	↓		↓	3.4	↓	39
	600	31	10	5.75	STD 3.0	300	TP10 (A)
	600	34		5.75		300	40
	↓	36		5.75	↓	↓	41
	600	32		5.5	STD 3.0	300	42
				6.25			43
	↓	↓		6.75	↓	↓	44
	1100	32		4.5	STD 3.1	300	45
						500	46
↓	↓	↓		↓	↓	400	47

(A) STANDARD THRUSTER ACCEPTANCE TEST POINT

Table 5. Characterization Test Data/Performance Summary for Thruster SNJ3

10481-11A

			TEST NUMBERS											
			1	2	3	4	5	6	7	8	9	10	11	
OPERATING PARAMETERS	V_b	V	901	1100	1100	1100	1100	1102	1103	1101	1102	1100	1100	
	J_b	A	2.003	2.003	2.004	2.004	2.005	2.004	2.003	2.003	1.995	2.003	2.005	
	V_D	V	32.0	32.0	32.0	32.0	32.0	34.0	<36.0>	32.0	32.0	32.0	32.0	
	J_D	A	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	14.0	13.76	13.24	
	J_E	A	12.0	12.0	12.0	12.0	12.0	12.0	12.0	11.0	12.0	11.76	11.24	
	J_{MB}	A	2.10	2.00	2.30	2.40	2.60	2.10	2.10	2.10	2.10	2.10	2.11	
	V_{CK}	V	4.12	4.08	4.12	4.09	4.38	3.96	3.91	4.04	4.12	4.10	4.28	
	J_{CK}	A	0.943	0.942	0.942	0.943	0.945	0.943	0.942	0.939	0.947	0.940	0.938	
	V_{ACCEL}	V	-337	-341	-341	-341	-341	-342	-340	-528	-386	-340	-340	
	J_{ACCEL}	mA	4.0	3.61	3.65	3.69	3.64	3.20	3.17	3.41	3.36	3.79	3.88	
	V_{NK}	V	14.97	14.98	14.97	14.96	14.95	14.97	15.03	15.01	15.00	15.01	15.01	
	J_{NK}	A	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	
	V_G	V	10.67	10.66	10.61	10.60	10.58	10.61	10.65	10.68	10.68	10.64	10.63	
FLOWS	T_{MV}	°C	313	311	311	310	309	309	311	311	312	311	311	
	T_{CV}	°C	322	322	329	329	343	318	319	326	327	322	321	
	T_{NV}	°C	305	304	303	303	303	302	306	305	305	303	303	
	$\dot{m}_{MV}$	eq A	2.010	1.910	1.910	1.860	1.820	1.820	1.910	1.910	1.960	1.910	1.910	
	$\dot{m}_{CV}$	eq A	0.065	0.065	0.077	0.077	0.103	0.059	0.061	0.071	0.073	0.065	0.064	
	$\dot{m}_{NV}$	eq A	0.030	0.030	0.029	0.029	0.029	0.028	0.031	0.030	0.030	0.029	0.029	
	$\dot{m}_t$	eq A	2.105	2.005	2.016	1.966	1.952	1.907	2.002	2.011	2.063	2.004	2.003	
	η_{mD} (UNC)	%	96.5	101.4	100.9	103.5	104.3	106.7	101.6	101.1	98.1	101.4	101.6	
	η_{mD}	%	91.5	95.4	95.0	97.6	98.4	99.0	92.1	95.5	92.9	95.8	96.5	
	η_m (UNC)	%	95.2	99.9	99.4	101.9	102.7	105.1	100.0	99.6	96.7	100.0	100.1	
POWER	P_b	W	1805	2203	2204	2204	2206	2209	2209	2205	2198	2203	2206	
	P_V	W	10.5	9.2	10.5	9.4	11.2	8.6	9.4	9.6	14.91	8.1	8.8	
	P_t	W	2261	2658	2661	2660	2664	2687	2712	2661	2659	2649	2637	
	η_e	%	79.8	82.9	82.8	82.9	82.8	82.2	81.5	82.9	82.7	83.2	83.7	
BEAM	α		0.9692	0.9653	0.9660	0.9669	0.9671	0.9580	0.9452	0.9675	0.9690	0.9675	0.9708	
	F_T		0.9868	0.9875	0.9881	0.9882	0.9876	0.9876	0.9866	0.9853	0.9859	0.9876	0.9878	
	γ		0.9564	0.9532	0.9545	0.9555	0.9551	0.9461	0.9325	0.9533	0.9553	0.9555	0.9590	
	β		0.9474	0.9408	0.9419	0.9435	0.9439	0.9283	0.9065	0.9446	0.9470	0.9446	0.9502	
	J_b^{++}/J_b^{+}		0.1175	0.1343	0.1314	0.1274	0.1265	0.1675	0.2301	0.1246	0.1185	0.1246	0.1106	
MISC	η_T	%	69.5	75.2	75.0	77.1	77.6	77.3	70.9	75.0	73.0	76.0	77.1	
	F	mN	117.3	129.1	129.4	129.5	129.5	128.3	126.5	129.2	127.9	128.0	128.8	
	I_{SP}	sec	2734	3161	3149	3233	3256	3303	3101	3153	3069	3170	3186	
	P_{tank}	Pa	1.1^{-4}	1.6^{-4}	2.9^{-4}	2.3^{-4}	2.1^{-4}	2.1^{-4}	1.1^{-4}	1.6^{-4}		1.2^{-4}	1.5^{-4}	

Table 5. Continued

10481-118

			TEST NUMBERS										
			12	13	14	15	16	17	18	19	20	21	22
OPERATING PARAMETERS	V_b	V	1100	795	731	819	818	1100	1100	820	822	818	818
	J_b	A	1.599	1.599	1.297	1.297	1.300	1.299	1.299	1.298	1.298	1.299	1.298
	V_D	V	32.0	32.0	32.0	32.0	32.0	32.0	32.0	34.0	36.0	32.0	32.0
	J_D	A	11.6	11.6	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8	9.8
	J_E	A	10.0	10.0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
	J_{MB}	A	2.50	2.50	2.70	2.70	2.70	2.70	2.70	2.70	2.70	2.2	2.4
	V_{CK}	V	4.66	4.67	5.22	5.21	5.25	5.20	5.22	5.13	5.07	5.30	5.29
	J_{CK}	A	0.936	0.938	0.937	0.938	0.938	0.937	0.937	0.937	0.937	0.938	0.938
	V_{ACCEL}	V	-308	-304	-302	-518	-380	-525	-387	-303	-303	-303	-303
	J_{ACCEL}	mA	2.72	3.29	2.51	2.28	2.15	2.02	2.07	2.00	1.89	2.16	2.22
	V_{NK}	V	15.03	15.02	15.01	15.01	15.01	15.00	15.00	14.99	14.98	14.96	14.98
	J_{NK}	A	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10	2.10
	V_G	V	10.70	10.66	10.80	10.77	10.74	10.79	10.75	10.73	10.73	10.72	10.72
FLOWS	T_{MV}	°C	304	304	296	295	295	295	295	295	294	296	296
	T_{CV}	°C	334	331	334	336	336	336	337	333	330	331	334
	T_{NV}	°C	308	308	310	309	310	309	309	310	310	310	310
	$\dot{m}_{MV}$	eq A	1.590	1.590	1.290	1.260	1.260	1.260	1.260	1.260	1.230	1.290	1.290
	$\dot{m}_{CV}$	eq A	0.085	0.079	0.085	0.089	0.089	0.089	0.091	0.083	0.078	0.079	0.085
	$\dot{m}_{NV}$	eq A	0.032	0.032	0.034	0.033	0.034	0.033	0.033	0.034	0.034	0.034	0.034
	$\dot{m}_t$	eq A	1.607	1.601	1.309	1.382	1.383	1.382	1.384	1.377	1.342	1.403	1.409
	η_{mD} (UNC)	%	95.5	95.8	94.3	96.1	96.4	96.3	96.2	96.6	99.2	94.9	94.4
	η_{mD}	%	90.7	93.4	91.4	92.9	92.8	92.8	92.9	92.0	93.5	91.4	91.0
	η_m (UNC)	%	99.5	99.9	99.1	93.8	94.0	94.0	93.9	94.3	96.7	92.6	92.1
POWER	P_b	W	1759	1271	948	1062	1063	1429	1429	1064	1067	1063	1062
	P_V	W	14.5	11.2	10.2	9.99	10.9	10.7	11.2	10.7	10.5	10.1	10.4
	P_t	W	2151	1659	1284	1398	1400	1766	1767	1417	1437	1398	1398
	η_e	%	81.8	76.6	73.8	76.0	75.9	80.9	80.9	75.1	74.3	76.0	76.0
BEAM	α		0.9707	0.9750	0.9818	0.9802	0.9780	0.9790	0.9799	0.9718	0.9660	0.9786	0.9788
	F_T		0.9868	0.9868	0.9861	0.9830	0.9851	0.9836	0.9856	0.9867	0.9867	0.9865	0.9865
	γ		0.9579	0.9621	0.9682	0.9635	0.9634	0.9629	0.9658	0.9589	0.9532	0.9654	0.9656
	β		0.9500	0.9750	0.9690	0.9662	0.9625	0.9642	0.9657	0.9519	0.9419	0.9635	0.9638
	J_b^{++}/J_b^{+}		0.1110	0.0932	0.0662	0.0725	0.0811	0.0771	0.0737	0.1066	0.1315	0.0787	0.0780
MISC	η_T	%	74.7	70.8	68.6	66.2	66.2	70.5	70.9	65.1	65.3	65.6	65.3
	F	mN	102.7	89.6	69.3	73.1	73.0	84.7	84.8	72.1	71.5	73.0	73.0
	I_{SP}	sec	3164	2711	2596	2590	2592	3004	3009	2590	2645	2558	2546
	P_{tank}	Pa	1.5^{-4}	1.5^{-4}	1.3^{-4}	1.9^{-4}	3.3^{-4}	2.3^{-4}	2.8^{-4}	4.8^{-4}	4.4^{-4}	4.3^{-4}	5.3^{-4}

Table 5. Continued

10481-11C

			TEST NUMBERS										
			23	24	25	26	27	28	29	30	31	32	33
OPERATING PARAMETERS	V_b	V	819	818	820	819	819	1099	899	647	899	1100	1100
	J_b	A	1.297	1.298	1.297	1.295	1.295	0.996	0.998	0.997	0.752	0.752	0.752
	V_D	V	32	32	32	32	32	32	32	32	32	32	32
	J_D	A	9.8	9.8	10.3	9.3	10.8	8.0	8.0	8.0	6.5	6.5	6.5
	J_E	A	8.5	8.5	9.0	8.0	9.5	7.0	7.0	7.0	5.75	5.75	5.75
	J_{MB}	A	3.2	3.4	2.7	2.7	2.7	2.9	2.9	2.9	3.0	3.0	3.0
	V_{CK}	V	5.41	5.54	5.06	5.55	5.20	6.10	6.08	6.08	7.12	7.18	7.16
	J_{CK}	A	0.938	0.939	0.938	0.938	0.939	0.937	0.937	0.937	0.937	0.937	0.937
	V_{ACCEL}	V	-302	-302	-302	-302	-302	-306	-303	-299	-303	-521	-383
	J_{ACCEL}	mA	2.13	2.08	2.18	2.32	2.09	1.51	1.56	1.76	1.10	1.13	1.07
	V_{NK}	V	15.04	15.03	15.03	15.02	15.01	15.69	15.69	15.67	15.69	15.70	15.70
	J_{NK}	A	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
	V_G	V	10.75	10.77	10.82	10.78	10.76	10.74	10.70	10.69	10.80	10.83	10.81
FLOWS	T_{MV}	°C	297	296	296	297	294	285	286	287	274	274	274
	T_{CV}	°C	349	356	338	336	352	346	343	340	356	357	357
	T_{NV}	°C	310	310	310	310	309	309	309	309	314	314	314
	$\dot{m}_{MV}$	eq A	1.330	1.290	1.290	1.330	1.230	0.969	0.991	1.000	0.710	0.710	0.710
	$\dot{m}_{CV}$	eq A	0.116	0.133	0.092	0.089	0.123	0.108	0.103	0.097	0.133	0.137	0.137
	$\dot{m}_{NV}$	eq A	0.034	0.034	0.034	0.034	0.033	0.033	0.033	0.033	0.037	0.037	0.037
	$\dot{m}_t$	eq A	1.480	1.457	1.416	1.453	1.386	1.110	1.127	1.130	0.880	0.884	0.884
	η_{mD} (UNC)	%	89.7	91.2	93.8	91.3	95.7	92.5	91.2	90.9	89.2	88.8	88.8
	η_{mD}	%	86.5	87.8	90.3	88.6	91.7	90.1	88.8	88.5	87.3	87.1	87.5
	η_m (UNC)	%	87.6	89.1	91.6	89.1	93.4	89.7	88.6	88.2	85.5	85.1	85.1
POWER	P_b	W	1062	1062	1064	1061	1061	1095	897	645	676	827	827
	P_V	W	16.7	13.7	9.9	9.6	12.3	10.6	11.4	12.5	13.0	13.8	13.8
	P_t	W	1405	1402	1416	1381	1431	1382	1185	1230	924	1076	1076
	η_e	%	75.6	75.7	75.1	76.8	74.1	79.2	75.7	52.4	73.2	76.9	76.9
BEAM	α		0.9789	0.9782	0.9779	0.9827	0.9757	0.9850	0.9841	0.9844	0.9878	0.9889	0.9913
	F_T		0.9860	0.9862	0.9858	0.9860	0.9859	0.9843	0.9848	0.9845	0.9830	0.9807	0.9815
	γ		0.9652	0.9647	0.9640	0.9689	0.9619	0.9695	0.9691	0.9691	0.9710	0.9698	0.9730
	β		0.9640	0.9628	0.9623	0.9705	0.9585	0.9743	0.9729	0.9733	0.9792	0.9810	0.9852
	J_b^{++}/J_b^{+}		0.0776	0.0805	0.0817	0.0628	0.0906	0.0541	0.0573	0.0564	0.0435	0.0395	0.0306
MISC	η_T	%	61.7	62.8	63.9	64.2	64.0	66.8	63.0	43.4	59.0	61.5	62.0
	F	mN	73.1	73.0	73.0	73.2	72.7	65.3	59.1	50.1	44.6	49.3	49.5
	I_{SP}	sec	2422	2460	2531	2473	2574	2886	2575	2177	2490	2738	2747
	P_{tank}	Pa	1.1^{-4}	1.7^{-4}	2.4^{-4}	3.7^{-4}	3.2^{-4}	5.3^{-4}	5.5^{-4}	4.8^{-4}	4.8^{-4}	5.1^{-4}	4.3^{-4}

Table 5. Continued

10481-11D

			TEST NUMBERS										
			34	35	36	37	38	39	40	41	42	43	44	
OPERATING PARAMETERS	V_b	V	600	599	598	599	598	598	601	603	598	599	599	
	J_b	A	COULD	0.752	0.752	0.752	0.752	0.752	0.752	0.752	0.753	0.753	0.753	
	V_D	V	NOT	32	32	32	32	32	34	36	32	32	32	
	J_D	A	GET	6.5	6.5	6.5	6.5	6.5	6.5	6.5	6.25	7.0	7.5	
	J_E	A	V_{ACCEL}	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.50	6.25	6.75	
	J_{MB}	A	= -500	3.0	2.4	2.8	3.2	3.4	3.0	3.0	3.0	3.0	3.0	
	V_{CK}	V		6.91	6.92	6.56	6.78	6.84	6.60	6.60	6.98	6.76	6.76	
	J_{CK}	A		0.940	0.947	0.946	0.939	0.939	0.945	0.939	0.939	0.945	0.947	
	V_{ACCEL}	V		-367	-298	-297	-297	-297	-298	-298	-298	-298	-298	
	J_{ACCEL}	mA		1.24	1.27	1.30	1.25	1.26	1.17	1.15	1.25	1.30	1.38	
	V_{NK}	V		15.71	15.70	15.70	15.69	15.67	15.72	15.74	15.71	15.69	15.68	
	J_{NK}	A		2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1	
	V_G	V		10.79	10.77	10.91	10.94	10.92	10.88	10.84	10.87	10.84	10.86	
FLOWS	T_{MV}	°C		277	277	277	276	276	277	276	278	275	271	
	T_{CV}	°C		348	339	337	355	357	341	339	344	358	370	
	T_{NV}	°C		314	314	316	316	316	316	316	316	316	316	
	$\dot{m}_{MV}$	eq A		0.772	0.772	0.772	0.752	0.752	0.772	0.752	0.792	0.729	0.652	
	$\dot{m}_{CV}$	eq A		0.114	0.094	0.091	0.132	0.137	0.098	0.094	0.104	0.140	0.183	
	$\dot{m}_{NV}$	eq A		0.037	0.037	0.039	0.039	0.039	0.039	0.039	0.039	0.039	0.039	
	$\dot{m}_t$	eq A		0.923	0.903	0.902	0.923	0.928	0.909	0.885	0.935	0.908	0.874	
	η_{mD} (UNC)	%		84.9	86.8	87.1	85.1	84.6	86.4	88.9	84.0	86.7	90.2	
	η_{mD}	%		84.0	85.6	85.9	83.9	83.2	84.6	86.1	82.8	85.1	88.3	
	η_m (UNC)	%		81.5	83.3	83.4	81.5	81.0	82.7	85.0	80.5	82.9	86.2	
POWER	P_b	W		450	450	450	450	450	452	453	450	451	451	
	P_V	W		12.7	12.3	13.6	15.8	14.7	12.5	12.4	12.7	14.32	15.15	
	P_t	W		697	696	697	700	699	699	699	689	715	732	
	η_e	%		64.6	64.7	64.6	64.3	64.4	64.7	64.8	65.3	63.1	61.6	
BEAM	α			0.9938	0.9917	0.9918	0.9917	0.9903	0.9873	0.9815	0.9915	0.9892	0.9876	
	F_T			0.9817	0.9823	0.9820	0.9815	0.9822	0.9815	0.9824	0.9826	0.9823	0.9812	
	γ			0.9658	0.9741	0.9739	0.9734	0.9727	0.9690	0.9642	0.9742	0.9717	0.9690	
	β			0.9895	0.9859	0.9861	0.9858	0.9835	0.9784	0.9684	0.9854	0.9816	0.9788	
	J_b^{++}/J_b^{+}			0.0215	0.0291	0.0286	0.0293	0.0341	0.0452	0.0674	0.0300	0.0382	0.0442	
MISC	η_T	%		49.1	51.1	52.4	49.7	49.4	50.2	51.2	49.9	49.4	55.6	
	F	mN		36.2	36.5	36.5	36.5	36.5	36.4	36.3	36.6	36.5	36.4	
	I_{SP}	sec		1927	1985	1989	1941	1929	1967	2013	1920	1974	2045	
	P_{tank}	Pa		4.4^{-6}	3.9^{-6}	8.0^{-5}	2.7^{-6}	3.3^{-4}	3.2^{-4}	3.9^{-4}	4.8^{-4}	4.8^{-4}	8.2^{-4}	

Table 5. Continued

10481-11E

			TEST NUMBERS 45	46	47
OPERATING PARAMETERS	V_b	V	1100	1100	1100
	J_b	A	0.752	0.752	0.752
	V_D	V	32	32	32
	J_D	A	5.25	5.25	5.25
	J_E	A	4.50	4.50	4.50
	J_{MB}	A	3.1	3.1	3.1
	V_{CK}	V	7.79	7.85	7.91
	J_{CK}	A	0.945	0.938	0.938
	V_{ACCEL}	V	-306	-521	-385
	J_{ACCEL}	mA	1.22	1.29	1.29
	V_{NK}	V	15.66	15.70	15.69
	J_{NK}	A	2.1	2.1	2.1
	V_G	V	10.88	10.86	10.85
FLOWS	T_{MV}	°C	278	278	278
	T_{CV}	°C	346	346	347
	T_{NV}	°C	316	315	315
	$\dot{m}_{MV}$	eq A	0.792	0.792	0.792
	$\dot{m}_{CV}$	eq A	0.108	0.108	0.112
	$\dot{m}_{NV}$	eq A	0.039	0.038	0.038
	$\dot{m}_t$	eq A	0.939	0.938	0.942
	η_{mD} (UNC)	%	83.6	83.6	83.2
	η_{mD}	%	82.8	82.6	82.5
	η_m (UNC)	%	80.1	80.2	79.8
POWER	P_b	W	827	827	827
	P_V	W	12.2	13.9	11.9
	P_t	W	1035	1036	1035
	η_e	%	79.9	79.8	79.9
BEAM	α		0.9946	0.9931	0.9952
	F_T		0.9828	0.9806	0.9819
	γ		0.9775	0.9738	0.9772
	β		0.9907	0.9883	0.9918
	J_b^{++}/J_b^{+}		0.0189	0.0240	0.0167
MISC	η_T	%	61.2	60.7	60.9
	F	mN	49.7	49.5	49.7
	I_{SP}	sec	2598	2591	2589
	P_{tank}	Pa	6.9^{-4}	5.6^{-4}	6.9^{-4}

These factors have already been analyzed in detail for these data by R.T. Bechtel of LeRC; his analysis is included as Appendix B. This analysis shows that the thrust correction factor for beam divergence, F_T, depends primarily on accelerator voltage V_{accel} (as would be expected) and is relatively insensitive to variations in other operating parameters. The thrust correction for doubly charged ions, α, depends primarily on discharge voltage V_D and to a lesser degree on discharge current J_E (for any given beam current). The value of α also decreases with increasing beam current. These variations are also anticipated and in agreement with theoretical analyses of doubly charged ion production. One significant observation is that, since α is relatively independent of beam voltage V_b (at any given beam current), changing the specific impulse I_{sp} would not be expected to affect thruster lifetime (as determined by screen grid wear). A second observation is that, since the value of α is also relatively independent of the magnetic baffle excitation J_{MB}, assignment of J_{MB} would not be expected to affect thruster lifetime (as determined by screen grid wear). Because of the relatively small dispersion in the measured values of these correction factors as a function of variations in operating parameters, it is reasonable to conclude that the correction factors will not be the dominant source of error in determining thrust or thruster efficiency (unless there is a systematic error in the measurement technique).

The characterization test demonstrated that it is possible to operate a J-series thruster over a wide range of operating parameters that produce thrust ranging from 45 to 129 mN at specific impulse ranging from 1927 sec to 3303 sec. No operational instabilities were noted over the range of values in the test.

SECTION 6

CONCLUSIONS

The work performed under this program comprised the first step in upgrading the 900-series 30-cm mercury ion thruster to the J series. The block of design changes that was formulated for correcting known and potential design deficiencies was successfully implemented in a thruster and verified. Only one design change (ion optics assembly) required iteration (under another contract), and thruster performance capabilities are now considered to satisfy the design goals. The design verification testing performed under this program should not be considered all inclusive in that the scope of this program was intended to show feasibility for operating the thruster over the intended envelope of power levels and specific impulse values. Many performance characteristics (wearout rates, dispersion between thrusters, etc.) remain to be documented; however, the results obtained under this program, and under the subsequent contract (NAS 3-21357), indicate that the J-series thruster should be capable of meeting all of the design goals. It is anticipated that this conclusion will be supported by the results from extensive testing and thruster qualification work being done under other programs.

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APPENDIX A

ACCEPTANCE TEST PROCEDURES

(Original Form)

The inspection and process documents (IPDs) for the 30-cm thruster acceptance test are reproduced here in the form in which they were originally written and used for testing of thruster SN J1. In preparing these procedures, the goal was to prepare a description of the tests that could be used by personnel who have only limited experience with the characteristics of ion thrusters. Because of the difficulties encountered in the initial testing of thruster SN J1, these procedures were inadequate, and they were subsequently revised. For the record, IPD 138 through IPD 143 are included.

SPECIFICATION TITLE	APPROVALS			DATE	REV
30 Cm Thruster Acceptance Test Procedure					

1.0 SCOPE

This specification establishes the procedures for performing acceptance tests on 30 cm thrusters. The purpose of the thruster acceptance test is to verify the characteristics, capabilities, and performance of the thruster. Towards this end, this acceptance test will provide data and information to:

a) verify that a completed thruster operates and performs in the intended designed manner;

b) provide test data to allow for performance and physical comparison of different thrusters;

c) form a data base for each thruster to allow for thruster performance and physical comparisons at various stages during a thruster's useful life with the beginning of life conditions.

2.0 APPLICABLE DOCUMENTS

2.1 Facility Specifications

2.1.1 IPD-PR-139 Thruster Test Facility

2.1.2 IPD-PR-140 Power Processor

2.1.3 IPD-PR-141 Instrumentation and Calibration

2.2 Engineering Specifications

2.2.1 IPD-PR-142 Preliminary Thruster Preparation

2.2.2 IPD-PR-143 Data Formats for Thruster Testing

3.0 REQUIREMENTS

3.1 Equipment

3.1.1 30 cm thruster

3.1.2 Facilities per paragraph 2.1

3.1.3 Data sheets per paragraph 2.2.2

4.0 PROCEDURE

4.1 Thruster Preparation

4.1.1 Perform preliminary thruster measurements and install thruster in test facility per IPD-PR-142

TECH: ______________________

DATE: ______________________

4.2 Facility Pump Down

4.2.1 Allow facility to pump until base pressure is 5×10^{-5} torr or less.

TECH: ______________________

DATE: ______________________

4.3 Initial Cathode Conditioning

4.3.1 Connect power processor as specified in IPD-PR-140 and instrumentation as specified in IPD-PR-141. The circuit diagram is shown for reference as Fig. 4.1.

TECH: ______________________

DATE: ______________________

4.3.2 Record the serial number and other pertinent information as required on the initial start-up data form (specified in IPD-PR-143 as form

TECH: ______________________

DATE: ______________________

4.3.3 Condition thruster and neutralizer cathodes.

4.3.3.1 Facility pressure must be less than 5×10^{-5} torr.

4.3.3.2 Supply 2.5A current to both thruster cathode and neutralizer cathode heaters (I_3 and I_5). Maintain heater current for 3 hours. Record time and data on data sheet.

4.3.3.3 Turn off heaters and allow to cool for a minimum of one-half hour. Record time and pertinent data on data sheet.

4.3.3.4 Supply 4.2A current to the thruster cathode heater (I_3) and 4.0A to the neutralizer cathode heater (I_5). Maintain heater current for 1 hour. Record the time and pertinent data on the data sheet.

4.3.3.5 Turn off heaters and allow to cool for a minimum of one hour. Record the time and other pertinent data on the data sheet. Proceed with normal thruster start-up.

TECH:____________________

DATE:____________________

4.4 Thruster Start-up

4.4.1 Facility pressure must be less than 8×10^{-6} torr.

4.4.2 Ensure that the thruster has not been exposed to air since previous cathode conditioning or see paragraph 4.3.

TECH:____________________

DATE:____________________

4.4.3 Before proceeding with the start-up procedure, set the power processor control references to produce the conditions prescribed below. Refer to the circuit diagram of Fig. 4.1 for definition of the monitoring points and symbols. References may be set using previously determined calibrations (see IPD-PR-140) or calibrate the power processor on load resistors to obtain the control references.

4.4.3.1 Current references for the discharge, cathode-keeper, and neutralizer-keeper power supplies are set to the following values for start-up

$J_9 = 6.0$ A

$J_{NK} = 2.1$ A

$J_{CK} = 1.0$ A

4.4.3.2 Voltage controls for the screen and accel power supplies should be set such that

$V_{11} = 600$ V

$V_{10} = 300$ V

4.4.3.3 Control references for the proportional control (closed loop) of the vaporizer supplies should be adjusted such that:

Cathode vaporizer supply, $V_D = 36$ V

Neutralizer vaporizer supply, $V_{NK} = 15.5$ V

Main Vaporizer supply, $J_b = 0.75$ A

4.4.3.4 The neutralizer and cathode heater power supplies should be interlocked such that these power supplies cannot supply heater current if

$$J_7 \geq 0.7 \text{ A}$$

$$J_9 \geq 4 \text{ A}$$

respectively. If the power processor is not so equipped, the thruster operator must monitor these heater power supplies to ensure that this condition is satisfied in order to prevent damage to the cathode and neutralizer heater elements.

4.4.4 The first phase of the start-up procedure is a cathode and thruster pre-heat period. The pre-heat period is timed and requires 35 minutes. Do not begin the preheat phase unless the vaporizer temperatures are less than 70°C. Record the initial temperatures on the start-up data sheet. All power supplies should be off at the beginning of the pre-heat phase.

4.4.4.1 Turn on the cathode heater, neutralizer heater and isolator heater power supplies. Set the heater current as follows:

$$J_{CH} = J_3 = 4.2 \text{ A}$$

$$J_{NH} = J_5 = 4.0 \text{ A}$$

$$J_{IH} = J_4 = 7.0 \text{ A}$$

Record the time that preheat began on the data sheet. Note that J_4 supplies parallel combination of the main and cathode isolator heaters.

4.4.4.2 Five minutes after beginning pre-heat, check each of the following heater voltages to ensure that

$$V_{CH} = V_3 \geq 10 \text{ V}$$

$$V_{NH} = V_4 \geq 15 \text{ V}$$

$$V_{IH} = V_5 \geq 10 \text{ V}$$

If any of these voltages are less than indicated above, stop the preheat and determine whether a heater failure has occurred. Make appropriate entries on data sheet.

4.4.4.3 After 18 minutes has elapsed, reduce the isolator heater current, J_4, to 5.0 A and continue pre-heat for the remaining 17 minutes.

4.4.5 After 35 minutes of pre-heat has elapsed, the heat phase of the start-up procedure begins. Record the time and perform the following.

4.4.5.1 Turn off the isolator heater power supply ($J_4 = 0$). Record the vaporizer temperatures on the data sheet.

4.4.5.2 Turn on the cathode vaporizer and neutralizer vaporizer power supplies (2 & 6), and the cathode and neutralizer keeper supplies (7 & 8), and the discharge supply (9).

4.4.5.3 Cathode and neutralizer vaporizer power supplies should be operating in proportional control.

4.4.5.4 Monitor the neutralizer and cathode keeper voltage and current to determine when the keeper discharges ignite. Record the time of ignition for each keeper and for the main discharge also (J_9). When $J_7 > 0.7A$ and $J_9 > 4A$, check to make certain that I_3 and I_5 have been shut off.

4.4.5.5 If $J_E = J_9 > 4A$, set $J_{MB} = J_{12} = 2$ A and set the reference for control of V_D to 32V. Operate the thruster discharge for 8 min. and then proceed as indicated in para. 4.4.5.6.
If $J_E = J_9 < 4A$, and this is the first attempt to complete the heat period proceed as indicated below. If this is not the first attempt to complete the heat phase, shut off power and notify the project manager. Describe any anomalous observances on the data sheet, including any procedures dictated by the project manager.

4.4.5.5.1 Adjust the power processor for

$J_3 = 4.2$ A

$J_4 = 5.0$ A

$J_5 = 4.0$ A

All other power supplies off, and proceed as directed starting in para. 4.4.4.3.

4.4.5.6 Check the value of J_7, if $J_7 > 0.7$ A, continue at para. 4.4.6. If $J_7 < 0.7$ and this is the second attempt to complete the heat phase, terminate start-up and notify project manager. If this is the first attempt, proceed as follows.

4.4.5.6.1 Turn on main vaporizer power supply and control at $J_1 = 1.0$ A (not proportional control).

4.4.5.6.2 Check to make certain that

$J_6 \approx 2.0$ A

$J_5 = 4.0$ A

4.4.5.6.3 If $J_{NK} > 0.7$ A proceed to para. 4.4.6. If J_{NK} remains less than 0.7 A for more than 5 minutes, terminate start-up and notify the project manager.

4.4.6 This phase is the final period of start-up and provides for the establishment of the ion beam in closed loop, proportional control. This has been termed the run phase and is initiated as follows.

4.4.6.1 Check the following parameters values

$J_2 \leq 2A$ in proportional control

$J_3 = 0$

$J_4 = 0$

$J_5 = 0$

$J_6 \leq 2A$ in proportional control

4.4.6.2 Ensure that the vacuum facility pressure is less than 10^{-5} Torr.

4.4.6.3 Application of the extraction voltages is the next step; adjust the controls in the order indicated to establish the "beam on" condition

V_{NK} = 15.2 (control reference → 410

$J_{NK} = J_8$ = 1.8 A (J_{NK}) → 510

J_{12} = 2.7 A (J_{MB})

J_1 → Proportional control, 1.5 A max

V_{11} = 600
simultaneously
V_{10} = -300

If excessive arcing (overcurrent) occurs (more than 10 in 30 sec), turn off the screen (11) and accel (10) voltages. Place the main vaporizer control (J_1) in manual controlled to 1A.

4.4.6.4 If para. 4.4.6.3 has been completed successfully (beam on and vaporizer in proportional control) proceed the 4.4.6.5 If excessive arcing resulted while attempting to perform 4.4.6.3 and the high voltage power supplies were turned off, repeat steps 4.4.6.3. If step 4.4.6.3 has been repeated more than 5 times, terminate test and consult project manager.

4.4.6.5 The thruster is now operating in closed-loop proportional control at 0.75 A beam current. In this step the beam current will be increased to 2A according to the control parameters given in Table 4.1. Before proceeding, check the accelerator current, J_A. If J_A > 5 mA, turn off the main vaporizer power supply until J_A < 2 mA, then turn on the main vaporizer power supply again and proceed as follows. Adjust the parameters in the table in the following order

- Emission Current
- Beam Voltage
- Beam Current
- Neutralizer Keeper Voltage

Operate at each new value of beam current for at least one minute to ensure that control has stabilized. Watch for the so-called "low mode" condition that is identified by J_A > 5 mA and J_b less than set-point. If difficulties are encountered, stabilize thruster operation at last stable set-point and contact the project manager.

Table 4.1

Thruster Throttling Set-Point

Set Point	Emission current J_E	Beam Voltage V_b	Beam Current J_b	Neutralizer Keeper Voltage V_{NK}
1	5.75	600	0.75	16.5
2	6.0	620	0.8	16.5
3	6.3	640	0.85	16.5
4	6.5	660	0.9	16.5
5	7.0	700	1.0	16.5
6	7.5	740	1.1	16.5
7	8.0	780	1.2	16.5
8	8.5	820	1.3	15.5
9	9.0	860	1.4	15.5
10	9.5	900	1.5	15.5
11	10.0	940	1.6	15.5
12	10.5	980	1.7	15.5
13	11.0	1020	1.8	15.5
14	11.5	1060	1.9	15.5
15	12	1100	2.0	15.5

4.4.7 When point 15 of Table 4.1 has been stabilized, thruster start-up is complete and the run phase has been established. Record the time and a complete set of parameters.

J_{MV}, V_{MV}

J_{CV}, V_{CV}

J_{NV}, V_{VN}

J_{CK}, V_{CK}

J_{NK}, V_{NK}

J_E , V_D

J_A , V_A

J_b , V_b

J_G , V_G

J_{MB}, V_{MB}

T_{CV} , T_{MV}, T_{NV}

4.4.7.1 Adjust the following parameters (not specified in Table 4) to the following values if necessary

J_{CK} = 1.0

V_A = -300

V_D = 32

4.4.7.2 Check to make sure $J_3 = J_4 = J_5 = 0$. Operate thruster at throttling set-point 15 for 10 minutes.

4.4.7.3 If step 4.4.7.2 has been completed, and the thruster is operating stably, the run phase is established and acceptance test procedures can be continued. If any anomalies occurred during the start-up procedure, write a brief description and summary. Include this write-up with the data package.

4.5 Discharge and Neutralizer Characterization

4.5.1 For the initial characterization, operate the thruster at the control parameters listed for set point #15 in Table 4.1 (test point 1 in Table 4.1). Note that references for V_D and J_{NK} are 32 V and 1.8 A respectively. In successive characterizations, adjust the parameters for the test point in Table 5.1 that is being elvauated (4, 6, 7 or 9).

4.5.2 With the thruster operating stably under the conditions listed in para. 4.5.1, record all operating parameters, including vaporizer temperatures. The neutralizer control characteristic can now be documented as follows.

4.5.2.1 Figure 4.2 shows a qualitative example of the neutralizer keeper-voltage/vaporizer-temperature characteristic to be determined here. Note that there is a minimum value of V_{NK} and a minimum stable reference point that will be identified by the test procedures described below.

4.5.2.2 Decrease the reference to produce a 0.5 V decrease in V_{NK}. Again observe the vaporizer current to determine when steady state has been established. If vaporizer current remains at maximum and vaporizer temperature continues to increase, see para. 4.5.2.5.

4.5.2.3 When steady state has been established as described in para. 4.5.2.2, record V_{NK}, T_{NV}, J_{NV}, V_{NV} and V_g.

4.5.2.4 Repeat steps 4.5.2.2 and 4.5.2.3 until steady state cannot be obtained, (V_{NK} continues to rise with J_{NV} at max value).

4.5.2.5 The reference set point for V_{NK} prior to the attempted 0.5 V change is the minimum stable reference point - note this on the data sheet and return the reference for V_{NK} to 2 V above this value. As the new reference point is being established by the vaporizer control, monitor V_{NK} and note the minimum value of V_{NK} observed (as seen in Fig. 4.2) and record on the data sheet.

4.5.2.6 Re-establish conditions with reference for V_{NK} set to 15 V.

4.5.2.7 Increase the neutralizer vaporizer reference setpoint to produce a 0.5 V increment in the neutralizer keeper voltage, V_{NK} (e.g., to 16.0 V for the first variation). Observe the vaporizer current to determine whether steady state has been reached.

4.5.2.8 When steady state has been reached, record values of V_{NK}; neutralizer vaporizer temperature, T_{NV}, neutralizer vaporizer current and voltage, I_{NV} and V_{NV}; and the neutralizer coupling voltage, V_g on the data sheets. If neutralizer keeper discharge extinguishes, proceed to para. 4.5.2.10.

4.5.2.9 Repeat steps 4,5.2.7 and 4.5.2.8 until V_{NK} is 18 V or the neutralizer keeper discharge extinguishes.

4.5.2.10 Re-establish operating conditions with reference for V_{NK} set to 15 V.

4.5.3 The thruster should now be operating stably again and the magnetic baffle control characteristic can now be documented as follows:

4.5.3.1 Establish thruster operation for parameters of test point no. 9 in Table 5.1 with J_{MB} = 2.7 A.

4.5.3.2 Reduce the magnetic baffle current (J_{MB}) by 0.1 A.

4.5.3.3 Observe thruster operation for several minutes to determine control loop stability. If the cathode-vaporizer/discharge-voltage control loop appears to beoperating in stable, proportional control then record the following parameters on Data Form #2 (Magnetic Baffle/Discharge Data).

Magnetic Baffle Current J_{MB}

Cathode Vaporizer Temperature T_{CV}

Main Vaporizer Temperature T_{MV}

Accelerator Current J_A

Cathode Keeper Voltage V_{CK}

4.5.3.3 Continued

After recording these data, repeat the step of 4.5.3.2 until stable operation is impossible to obtain then return the setting for J_{MB} to the last stable point recorded and proceed to para. 4.5.3.4.

4.5.3.4 Increase the magnetic baffle current (J_{MB}) to 0.2A above the minimum stable value (as determined in 4.5.3.2 above) for the conditions of the test point just characterized. Repeat the characterization as described in para. 4.5.3.2 and 4.5.3.3 for each of the following test points (Table 5.1), in the order listed: Test point 7 (J_b = 1 A), 6 (J_b = 1.3 A), 4 (J_b = 1.6 A) and 1 (J_b = 2.0).

4.5.3.5 Record the minimum stable value of J_{MB} on the summary sheet entitled "Acceptance Test Data for Principle Throttling Points".

4.5.3.6 On the basis of the minimum stable value J_{MB}, and the cathode vaporizer temperatures recorded, specify values of J_{MB} for Table 5.1 that

a) are greater than the minimum value

b) require cathode vaporizer temperatures to produce 100 mA cathode flow rate

e) produce min J_A

d) demand the least number of different J_{MB} set points.

4.6 Thruster Performance Evaluation

4.6.1 Performance evaluation consists of measuring the ion beam characteristics as a function of the electrical power and propellant input to the thruster

4.6.2 Ion beam characteristics are determined by measuring the following:

4.6.2.1 Ion beam current, J_b is measured as shown in the measurement circuit diagram of Fig. 4.1.

4.6.2.2 Ion beam voltage, V_b is measured as $V_{11} + V_9 - V_g$ (as defined in the circuit diagram of Fig. 4.1).

4.6.2.3 Correction factors to measured beam current for doubly charged ions and non-axial current components are measured using a collimated mass spectrometer as described in Section of IPD-PR-141.. The thrust factor, γ is the ratio of the actua thrust produced to that calculated from the measured beam current and voltage, J_b and V_b.

4.6.3 Thruster electrical inputs fall into two categories, independent and dependent as described below.

4.6.3.1 Independent electrical parameters are defined to meet the requirements of the thruster application (within the limits of the thruster capabilities). With reference to Fig. 4.1 these electrical parameters are:

Accelerator voltage, V_A

Ion beam voltage, V_b

Ion beam current, J_b

Discharge voltage, V_D

Emission current, J_E

Neutralizer keeper voltage, V_{NK}

Magnetic baffle current, J_{MB}

Cathode keeper current, J_{CK}

Neutralizer keeper current, J_{NK}

These parameters are not totally independent, in a strict sense, but can be specified independently over some range of values that depends both on the dimensional adjustments of the thruster and on the choice of the other parameters. It is necessary to specify a consistent set of these parameters for each thruster performance evaluation.

4.6.3.2 Dependent electrical inputs are properties of the thruster and of the independent electrical parameters listed above. These include:

Cathode vaporizer voltage and current, V_{CV} and J_{CV}

Main vaporizer voltage and current, V_{MV} and J_{MV}

Neutralizer vaporizer voltage and current, V_{NV} and J_{NV}

Accelerator drain current, J_A

Cathode keeper voltage, V_{CK}

4.6.4 The propellant input to the thruster is also dependent on the choice of the indpendent electrical parameters and the thruster.

4.6.4.1 Propellant input is measured using calibrated reservoirs as described in IPD-PR-141.

4.6.4.2 Propellant flow rate to each vaporizer is determined by recording the quantity of mercury contained in the corresonding reservoir at intervals of 5 minutes or more. The thruster should be operated steady state until a minimum of 6 reservoir readings are obtained. The flow is computed by graphically or numerically fitting a straight line to the data recorded and obtaining the slope in units of cm^3 per hour. Conversion to equivalent amperes is based on the relationship:

$$1\ cm^3/hr\ @\ 20^oC = 1.809A$$

4.6.4.3 The propellant flow rate for each vaporizer is determined for each set of independent parameters as described in paragraph 4.6.4.2 above and recorded on a data summary sheet.

4.5.6 A performance summary is prepared as follows:

4.6.5.1 A data summary sheet is prepared that includes the following parameters.

$\dot{m}_{MV}$ - Main vaporizer propellant flow in equivalent amperes.

$\dot{m}_{CV}$ - Cathode vaporizer propellant flow in equivalent amperes.

$\dot{m}_{NV}$ - Neutralizer vaporizer propellant flow in equivalent amperes.

γ - Thrust correction factor from measurement described under paragraph 4.6.2.3.

F_T - Thrust correction factor due to beam divergence (ref. 4.6.2.3)

J_b - Ion beam current (ref. 4.6.2.1)

V_b - Ion beam voltage (ref. 4.6.2.2)

P_T - Total power into the thruster (ref. 4.6.5.2)

F - Actual thrust (ref. 4.6.5.3)

η_{MD} - Propellant efficiency, discharge chamber only (ref. 4.6.5.4)

E_{Imin} - Minimum eV/ion (per para. 4.7)

η_{MT} - Total propellant efficiency (ref. para. 4.6.5.5)

η_e - Electrical efficiency (ref. para. 4.6.5.6)

η_T - Thruster efficiency (ref. para. 4.6.5)

I_{sp} - Specific impulse

4.6.5.2 The total power input, P_T, is obtained from the electrical parameters as follows:

$$P_T = J_{MV} V_{MV} + J_{CV} V_{CV} + J_{NV} V_{NV} + J_{NK} V_{NK} + J_{CK} V_{CK} + J_E V_D + J_A V_A + J_b V_b + J_B V_G + J_{MB} V_{MB}$$

These parameters are measured at the points indicated in the circuit diagram shown in IPD-PR-141. The values used for computation will be the last readings recorded during the propellant flow rate measurement.

4.6.5.3 The actual thrust is computed from the measured beam current and voltage as follows:

$$F = 2.039 \times 10^{-3} \gamma \ J_b \ \sqrt{V_b} \quad \text{(in N)}$$

4.6.5.4 The discharge chamber propellant utilization, corrected for double ions is computed by

$$\eta_{MD} = \frac{J_b}{\dot{m}_{CV} + \dot{m}_{MV}} \left[\frac{\gamma}{F_T} \left(1 + \frac{\sqrt{2}}{2}\right) - \frac{\sqrt{2}}{2} \right]$$

4.6.5.5 The total propellant efficiency, η_{MT}, is computed for use in total efficiency and is not corrected for doubly charged ions.

$$\eta_{MT} = \frac{J_b}{\dot{m}_{CV} + \dot{m}_{MV} + \dot{m}_{NV}}$$

4.6.5.6 The electrical efficiency, η_e, is computed by

$$\eta_e = \frac{J_b \ V_b}{P_T}$$

4.6.5.7 The overall thruster efficiency, η_T, is computed by

$$\eta_T = \eta_e \ \eta_{MT} \ \gamma^2$$

4.6.5.8 The specific impulse is computed by

$$I_{sp} = 100.1 \gamma \ \eta_{MT} \ \sqrt{V_b}$$

4.7 Determination of Minimum Discharge Current Operating Point

4.7.1 The thruster operating point is established as specified by the independent parameters for the case in question. The minimum discharge current is then determined by reducing the value of I_E in 0.2 A increments as described in the following paragraph.

4.7.2 Adjust J_E to obtain $J_E = 5J_b + 2$ for the specified value of J_b. All vaporizer control loops should be operating in closed loop control. Record the value of J_{CV} and J_{MB} for initial operation at $J_E = 5\ J_b + 2$. Proceed to reduce J_E until the main vaporizer conrtrol loop loses control (beam current continues to decrease with vaporizer heater current at maximum) by the procedure below:

4.7.2.1 Reduce the value of J_E as indicated on the data format.

4.7.2.2 Adjust J_{MB} to restore the value of J_{CV} noted for initial value of J_E.

4.7.2.3 After control has stabilized, record J_A.

4.7.3 Examine the values of J_E vs. J_A obtained per para. 4.7.2 and determine the minimum value as; a the value of the emission current at which J_A is twice the value of J_A for $J_E = 5J_b + 2$, or b) the value of the emission current for which vaporizer control was lost (whichever value is greater). Record the minimum value of J_E on the data summary sheet.

4.8 Recycle Verification

4.8.1 Recycle verification consists of inducing a transient overcurrent condition in the screen or accelerator power supplies and observing the return to normal operation.

4.8.2 Evaluate recycle conditions by inducing a minimum of 10 transient overcurrents and observing the restoration of thruster control. The method for inducing the overcurrent condition varies with the power processor used. Some possibilities are:

4.8.2.1 Simulate the overcurrent signal in the screen or accel power supply control circuit (recycle pushbutton on some test consoles).

4.8.2.2 Momentarily shut off accel power supply.

4.8.2.3 Momentarily short circuit the accel power supply. (Need note on duration of short circuit).

4.8.3 Write a brief descriptive narrative to document the results of the recycle verification test (May be written directly on the data sheet or attached to it). Include oscilloscope waveforms of a typical recycle oepration to document neutralizer keeper current, J_{NK}, discharge current, J_E, and beam current, J_b, through the recycle period.

4.9 Oscillation Verification

Oscillatory behavior is known to exist in several of the thruster parameters. This behavior is a function of the power supplies used to operate the thruster, in addition to the thruster characteristics. Documentation of this behavior constitutes a survey of any time dependent behavior observable on the beam current, J_b, the discharge current, J_E, the cathode keeper current, J_{CK}, and the neutralizer keeper current, J_{NK}. Measurement is made with an oscilloscope and an inductively coupled current probe as described in IPD-PR-141. The procedure is described below.

4.9.1 Stabilize the thruster opeation for the independent parameter selection to be documented. Record all thruster parameters.

4.9.2 Photograph oscilloscope waveforms of J_b, J_E, and V_D, using time scales of 1 msec/division and 0.1 msec/division. Photographs should show the phase relationship of any time dependent behavior to that of J_E.

4.9.3 Prepare a short description of the experiments and the power supplies used. If possible indicate the output capacitance and/or inductance of power supplies in question. Attach the oscilloscope waveform photographs (with time and amplitude scales appropriately identified) and include in the data package.

4.10 Measurement of the Extraction System Perveance

The ion extraction system perveance defines the minimum value of extraction voltage that is required to effectively extract and focus an ion beam of a specified current value. The procedure is performed as described below.

4.10.1 Stabilize thruster operation for the independent parameter selection to documented. Record the value of all thruster parameters on the data sheet. All control loops should be operating in proportional control.

4.10.2 Increase the discharge losses to 250 eV/ion by increasing the discharge current, J_E. Adjust the magnetic baffle current, J_{MB}, to restore J_{CV} to the value recorded in 4.10.1.

4.10.3 Reduce the beam voltage, V_b, by 50 V and the accelerator voltage constant at 300 V.

4.10.4 Allow control loops to stabilize and record V_b, J_A, J_{MB} and J_{MV}.

4.10.5 Repeat steps 4.10.3 and 4.10.4 until J_A increases rapidly or until the main vaporizer control is lost (J_{MV} goes to its maximum value).

4.10.6 Plot J_A as a function of $V_b + |V_A|$. The "perveance limit" is defined as the voltage at which J_A begins to increase rapidly as shown in Fig. 4.3. Determine $V_{TOT} = V_b + |V_A|$ for the "perveance limit" as indicated from the points plotted and recorded on the data sheet.

4.10.7 Restore thruster operation for the selection of independent parameters being documented. Allow control loops to stabilize.

4.10.8 Determine the "backstreaming limit" by reducing the accelerator voltage, V_A in 10 volt changes until backstreaming of electrons into the discharge chamber occurs. This condition is detected by monitoring the beam current, J_b, for a sharp, momentary increase at the time the accelerator voltage is decreased, followed by a reduction in main vaporizer current, J_{MV}. Record the accel voltage, V_A, for which this indication occurs on the data sheet.

4.11 Thruster Shutdown

A standardized thruster shutdown procedure is employed to ensure reliable thruster start-up as follows:

4.11.1 Reduce J_b in 0.1 steps by adjusting the parameters specified in Table 4.1 in the reserve order of the manner prescribed in para. 4.

4.11.2 When set-point 1 is reached, shut off all power supplies.

5.0 ACCEPTANCE TEST

Acceptance testing is performed on all new thrusters and periodically on reworked thrusters or thrusters that have been subjected to some form of qualification testing. The acceptance tests are conducted as described in the following paragraphs. The personnel performing the acceptance test should familiarize themselves with the content of this IPD and the IPD's specified in para. 2 before proceeding. If it appears necessary to modify any procedures in performing the acceptance tests, the project manager should be consulted first, and the variance(s) in procedure should be thoroughly documented.

5.1 The thruster is first installed in the test facility as per paragraphs 4.1 and 4.2 of this IPD. The acceptance tests require several days of testing to complete and therefore the procedures for start-up and operation are different, depending on whether the thruster is being started up for the first time (para. 4.3) or re-started for the next series of tests (para. 4.4). The thruster is operated at a pre-determined set of test-points (para. 5.2) for which the documentation procedures described in para. 4.5 through 4.10 are also specified. Thruster shutdown between segments of the test is described in para. 4.11.

5.1.1 The first segment of the acceptance test provides for initial cathode conditioning, recycle verification, oscillation documentation and determination of reference values for J_{MB} and V_{NK} (see para. 5.3). It should be possible to complete these tests on the first day of testing.

5.1.2 The remaining block of tests is for collecting data as prescribed by para. 5.4 to establish the thruster's "signature" for comparison with "signatures" of other thrusters or standards. These tests may be performed in any sequence to satisfy the data requirements as listed. It is not considered to be important whether these tests are performed continuously or in segments.

5.1.3 The procedures prescribed in this document should be followed carefully, but an effort should be made to limit total thruster operating time to 50 hours or less.

5.2 The thruster test points are determined by a combination of selected independent parameters, as described in paragraph 4.6.3.1. Speceification of the nine independent parameters is prescribed in this paragraph.

5.2.1 Three of the nine independent parameters remain fixed for all acceptance test points. These are:

$$V_A = -300V$$

$$J_{NK} = 1.8A$$

$$J_{CK} = 1.0A$$

5.2.2 Four more of the parameters are specified in combinations as shown in Table 5.1.

5.2.3 The reference parameters for magnetic baffle current and neutralizer keeper voltage have to be determined as the first part of the acceptance test. Determination is made for points 1,4,6,7 and 9 of Table 5.1 to establish the empirical relationships J_{MB} (J_E) and V_{NK} (J_b). These relationships are then used to provide values of J_{MB} and V_{NK} for all points in the table.

5.3 The acceptance testing begins with cathode conditioning per para. 4.3 and thruster start-up per para. 4.4. Successful completion of these procedures establishes thruster operation for the initial conditions of test point 1 of Table 5.1. The first test determines the magnetic baffle and neutralizer keeper references.

5.3.1 Following the procedures described in para. 4.5, determine the magnetic baffle current and neutralizer keeper voltage references for test points 1,4,6,7 and 9 of Table 5.1.

5.3.2 Using the data obtained in para. 5.3.1, plot J_{MB} versus J_E and V_{NK} versus J_b. Fit a smooth curve to the experimental data. Use these curves to specify values of J_{MB} and V_{NK} for all of the test points in Table 5.1.

5.3.3 Set J_{MB} and V_{NK} to the appropriate values for test point 1 and verify recycle per para. 4.8 and document oscillations per para. 4.9. Describe any unusual findings on the data sheets.

5.3.4 This completes the initial or calibration section of the acceptance test.

5.4 Performance of the remainder of the acceptance test is more flexible in that the order of the procedure is somewhat arbitrary and may be determined by factors such as the availability of test equipment or personnel scheduling, etc.

5.4.1 To begin, stable thruster operation is obtained using the appropriate start-up procedure and then operation is established at the test point (Table 5.1) to be documented by increasing (or decreasing) the beam current in 0.1 A steps as described in para. 4.4.6.4.

5.4.2 Documentation consists of performing the procedures indicated in Table 5.2 for the test points of Table 5.1 and several other combinations of procedures as described below.

5.4.2.1 Complete the procedures as prescribed in Table 5.2.

5.4.2.2 Using the value of V_B obtained by determining the perveance limit, perform the minimum emission current procedure (para.4.7) for set points 1,4,6, and 8.

5.4.2.3 Set up the operating conditions for test point 6 and reduce the beam voltage, V_B, to its value at the perveance limit or 700 volts, whichever is greater. If unstable operation occurs, increase the values of V_B in small increments until stability is achieved. Note the requirements for stability and perform the efficiency and recycle procedures per para. 4.6 and 4.8.

5.5 The data obtained in performing the procedures as directed in para. 5.3 and 5.4 is now collected and assembled to form the Acceptance Test Documentation. The data format provided with IPD-PR-143 are used to facilitate this procedure. These data formats are completed and assembled in the order listed below.

Acceptance Test Documentation (Cover)

Acceptance Test Summary

Acceptance Test Data for Principle Throttling Points

Ion Extraction Assembly Perveance Summary

Neutralizer Keeper Voltage Characteristic

Oscillation Verificaton Summary

Oscilloscope Waveforms (5 pages)

Neutralizer Characterization Data (5 pages)

Magnetic Baffle/Discharge Characterization (2 pages)

Minimum Emission Current Data (2 pages)

Extraction System Perveance Data

Extraction Assembly Spacing Chart

Vaporizer Propellant Calibrations (2 pages)

Acceptance Test Operating Time Log

Thruster Operating Data (20 pages)
- Start-up Sheets
- Test Data
- Propellant Flow Data

Beam Probe Data (30 pages)

Table 5.1 Independent Parameter Specification for Acceptance Test

Test Point No.	Beam Current I_B	Beam Voltage V_B	Discharge Voltage V_D	Emission Current I_E	Magnetic Baffle Current I_{MB} (a)	Neutralizer Keeper Voltage V_{NK} (a)
1	2.0	1100	32	12		
2	2.0	1100	31	12		
3	2.0	1100	32	11.4		
4	1.6	940	32	10		
5	1.3	1100	32	8.5		
6	1.3	820	32	8.5		
7	1.0	700	32	7.0		
8	.75	1100	32	5.75		
9	.75	600	32	5.75		
10	.75	600	31	5.75		

Table 5.2 Experimental Procedures to be Performed for Documenting the Test Points of Table 5.1[(a)]

Test Point	Para. 4.6 Efficiencies	Para. 4.7 Min I_E	Para. 4.8 Recycle	Para. 4.9 Oscillations	Para. 4.10 Perveance
1	X	X			X
2	X				
3	X				
4	X	X		X	X
5	X				
6	X	X	X	X	X
7	X	X		X	
8	X		X		X
9	X	X	X	X	
10	X				

(a) Completed per para. 5.3.1 and 5.3.2.

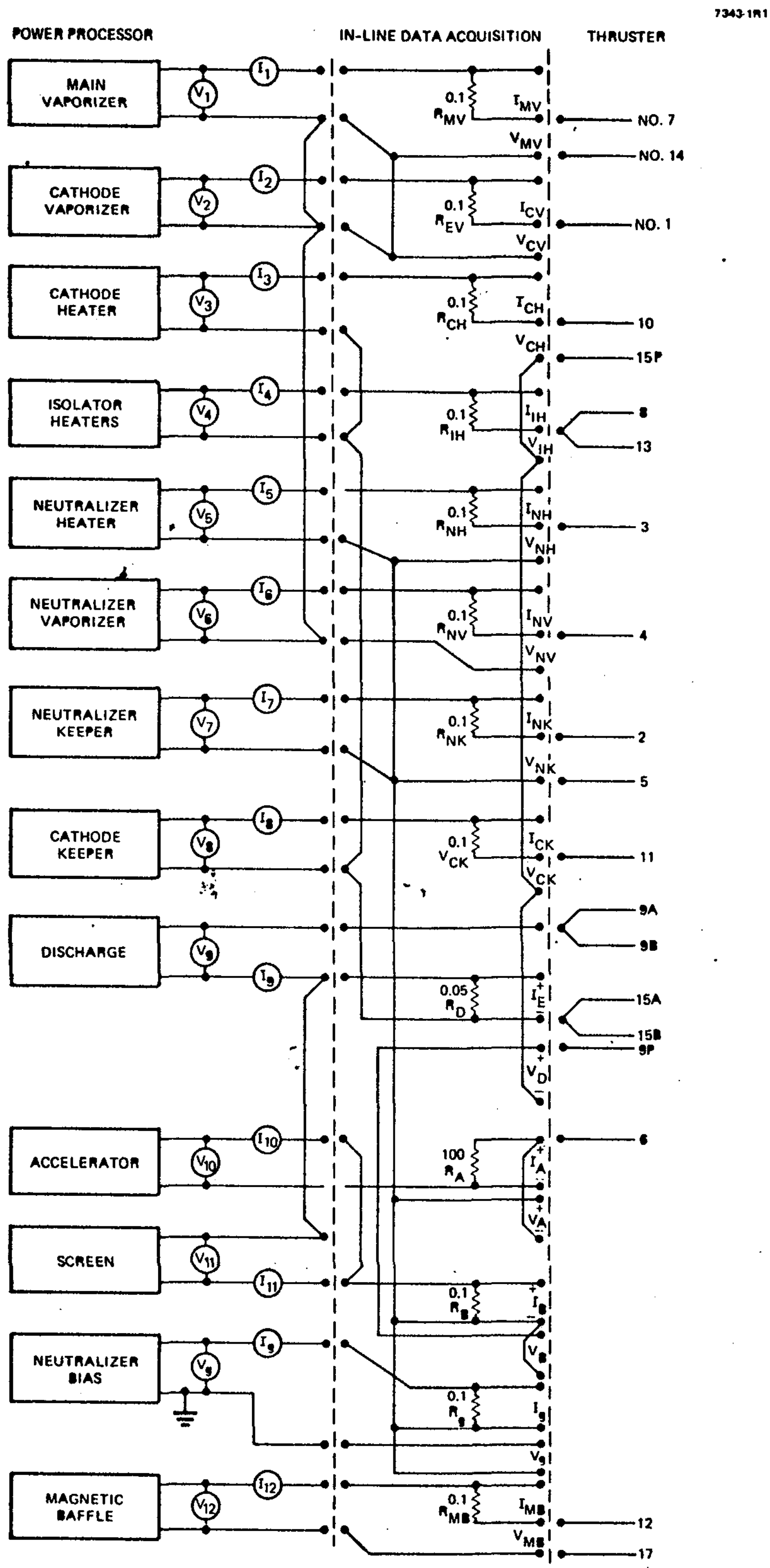

Fig. 4.1 Acceptance Test Circuit Diagram

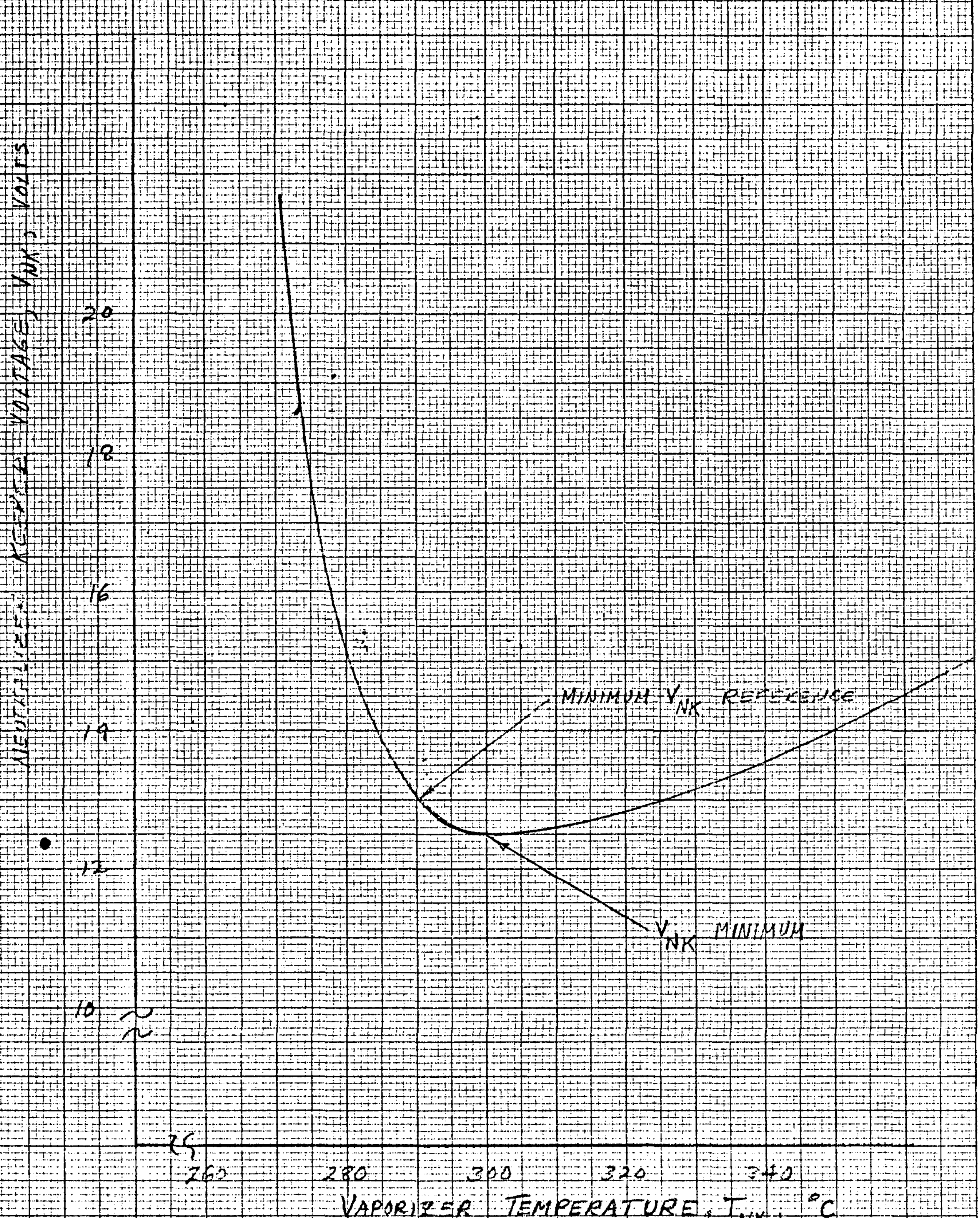

FIG. 4.2 TYPICAL V_{NK} vs T_{NV} CHARACTERISTIC

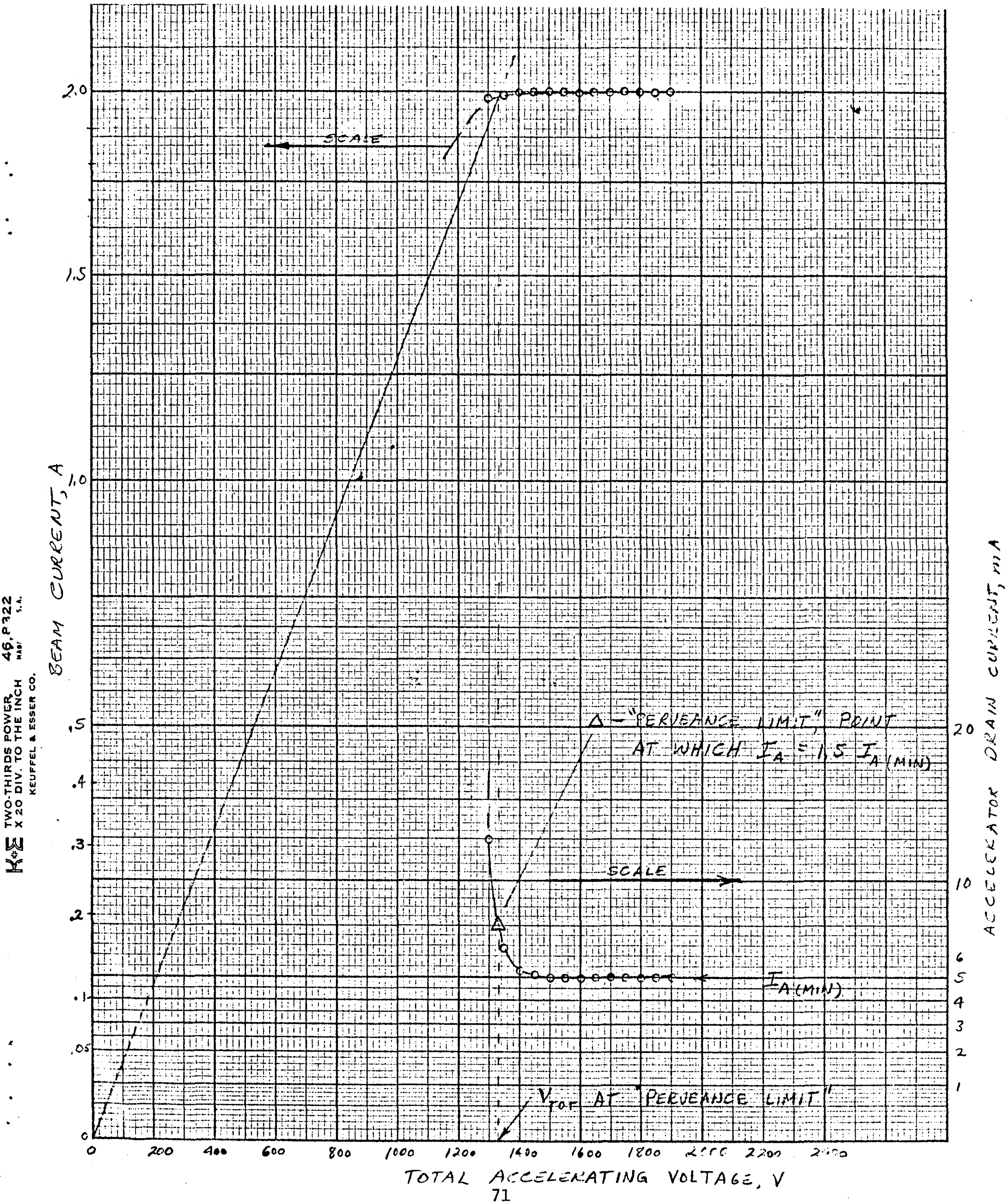

FIG. 4.3 TYPICAL PLOT FOR DETERMINING THE TOTAL ACCELERATING VOLTAGE AT THE "PERVEANCE LIMIT" (DEFINED AS THE CONDITION FOR WHICH I_A = 1.5 × THE MINIMUM VALUE OF I_A)

HUGHES RESEARCH LABORATORIES MALIBU, CALIFORNIA	SPECIFICATION NO. IPD-PR-139				
	PREPARED BY		PAGE	OF	
	R. L. Poeschel		1	6	
SPECIFICATION TITLE	APPROVALS			DATE	REV
Thruster Test Facility					

1.0 Scope

This specification establishes the facility requirements for testing of 30 cm ion thrusters.

2.0 Applicable Documents

2.1 IPD-PR-141

2.2 Thruster Interface Drawing

3.0 Requirements

3.1 Vacuum Chamber Test Facility

The vacuum chamber test facility required should be a minimum of 1.2 m internal diameter and provide a beam path of at least 3 m. An example of a suitable vacuum chamber configuration is shown as Fig. 1.

3.1.1 The minimum pumping requirements for the vacuum chamber are as follows:

- Oil diffusion pump with LN_2 or refrigeration baffle - 30,000 ℓ/s or greater.
- Cryogenic pumping - 7.5 m^2 or greater.

3.1.2 The vacuum chamber will be equipped with a water cooled beam target as indicated in Fig. 1. The beam target should be constructed of a low sputtering rate material such as titanium or stainless steel. A frozen mercury beam target is also satisfactory.

3.1.3 The vacuum chamber will be equipped with ionization gauges for monitoring ambient chamber pressure.

3.1.4 The vacuum chamber will be equipped with viewing and access ports to provide instrumentation as described in IPD-PR-141.

3.2 Thruster Mounting

A mounting for the thruster assembly will be provided as indicated in Fig. 2.

RL 13.021

3.2.1 The thruster mounting will provide accurate alignment of the thruster axis to the vacuum chamber axis. (It may be assumed that the thruster axis is accurately aligned to the gimbal pad surfaces; see drawing No. 1095023).

3.2.2 The thruster mounting will provide coverings to protect the thruster wiring harness from back-sputtered deposition as shown.

3.3 Propellant Reservoir

The thruster mounting or vacuum facility shall be provided with a burette type of mercury reservoir as shown in Fig. 3.

3.3.1 Propellant will be loaded into the larger reservoir under vacuum as described in paragraph 4.

3.3.2 The mercury head as indicated in Fig. 3 shall not be greater than 1 m. The mercury head must be positive unless the reservoir is appropriately pressurized.

4.0 Procedure

4.1 Propellant Loading Procedure

The main propellant reservoir for each vaporizer is filled under vacuum by the following procedure.

4.1.1 Valve number 1 (see Fig. 3) is closed and a mercury fill fitting configured as shown in Fig. 4 is attached to the top of the reservoir.

4.1.2 With valve A (Fig. 4) closed, evacuate the main reservoir burette to a pressure of 10^{-2} torr or less.

4.1.3 Slowly open valve A until mercury begins transferring into the main reservoir in small droplets.

4.1.4 When reservoir is filled, close valve A and vent the reservoir to atmosphere.

4.1.5 Remove the fill fitting and replace the dust cover on the main reservoir.

4.1.6 Using valve number 1, fill the calibrated burette to the desired level (by gravity flow).

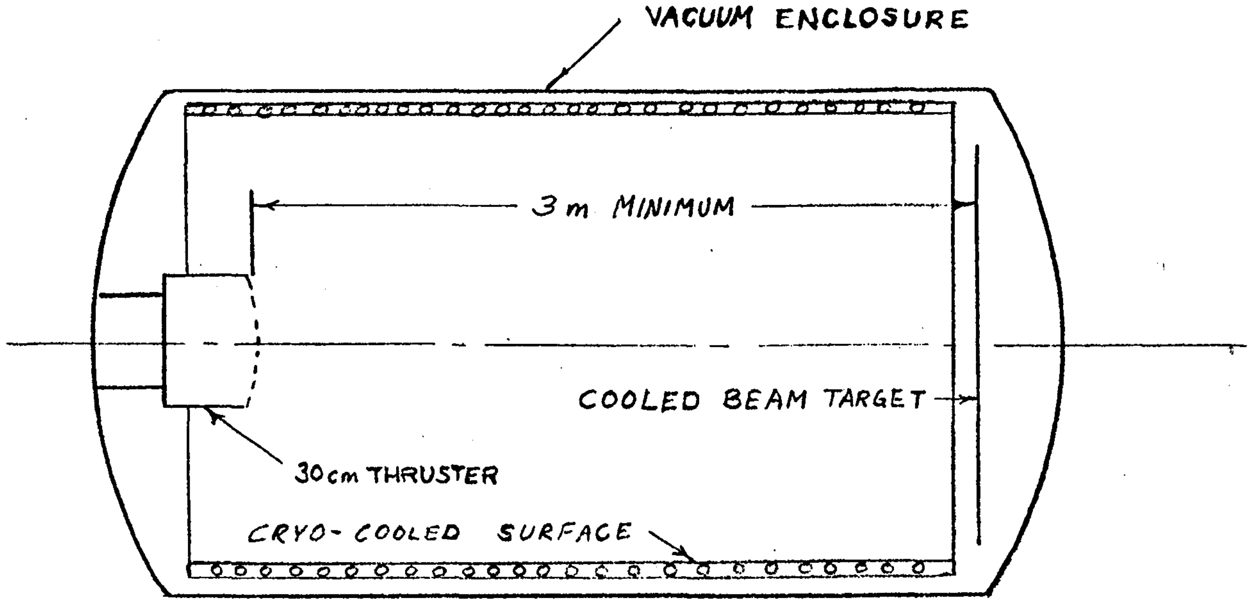

FIG. 1 VACUUM CHAMBER TEST FACILITY CONFIGURATION

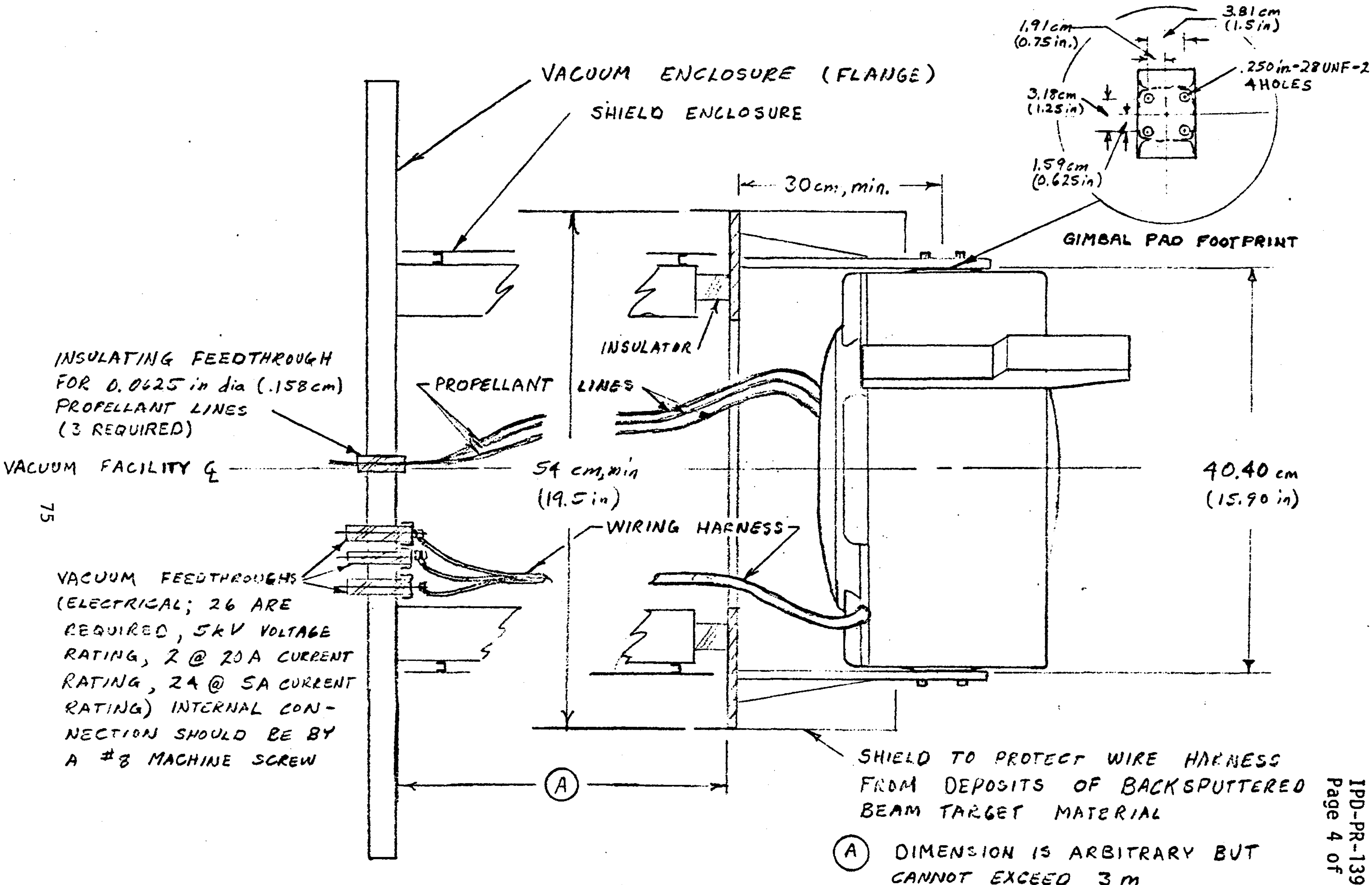

FIG. 2 MOUNTING FOR THRUSTER ASSEMBLY FOR INSTALLATION IN VACUUM CHAMBER TEST FACILITY

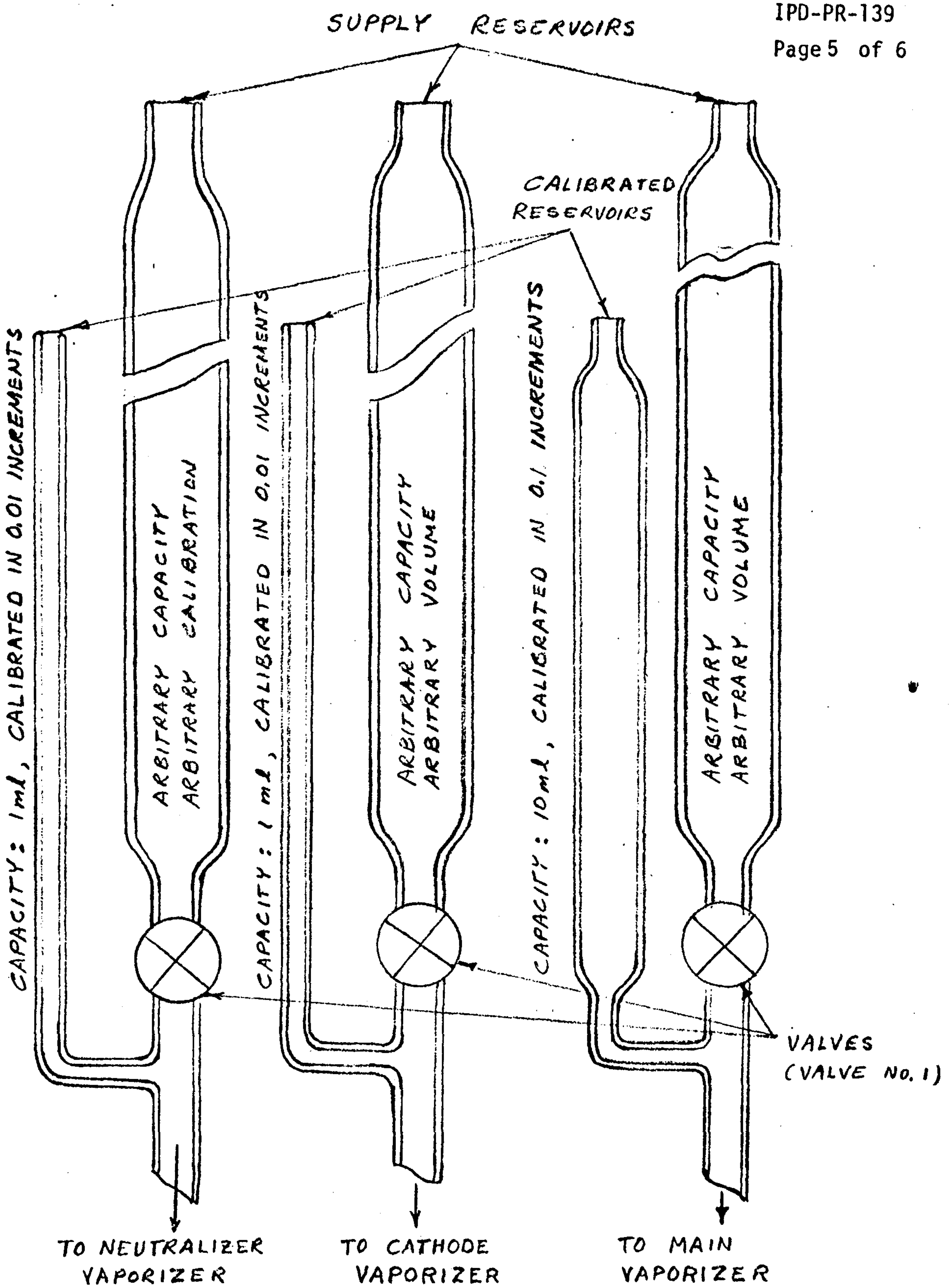

Fig. 3 CALIBRATED MERCURY PROPELLANT RESERVOIRS AND SUPPLY RESERVOIRS. RESERVOIRS ARE CONSTRUCTED FROM STANDARD CHEMICAL SUPPLY COMPANY BURETTES.

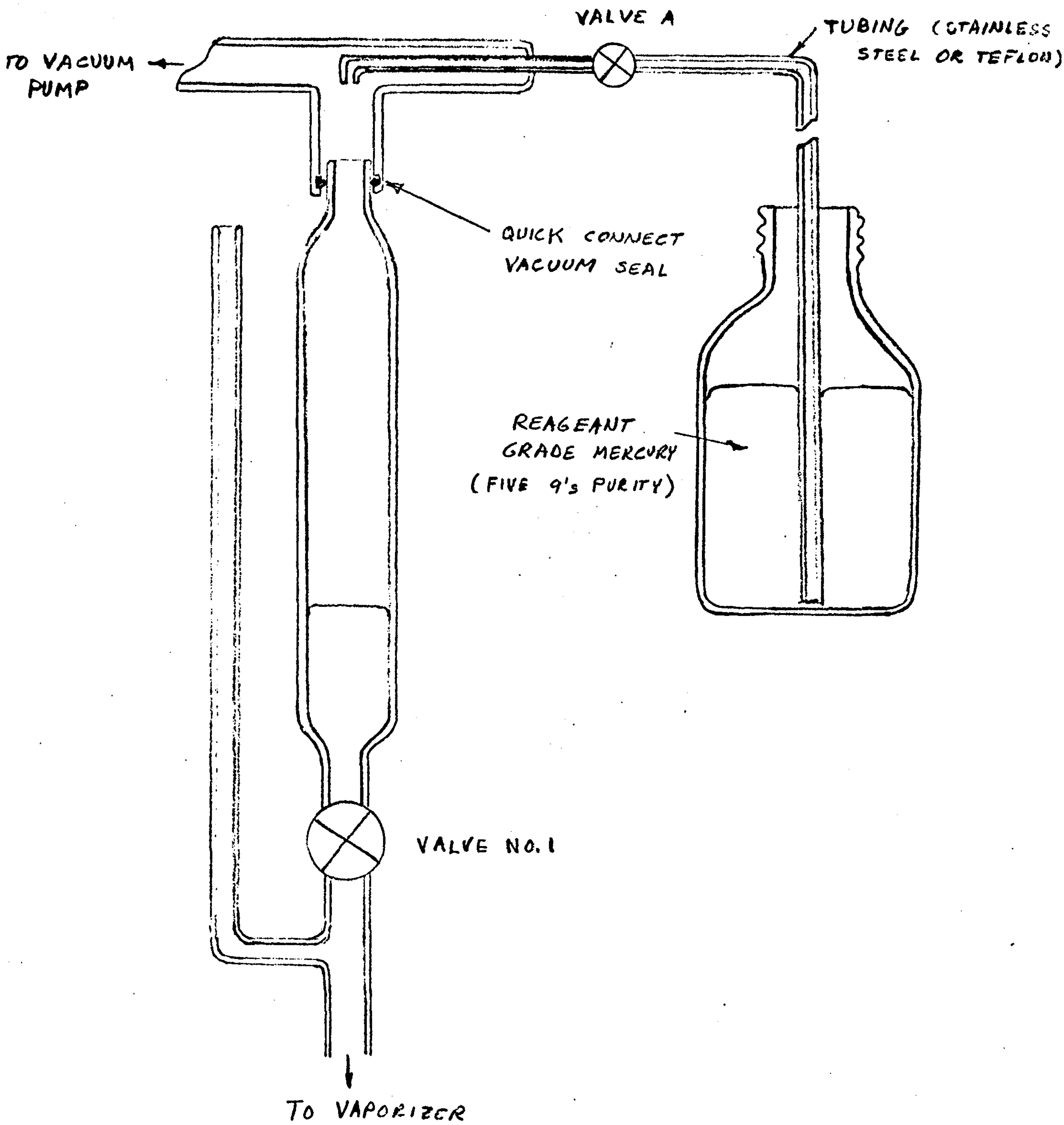

Fig 4 SIPHON TYPE FILLING SYSTEM FOR DE-GASSING AND LOADING MERCURY INTO THE SUPPLY RESERVOIR

HUGHES RESEARCH LABORATORIES MALIBU, CALIFORNIA	SPECIFICATION NO. IPD-PR-140		
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SPECIFICATION TITLE	APPROVALS			DATE	REV
30 cm Thruster Power Processor Specification					

1.0 SCOPE

This specification defines the power supplies, the control algorithms, and the wiring diagrams that are required for operating a 30 cm ion thruster of the 700, 800, 900 and J series. The resultant assembly of power supplies and circuitry is referred to as a power processor. Although exacting power processor specifications are not considered vital to thruster testing, the power processor must meet several general requirements to insure that future comparisons of any and all data are meaningful. Identification of the power processor used shall be entered in the test report.

2.0 APPLICABLE DOCUMENTS

2.1 IPD-PR-141. Instrumentation and calibration.

3.0 REQUIREMENTS

3.1 Power Supplies

3.1.1 A list of the power supplies that are required is provided in Table 1; the power supply designations and ratings are given.

3.1.2 The heater supplies designated as numbers 1 through 6 in Table 1 have no specific regulation requirements and may be either d.c. or a.c. (at any frequency less than 100 kHz.)

3.1.3 The vaporizer power supplies designated as numbers 1, 2, and 6 must be programmable. (i.e., it must be possible to control the output in proportion to an input control voltage).

3.1.3.1 In proportional control, the output of the main vaporizer supply (No. 1) is controlled in proportion to the screen current (I_{11}).

3.1.3.2 In proportional control, the output of the cathode vaporizer supply (No. 2) is controlled in proportion to the discharge supply output voltage (V_9).

3.1.3.3 In proportional control, the output of the neutralizer vaporizer supply (No. 6) is controlled in proportion to the neutralizer keeper voltage output (V_7)

Table 1. Power Supply Description and Ratings

Power Supply	Supply Number	Max Volts	Max Amps	Power, Watts
Main Vaporizer	1	14	2	28
Cathode Vapor.	2	10	2	20
Cath. Tip(Heater)	3	20	4.4	88
Isolator Heater	4	20	7	140
Neutra. Tip(Heater)	5	20	4.4	88
Neutra. Vapor.	6	10	2	20
Neutra. Keeper	7	25	2.2	55
Cathode Keeper	8	15	1.0	15
Discharge	9	50	14.0	700
Accelerator	10	500	.060	10
Screen	11	1100	2.1	2300
Magnetic Baffle	12	4	4	16

3.1.4 The keeper supplies, designated as numbers 7 and 8, are current regulated, d.c. power supplies with programmable current set points. Both power supplies should have an open circuit output voltage boost to provide at least 300 V output voltage for zero current conditions. The power supply output should be capable of rising to 50 V to maintain current control in the 50 mA to 1.0 A range of output current.

3.1.4.1 The cathode keeper power supply (No. 8) operates at 1 A output in typical operation.

3.1.4.2 The neutralizer keeper power supply (No. 7) operates at 1.7 A output in typical operation.

3.1.4.3 Both keeper power supplies should have an inductive output.

3.1.5 The discharge power supply is a current controlled, current regulated, d.c. power supply. If known, the regulation and output specifications should be recorded for future reference when performing thruster tests. Important parameters are:

- Output impedance
- Regulation percentage
- Frequency response

3.1.6 The screen and accelerator supplies (No.'s 11 and 10, respectively) are voltage regulated power supplies. Important parameters to be recorded are:

- Regulation percentage
- Output capacitance

3.1.7 The magnetic baffle power supply (No. 12) is a current controlled, current regulated d.c. power supply. Important parameters to be recorded are:

- Regulation percentage
- Output impedance
- Frequency response

3.1.8 The power supplies described above must be integrated into a power processor by the incorporation of control circuitry to provide overload protection and proportional control of the vaporizer and heater power supplies. The control approach has been described in detail in NASA CR 120919 and NASA TMX-71647 and can be succinctly represented by the block diagram shown as Fig. 1. Mechanization of this approach may vary, however the essential features are listed in the following paragraphs.

3.1.8.1 Overload protection should be provided such that overcurrents in either the screen or accel power supplies will initiate a programmed shutdown of the high voltage power supplies (10 and 11). This shutdown will be automatically followed by a programmed "recycle" to reestablish the operating conditions that existed prior to the overcurrent. The overcurrent conditions have been defined in NASA CR 120919 as follows:

- $I_{10} \geq$ 3.0 A for 0.5 sec

  or
- $I_{11} \geq$ 0.2 A for 1.0 sec

  or
- $I_{11} \geq$ 0.4 A for 0.1 sec

The overload recycle sequence is as follows:

1. Power supplies 10 and 11 off.
2. Reference currents for power supplies 7 and 9 set to recycle control point.
3. Power supplies 10 and 11 turned on.
4. Reference for power supplies 7 and 9 returned to the same control point as before the overcurrent.

The recycle control points for power supplies 7 and 9 are subject to periodic re-definition and may vary because of the individual power supplies. A nominal set of control references are 2.5 A for I_7 and 1.0 A for I_9. The time required in advancing from step 1 to 3 in the recycle sequence should not exceed 600 msec. The time required in advancing from step 1 to 4 should not exceed 850 msec.

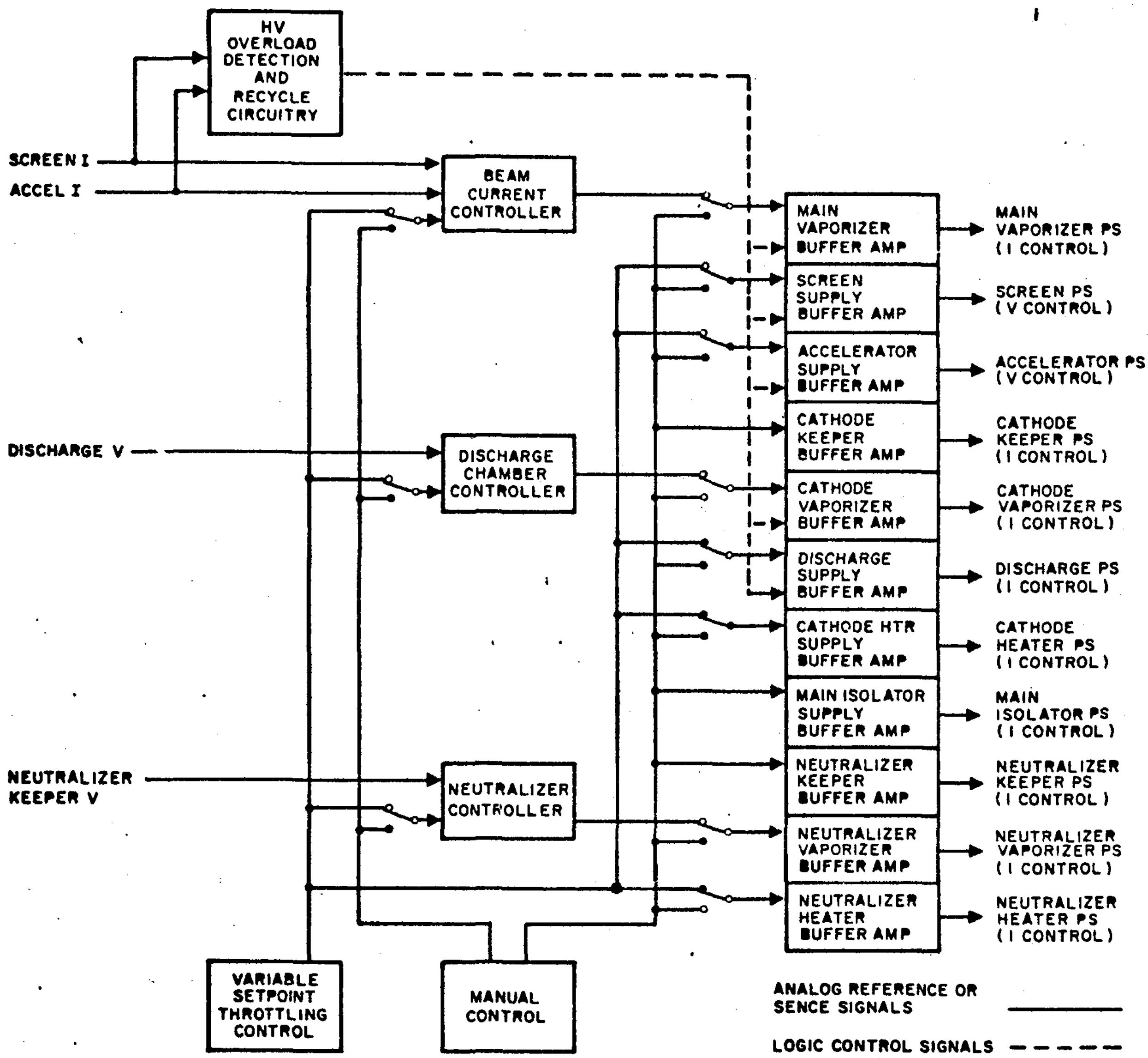


Fig. 1 Thruster Control System Block Diagram.

3.1.8.2 A closed loop proportional control is required for each of the vaporizer power supplies (1, 3, and 6). Figure 2 shows an example of a block diagram for the circuitry needed to control the main vaporizer. A control voltage is supplied as the beam current reference, I_{BR}, into an appropirate scaling circuit (shown here as scaling the reference from 2 V/A to 2.4 V/A). This signal is then transmitted to a comparator circuit where it is compared with the output of the beam current sensor, generating an error voltage, V_E, which in turn is scaled to provide the necessary control voltage, V_C, for the voltage programmable vaporizer power supply. Mechanization of this approach is not critical, however the control circuit gain and frequency response should not permit oscillation or drift when coupled with the thruster characteristic. As noted in para. 3.1.3., the feedback control for the cathode vaporizer is the discharge voltage, and for neutralizer vaporizer, the neutralizer keeper voltage.

3.1.8.3 The thruster control system block diagram shown in Fig. 1, contains a block labeled "Variable Setpoint Throttling Control". In most cases this block will have to be satisfied in the power processor by using a combination of pre-formulated, manually-determined references and automatically determined (electronically) references. One example of set-point references that should be given special attention covers a requirement for controlling the relationship between I_9 and I_3 and between I_7 and I_5. If practical, an interlock type circuitry logic should be incorporated such that

$$I_3 = 0 \text{ if } I_9 \geq 1.0 \text{ A}$$

$$I_5 = 0 \text{ if } I_7 \geq 1.0 \text{ A}$$

These restrictions prevent the cathode heaters from being damaged by excessive temperatures. If such logic is not practical, the operator must be especially cautious to prevent simultaneous operation of the heater in combination with high cathode emission currents. Heater turn off times and emission current levels should be monitored and recorded in detail when nominal control is required.

4.0 PROCEDURES

4.1 Power Processor Checkout

Periodically, and in particular prior to performing and acceptance test as prescribed in IPD-PR-138, the power processors used for operating 30 cm

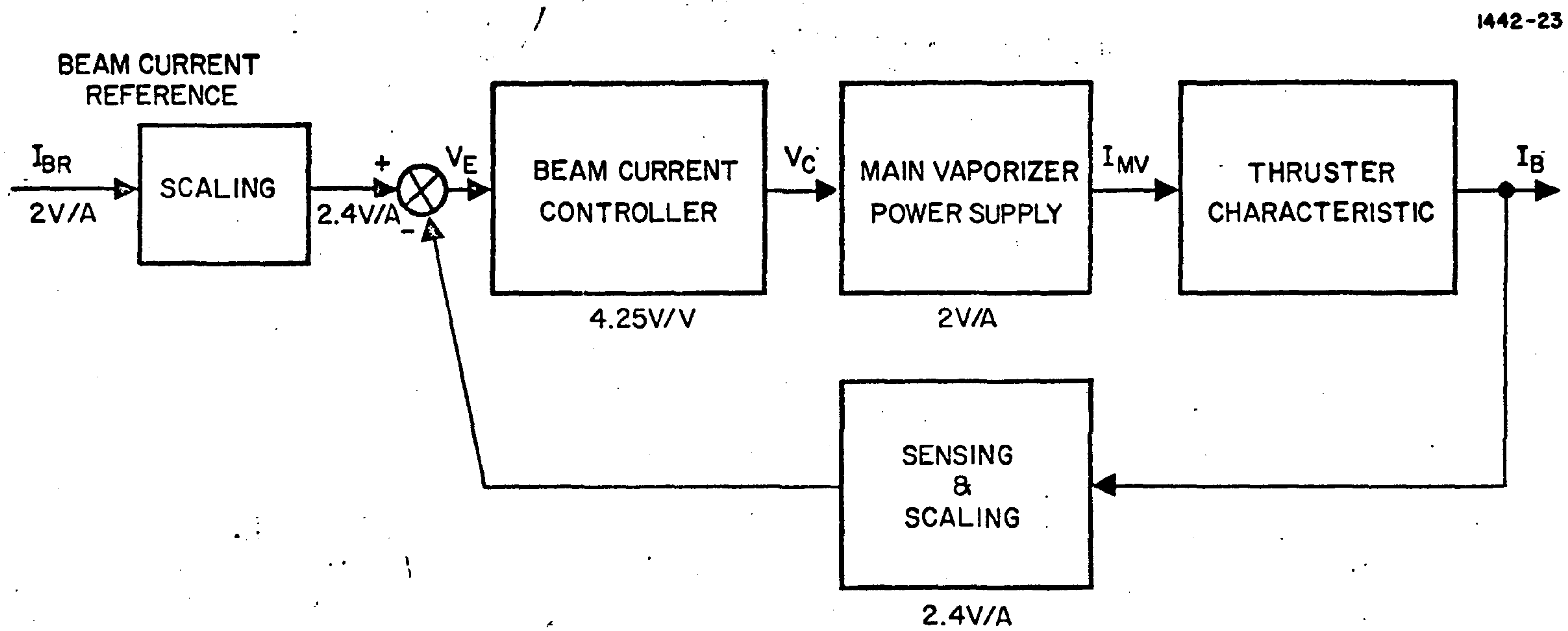


Fig. 2. Beam Current Closed Loop Control Block Diagram.

thrusters should be connected to resistive load banks and operated to verify the capability of the power processor to supply the currents and voltages in accordance with design specifications.

4.1.1 A check should be made with regard to the adjustment of reference set-points (control settings) for the following:

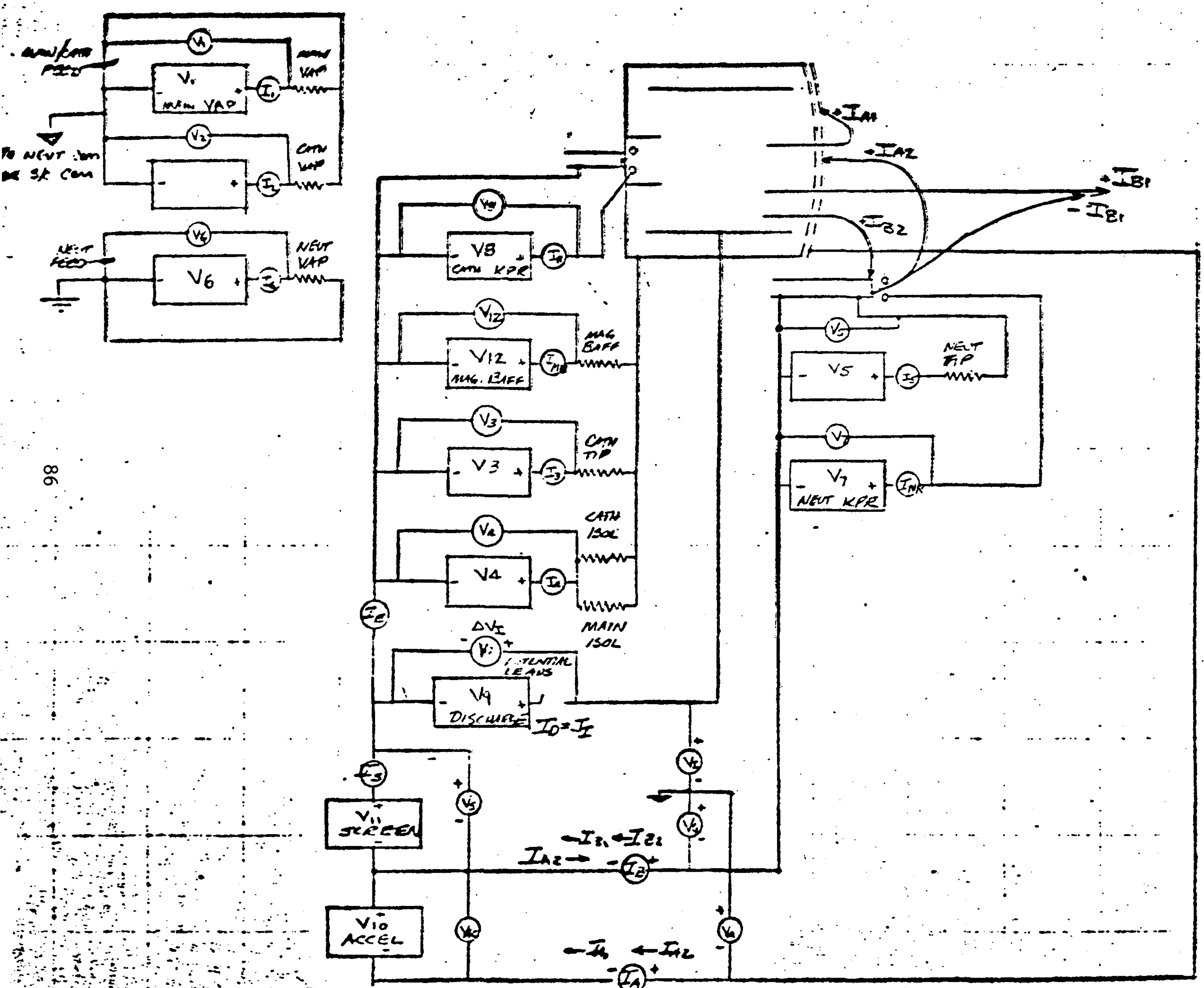
- Neutralizer keeper voltage
- Discharge voltage
- Beam current
- Beam voltage
- Accelerator voltage
- Discharge current

4.1.2 After completing the checkout operation of the power supplies on resistive loads, all heater supplies (1-6) should be adjusted for minimum current output. The current set-point for the neutralizer keeper supply (No. 7) should be adjusted to 2.1 A and for the cathode keeper power supply (No. 8) to 1.0 A. The discharge power supply (No. 9) controls should be adjusted for a current output of 6.0 A. The beam and accel power supply controls should be adjusted to provide 600 V and 300 V respectively. The output of the magnetic baffle power supply should be set to zero (or for min. current).

4.2 Power Processor/Thruster Connection

The connection of the power supplies to the thruster is shown schematically in Fig. 3 for the purpose of identifying current paths and listing current definitions. For performance evaluation, it is considered more appropriate to measure the quantities required directly using an "in-line" data acquisition circuit with connections as shown in Fig. 4 and described in more detail in IPD-PR-141.

4.2.1 After completion of power processor check-out and preliminary thruster preparation, the power processor is connected to the thruster using an in-line data acquisition circuit as shown in Fig. 4.



$$V_I = V8 = V_S + \Delta V_I - V_G$$
$$\Delta V_I \sim 36$$
$$V_G \sim 10$$
$$V_S > 600$$
$$V_I \approx V_S \quad (< 4\%)$$
$$V_{AC} = V_A - V_G$$
$$V_{AC} \approx V_A \quad (< 3\%)$$
$$I_D = I_E + I_S$$
$$I_B = I_{B1} + I_{B2} - I_{A2}$$
$$I_A = I_{A1} + I_{A2}$$
$$I_S = I_B - I_A$$
$$= I_{B1} + I_{B2} + I_{A1}$$
$$\mathcal{E}_I = \Delta V_I (I_D - I_B)/I_B$$

Fig. 3 Schematic Diagram of Thruster/Power-Supply Circuit and Current Paths

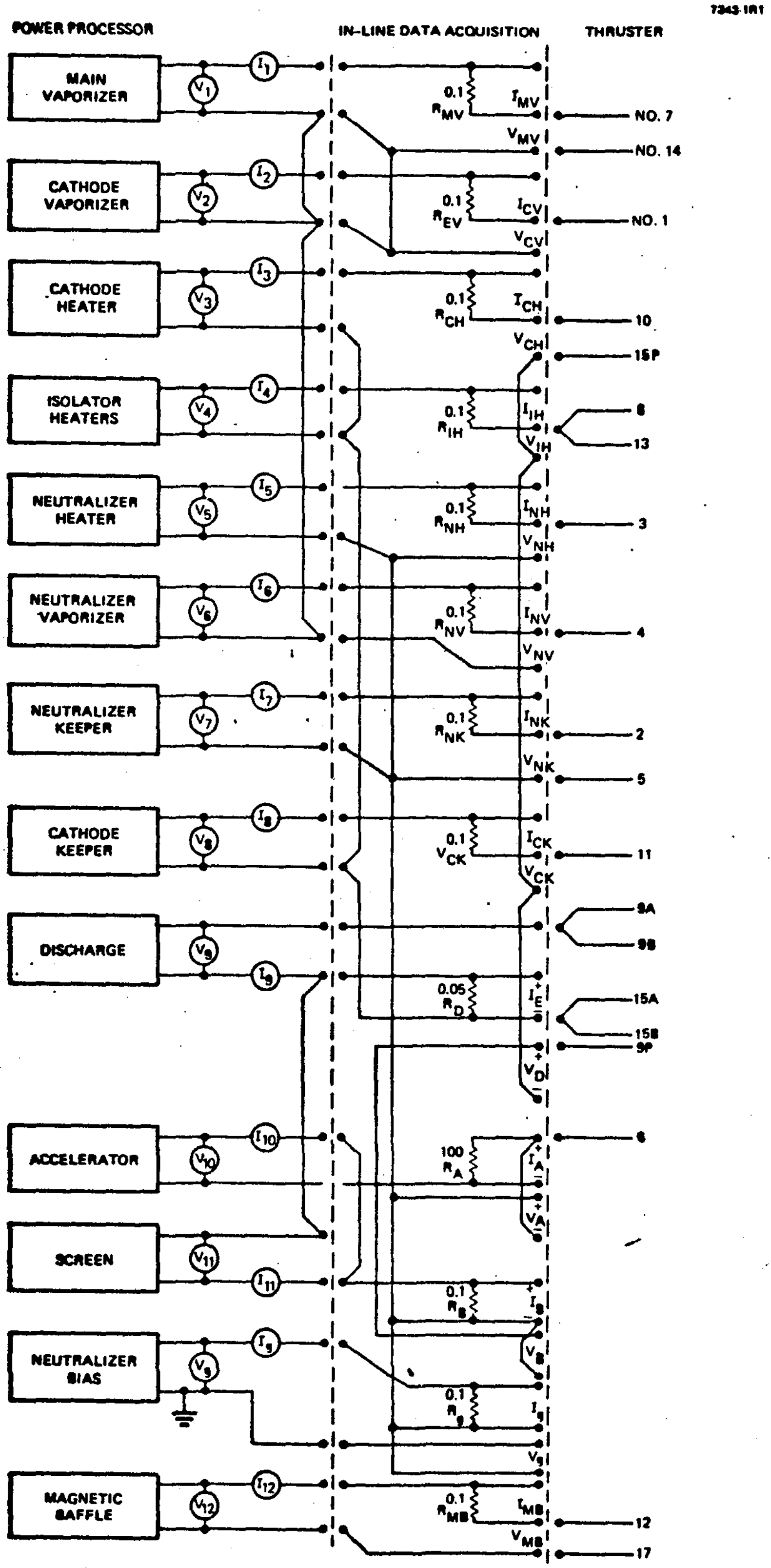


Fig. 4. Acceptance Test Circuit Diagram

SPECIFICATION TITLE

Instrumentation and Calibration

APPROVALS			DATE	REV

1. Scope

This document specifies the equipment, the wiring diagrams, and procedures that are necessary to provide the instrumentation for performance of acceptance tests and other evaluations of operating characteristics of 30 cm ion thrusters. Calibration procedures are also provided to ensure that accuracy of the data obtained is adequate for a discriminating comparison between test and accepted standards.

2. Applicable Documents

2.1 Facility Specifications

2.1.1 IPD-PR-139 - Thruster Test Facility

2.1.2 IPD-PR-140 - Power Processor

2.1.3 NASA CR134687

3. Requirements

3.1 Equipment required for thruster tests

3.1.1 Power Processor
A power processor or collection of power supplies as described in IPD-PR-140

3.1.2 In-Line Data Acquisition Circuit
An in-line circuit as shown in Figure 1 is required to make the measurements of current and voltage necessary for determining performance characteristics.

3.1.3 Propellant Reservoir as described in paragraph 3.3 of IPD-PR-139.

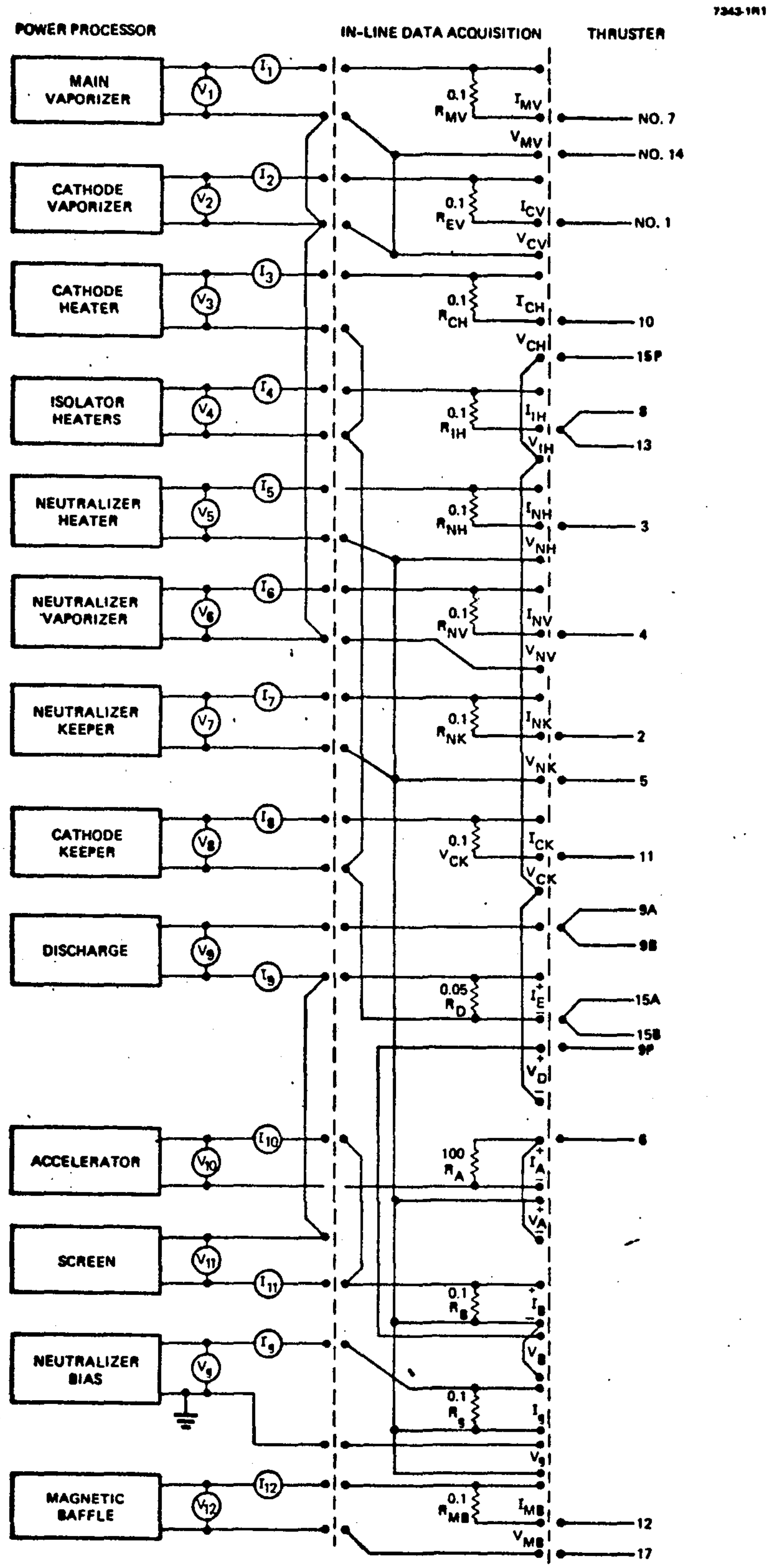


Fig. 1 Acceptance Test Circuit Diagram

3.1.4 Digital Multimeter

A high quality digital multimeter is an essential complement to the in-line data acquisition circuit in that all currents and voltages will be measured with this meter. The important specifications are:

- o 4½ digital display
- o .05% + 1 digital accuracy or better
- o Operable up to 1.1 kV above ground

A Keithley Model 178 is an example of a multimeter that has the required specifications.

3.1.5 Mass Spectrometer Ion Beam Probe

The vacuum facility must be equipped with a mass spectrometer ion beam probe for evaluating the thrust losses resulting from doubly charged ions and non-axial ion trajectories. A description of the probe and the data acquisition techniques has been given in the appendix of NASA CR134687.

3.1.6 Oscilloscope and Clamp-On Type Current Probe

An oscilloscope capable of displaying voltage and current waveforms at frequencies up to a minimum of 50 kHz is required. An inductively coupled probe or current transformer capable of sensing the discharge current (therefore insulated for at least 1200 V stand-off) is also required for recording voltage and current waveforms.

3.2 Calibration

3.2.1 Commercial Instrumentation

All commercial instruments will be calibrated in accordance with the manufacturers specifications with tracability to primary standards.

3.2.2 In-Line Data Acquisition Systems

Current sensing resistors will be measured with a resistance bridge that has been calibrated against primary standards. If values differ from those shown in Figure 1 by greater than 0.5%, the resistor should be replaced.

3.2.3 Mass Spectrometer Ion Beam Probe

Calibration of the mass spectrometer ion beam probe is performed routinely as part of the data acquisition procedure.

HUGHES RESEARCH LABORATORIES MALIBU, CALIFORNIA	SPECIFICATION NO. IPD-PR-142		
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SPECIFICATION TITLE	APPROVALS			DATE	REV
Preliminary Thruster Preparation					

1.0 SCOPE

This document specifies the procedures and tests to be performed during installation of a 30 cm thruster on a vacuum-chamber-facility thruster mounting in preparation for operation.

2.0 APPLICABLE DOCUMENTS

2.1 Facility specification IPD-PR-139.

2.2 Wiring interface drawing 1095023.

3.0 REQUIREMENTS

3.1 Materials

3.1.1 White gloves.

3.1.2 Machine screws, 8 each, .250 in x 28 UNF-2B, .74 in long.

3.1.3 MoS_2 thread lubricant

3.2 Equipment

3.2.1 30 cm thruster

3.2.2 Thruster mounting.

3.2.3 Hand tools.

3.2.4 "Megger" insulation tester.

3.2.5 Ohmeter for continuity checks.

3.2.6 Resistance bridge.

3.2.7 Copy of assembly record resistance measurements.

3.2.8 Vertical height gage or measuring fixture.

4.0 PROCEDURE

4.1 Mechanical Mounting

The first step in preparing the thruster for testing is installation of the thruster on a vacuum-chamber-facility thruster mounting as shown in Fig. 1.

4.1.1 Record the thruster serial number ______________________.

4.1.2 Lubricate the threads of the mounting fasteners (8 ea.,.250 in. x 28 UNF x .75 in. machine screws).

TECH: ______________________

4.1.3 Wear white gloves when handling the thruster and grasp the thruster case by the gimbal pads, in so far as possible. Remove the thruster from the shipping frame and place it on the mounting brackets as shown in Fig. 1, securing the thruster in place with 2 screws in each mounting pad (finger tight only).

4.1.4 Using a vertical height gauge and dial indicator or a similar measurement fixture as illustrated in Fig. 2, the alignment of the thruster (accelerator grid) is checked. Record the distance as measured in each of the four quadrants below. The top of the thruster (facing the accelerator) is designated as 12 o'clock.

12 o'clock ______________________

3 o'clock ______________________

6 o'clock ______________________

9 o'clock ______________________

TECH: ______________________

DATE: ______________________

4.1.5 In order to maintain the angular alignment, the difference between the 12 o'clock and 6 o'clock measurements and between the 3 o'clock and 9 o'clock measurements should not exceed 0.200 in (.5 cm). If the differences are greater, loosen the mounting fasteners and shift the thruster (using shim stock if necessary) to obtain the tolerance indicated. When this has been achieved, tighten the fasteners to torque and re-check the measurement. Install two more fasteners in each gimbal mounting and the mechanical installation is completed.

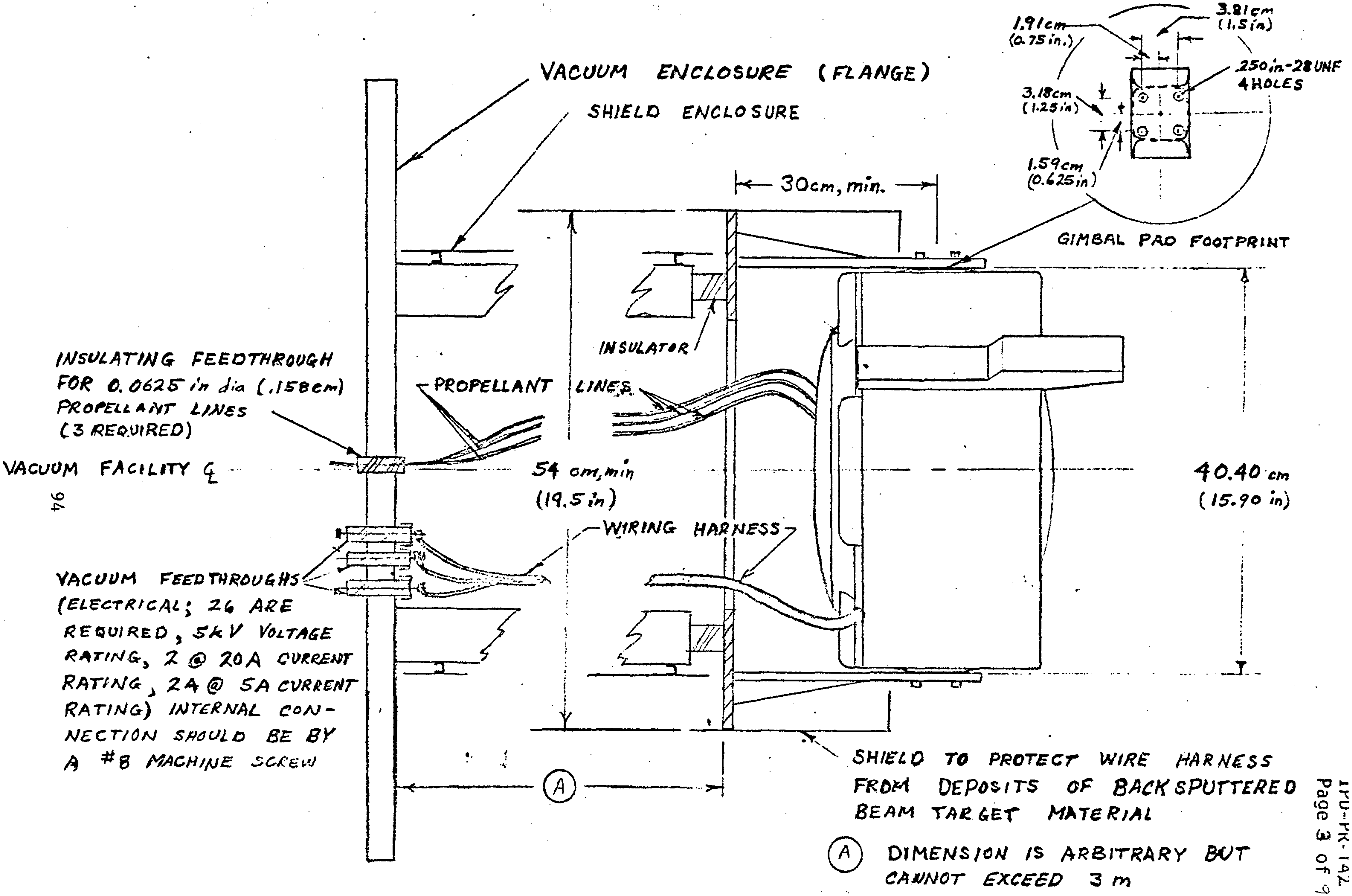


FIG. 1. MOUNTING FOR THRUSTER ASSEMBLY FOR INSTALLATION IN VACUUM CHAMBER TEST FACILITY

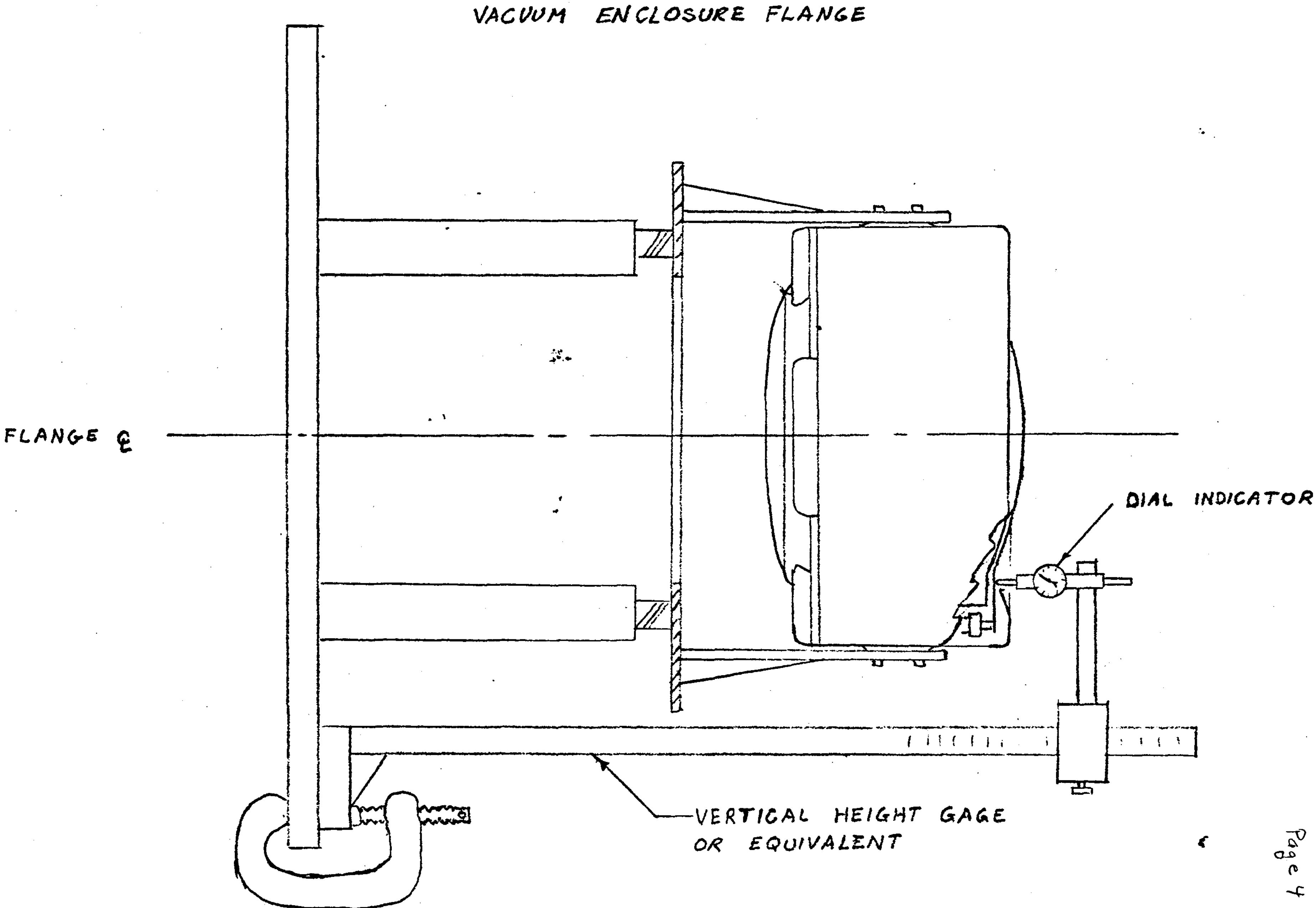


FIG. 2 MEASUREMENT PROCEDURE TO OBTAIN THRUSTER ALIGNMENT

4.2 Propellant Connection

The thruster is equipped with a manifold for the propellant supply that should be found with a blank plate covering the propellant input. The connections are made as follows:

4.2.1 Remove the blank plate used for thruster transit. Mask this plate and store for future use. Retain the fasteners for attaching the propellant manifold.

4.2.2 Position the test manifold that is equipped with a propellant line from each reservoir so that the index markings are aligned and replace the fasteners. Incorrect alignment will connect the reservoirs improperly. Certify that the alignment is correct.

TECH: ______________________

DATE: ______________________

4.3 Electrical Connections

The thruster is fitted with 2 wiring bundles with the wires numbered as shown on drawing 1095023. The wire bundles must be appropriately routed and connected to the terminals provided on the thruster mounting in such a way as to protect the wires from being coated by back-sputtered beam target material and against abrasion of the insulation.

4.3.1 Identify the wiring numbers in each wire bundle and connect to the terminals provided in such a way that connection of the power processor can be made as shown in Fig. 3 using the connectors that are external to the vacuum facility enclosure.

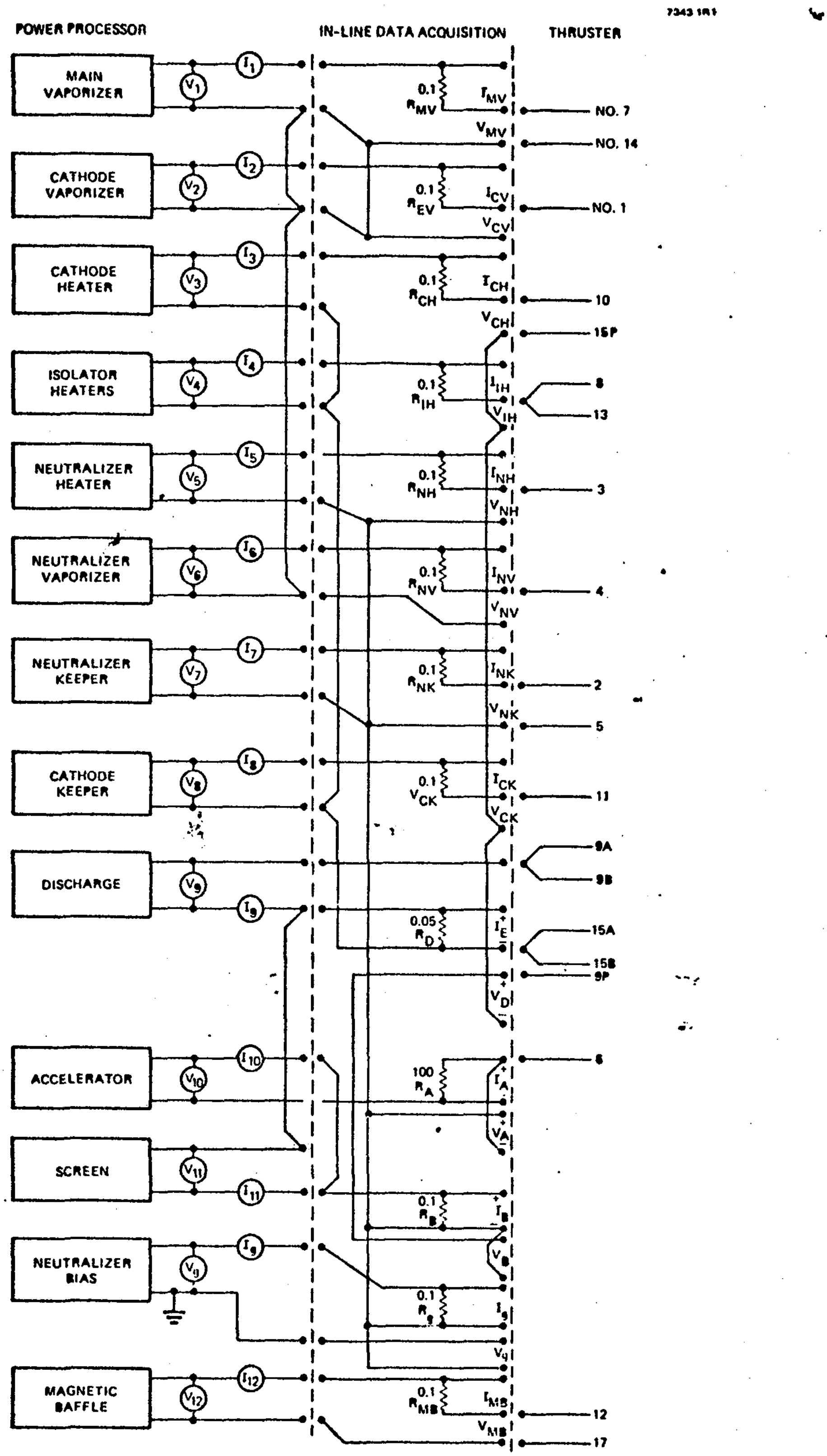


Fig. 3 Acceptance Test Circuit Diagram

4.3.2 Perform an electrical resistance checkout to complete the attached data sheet for comparison with the sheet prepared during the final phase of thruster assembly.

4.3.2.1 The heater and magnetic baffle coil resistance measurements (marked A on the data sheet) are to be measured with a resistance bridge. Resistance measurements should be made at the terminals on the exterior side of the vacuum seal. Record the resistance bridge type and calibration reference.

Resistance bridge ______________________________

____

Calibration: __________________________________

TECH: __________________________ DATE: __________

4.3.2.2 The measurements made to check the insulation capabilities (marked B on the data sheet) are made with a "megger" type insulation tester. Record the manufacturer and model number and voltage output of the instrument used.

Manufacturer and Model No. ______________________

____

TECH: __________________________ DATE: __________

4.3.2.3 The remaining continuity or insulation tests are made with a low voltage (battery operated) type of ohmeter. (These measurements are designated by a C on the data sheet.) Record the manufacturer and model number of the instrument used.

Manufacturer and Model Number ____________________

TECH: __________________________ DATE: __________

4.3.3 Compare the measurements made with those recorded earlier during final thruster assembly. Reconcile any differences and note below.

NOTES: ____

____

TECH: __________________

30 CM ION THRUSTER S/N ________ DATE ________

ASSEMBLY RECORD

Optics Assembly	S/N	________		
CIV Assembly	S/N	________	Cath-Keeper Spacing	________ "
NIV Assembly	S/N	________	Neut-Keeper Spacing	________ "
MIV Assembly	S/N	________		

ELECTRICAL RESISTANCE CHECKOUT

		Terminals	Resistance(Ω)
A	Cathode Heater	10-15	________ Ω
A	Main Vaporizer	7-14	________ Ω
A	Cathode Vaporizer	1-14	________ Ω
A	Neutralizer Vaporizer	4-14	________ Ω
A	Neutralizer Heater	3-5	________ Ω
A	Main Isolator	8-15	________ Ω
A	Cathode Isolator	13-15	________ Ω
A	Magnetic Baffle	12-15	________ Ω
B	HV Return - Outercase	15-Outercase(14)	________ Ω
B	HV Return - Accel	15-6	________ Ω
B	HV Return - Discharge	15-9	________ Ω
B	HV Return - Cath. Keeper	15-11	________ Ω
B	Accel - Outercase	6-Outercase	________ Ω
B	Neut. Keeper - Neut. Common	2-5	________ Ω
B	Neut. Common - Outer case	5-Outercase	________ Ω
C	All Terminals - Outercase	1 thru 15-Outercase	________ Ω

C: Thermocouple

Thermocouple #	Type	Location	Res.
________	________	________	________ Ω
________	________	________	________ Ω
________	________	________	________ Ω
________	________	________	________ Ω

Note 1: ________

Addit. Notes: ________

Checked by: ________

4.4 Final Inspection

Perform a visual inspection to ensure that all wiring is appropriately routed, shields are in place and secured, the vacuum sealing surface is in good condition, and that the thruster appears ready to install in the vacuum test facility. Final inspection should be certified by at least two persons by initially below.

TECH: ______________________

TEST ENGINEER: ______________________

DATE: ______________________

SPECIFICATION TITLE

Data Formats for Thruster Documentation

APPROVALS			DATE	REV

1. SCOPE

This document contains a set of data formats that are intended to represent the documentation for thruster operating characteristics when completed in accordance with the test procedures described in IPD-PR-138 and the additional instructions contained here.

2. APPLICABLE DOCUMENTS

2.1 IPD-PR-138

2.2 Assembly records for thruster being documented.

2.3 Power processor documents.

3. REQUIREMENTS

3.1 Data Formats

The following data formats are included in this IPD.

Acceptance Test Documentation (1)
Acceptance Test Operating Time Log (1)
Acceptance Test Summary (1)
Acceptance Test Data For Principle Throttling Points (1)
Oscillation Verification Summary (1)
Ion Extraction Assembly Perveance Summary (1)
Acceptance Test Operating Time Log (1)
Preliminary Cathode Conditioning (2)
Thruster Startup Procedure (6)
Acceptance Test Data Format (10)
Propellant Flow Data (5)
Extraction System Perveance Data (1)
Minimum Discharge Current Characterization (2)
Magnetic Baffle/Discharge Characterization (2)
V_{NK}/T_{NV} Characteristics (1)
Neutralizer Characterization Data (5)

4. PROCEDURE

4.1 Separate the data formats from the IPD and divide into two groups, Summary sheets and Data formats. Fill in the serial number data for the thruster to be tested on the summary sheets and set them aside for use in preparing the Acceptance Test Documentation. The remainder of the package comprises the data sheets for use in performing the tests as prescribed by IPD-PR-138.

ACCEPTANCE TEST DOCUMENTATION

THRUSTER S/N ______

ION OPTICS ELECTRODES S/N ____________

ION OPTICS MOUNTING S/N ____________

IV-M ASSEMBLY S/N ____________

IV-C ASSEMBLY S/N ____________

IV-N ASSEMBLY S/N ____________

TEST PERIOD ____________ to ____________

COMMENTS:

ACCEPTANCE TEST OPERATING TIME LOG

Date	Start-up			Beam on Time			Cumulative Beam on Time	Comments
	Start Time of Day	Beam on Time of Day	Total Time Hours	Beam on Time of Day	Beam off Time of Day	Hours		

ACCEPTANCE TEST SUMMARY

Date________ Thruster__________ Contract ____________

Thruster Property	Test Point 1	2	3	4	5	6	7	8	9	10
I_B, A										
V_B, V										
V_D, V										
I_E, A										
I_{MB}, A										
V_{NK}, V										
P_{tot}, A										
η_e										
$\dot{m}_{MV}$, A [1]										
$\dot{m}_{cv}$, A [1]										
$\dot{m}_{NV}$, A [1]										
$\dot{m}_{tot}$, A [1]										
η_{MD}, %										
η_{MT}										
F_t										
γ										
η_T, %										
I_{sp}, sec										
T, mN										

1 Equivalent amperes neutral flow

All points have V_A = -300, I_{NK} = 1.8 A, I_{CK} = 1.0 A

ACCEPTANCE TEST DATA FOR PRINCIPLE THROTTLING POINTS

	Unit	Data				
Test Point		1	2	3	4	5
Beam Voltage, V_B						
Beam Current, I_B						
Accel Voltage, V_A						
Accel Current, I_A						
Discharge Voltage, V_D						
Emission Current, I_E						
Cath. Keeper Voltage, V_{CK}						
Cath. Keeper Current, I_{CK}						
Mag. Baffle Voltage, V_{MB}						
Mag. Baffle Current, I_{MB}						
Main Vaporizer Voltage, V_{MV}						
Main Vaporizer Current, I_{MV}						
Cath. Vaporizer Voltage, V_{CV}						
Cath. Vaporizer Current, I_{CV}						
Neut. Vaporizer Voltage, V_{NV}						
Neut. Vaporizer Current, I_{NV}						
Neut. Keeper Voltage, V_{NK}						
Neut. Keeper Current, I_{NK}						
Neut. Coupling Voltage, V_g						
Neut. Coupling Current, I_g						
Main Vap. Temp., T_{MV}						
Cath. Vap. Temp., T_{CV}						
Neut. Vap. Temp., T_{NV}						
Min. Emission Current						
Min. Neut. Keeper Voltage						
Min. Mag. Baffle Current						

OSCILLATION VERIFICATION SUMMARY

DATE ______________________ THRUSTER ______________________

POWER PROCESSOR TYPE ______________________

NOTES ____

____

____

OSCILLATION FREQUENCIES % MODULATION

I_E ______________________ ______________

I_B ______________________ ______________

V_D ______________________ ______________

I_{NK} ______________________ ______________

I_{CK} ______________________ ______________

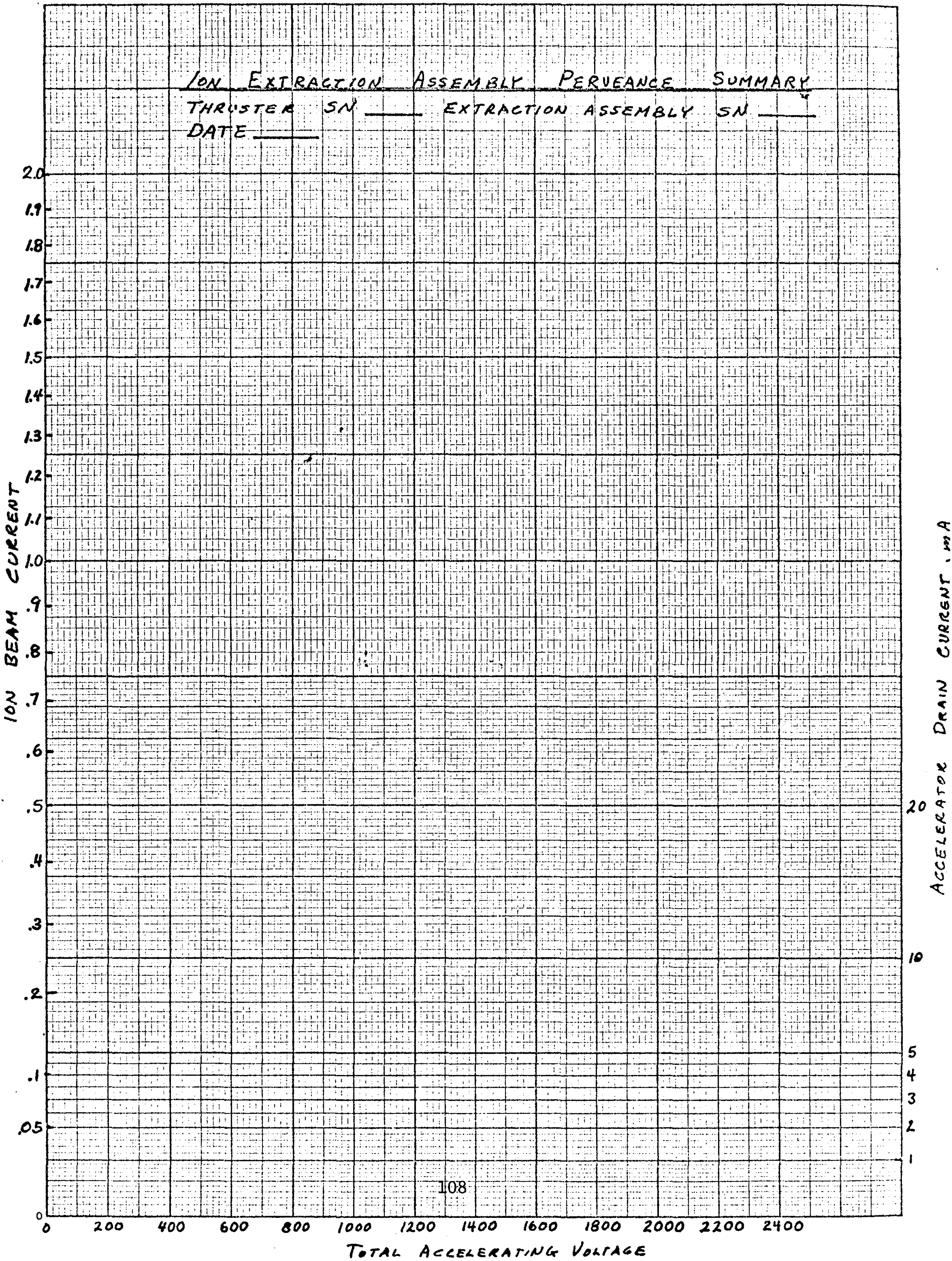
COMMENTS ____

____

____

____

____


ION EXTRACTION ASSEMBLY PERVEANCE SUMMARY
THRUSTER SN ____ EXTRACTION ASSEMBLY SN ____
DATE ____
ION BEAM CURRENT
2.0
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
.05
0
ACCELERATOR DRAIN CURRENT, mA
20
10
5
4
3
2
1
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200
2400
TOTAL ACCELERATING VOLTAGE

PRELIMINARY CATHODE CONDITIONING

THRUSTER SERIAL NUMBER ______________________________.

DATE THRUSTER INSTALLED IN VACUUM FACILITY ______________________.

VACUUM FACILITY DESCRIPTION ______________________________.

POWER PROCESSOR DESCRIPTION ______________________________.

PROCEDURE CONTROLLED BY IPD-PR-138

EVENT	TIME	FACILITY PRESSURE	THRUSTER CATHODE HEATER			NEUTRALIZER CATHODE HEATER		
			V_{CH}	I_{CH}	P_{CH}	V_{NA}	I_{NH}	P_{NH}
1. Turn on heater current (para. 4.3.3.2; low level)								
2. Readings after one hour.								
Readings after two hours								
4. Readings after three hours								
5. Turn off heaters								
6. Turn on heater current (high level)								
7. Readings after one hour								
8. Turn off heaters								

COMMENTS: ____

CONTRACT: ______ THRUSTER: ______ POWER CONDITIONING UNIT: ______

DATE: ______ TEST: ______ CHAMBER: ______

STARTUP PROCEDURE	ELAPSED TIME	TIME OF DAY	TANK PRESS	VAP TEMP			MAIN VAP		CATHODE VAP		NEUT VAP		CATHODE HEATER		NEUT HEATER		ISOLATOR HEATERS	
				MAIN	CATH	NEUT												
	MIN.	HRS	P_{TK} (Torr)	T_{MV} (°C)	T_{CV} (°C)	T_{NV} (°C)	V_{MV} (V)	J_{MV} (A)	V_{CV} (V)	J_{CV} (A)	V_{NV} (V)	J_{NV} (A)	V_{CH} (V)	J_{CH} (A)	V_{NH} (V)	J_{NH} (A)	V_{IH} (V)	J_{IH} (A)
1. MEASURE INITIAL ISOLATOR & VAPORIZER TEMP.																		
2. TURN ON ISOL. POWER	0																	
3. CATH HTR POWER ON	0																	
4. NEUT HTR POWER ON	0																	
5. HEATER VOLTAGE CHECK	5																	
6. REDUCE ISOLATOR HTR POWER	18																	
7. END OF "PREHEAT," ISOL POWER OFF	35																	
8. TURN ON CATH. & NEUT. VAPORIZER	35																	
9. CATH KEEPER VOLTAGE APPLIED	35																	
10. NEUT KEEPER VOLTAGE APPLIED	35																	
11. DISCHARGE VOLTAGE APPLIED	35																	
12. CATH IGNITION (KEEPER SUPPLY ____ AUX. P.S. ____ V = ____)																		
13. NEUT IGNITION (KEEPER SUPPLY ____ AUX. P.S. ____ V = ____)																		
14. DISCHARGE IGNITION																		
15. CHECK CATH & NEUT HEATER OFF	43																	
16. PARAMETERS TO RUN CONDITIONS																		
17. EXTRACTION VOLTAGES APPLIED																		
18. BEAM ESTABLISHED, NEUT COUPLED																		
19. BEAM ESTABLISHED AT 2A BEAM																		

NOTES:

Thruster ______________ Date ______________

ACCEPTANCE TEST DATA FORMAT

	Unit or Calibration Factor	Data				
Test Point						
Beam Voltage, V_B						
Beam Current, I_B						
Accel Voltage, V_A						
Accel Current, I_A						
Discharge Voltage, V_D						
Emission Current, I_E						
Cath. Keeper Voltage, V_{CK}						
Cath. Keeper Current, I_{CK}						
Mag. Baffle Voltage, V_{MB}						
Mag. Baffle Current, I_{MB}						
Main Vaporizer Voltage, V_{MV}						
Main Vaporizer Current, I_{MV}						
Cath. Vaporizer Voltage, V_{CV}						
Cath. Vaporizer Current, I_{CV}						
Neut. Vaporizer Voltage, V_{NV}						
Neut. Vaporizer Current, I_{NV}						
Neut. Keeper Voltage, V_{NK}						
Neut. Keeper Current, I_{NK}						
Neut. Coupling Voltage, V_g						
Neut. Coupling Current, I_g						
Main Vap. Temp., T_{MV}						
Cath. Vap. Temp., T_{CV}						
Neut. Vap. Temp., T_{NV}						
Vacuum Chamber Press						
Time of Day						

PROPELLANT FLOW DATA

DATE: ______________ THRUSTER ______________ RESERVOIR ______________

CALIBRATION FACTORS:

NEUTRALIZER ______________

CATHODE ______________

MAIN ______________

Test Point	Time of Day	Vaporizer Temperature			Reservoir Levels		
		T_{MV}	T_{CV}	T_{NV}	NV	CV	MV

EXTRACTION SYSTEM PERVEANCE DATA

DATE ____________________ THRUSTER ____________________ CHAMBER PRESS ____________________

I_B A	V_B Test Plan	V_B V	I_A mA	I_{CV} A	I_{MB} A	I_{MV} A	COMMENTS
2.0	1100						I_E = 12.0 T.P. #1
2.0	1100						I_E = 15.6 (250 eV/ion)
	1040						
	1000						
	950						
1.6	940						I_E = 10, T.P. #4
	1100						I_E = 12.5 (250 eV/ion)
	1000						
	950						
	900						
	850						
1.3	820						I_E = 8.5, T.P. #6
	1100						I_E = 10.1 (250 eV/ion)
	1000						
	900						
	850						
	800						
	750						
.75	1100						I_E = 5.75 T.P. #8
	1100						I_E = 5.85 (250 eV/ion)
	1000						
	900						
	800						
	750						
	700						
	650						

MINIMUM DISCHARGE CURRENT CHARACTERIZATION

Procedure Para. 4.7, IPD-PR-138

DATE ______________ THRUSTER ______________

I_E Test Plan A	I_E Measured A	I_{CV} A	I_{MB} A	I_{MV} A	I_A mA	COMMENTS
12.0						Test Point No. 1, Table 5.1
11.6						
11.2						
10.8						
10.6						
10.4						
10.2						
10.0						Test Point No. 4, Table 5.1
9.6						
9.2						
8.8						
8.6						
8.4						
8.2						
8.0						
8.5						Test Point No. 6, Table 5.1
8.0						
7.5						
7.0						
6.8						
6.6						
6.4						
6.2						

MINIMUM DISCHARGE CURRENT CHARACTERIZATION

(Continued)

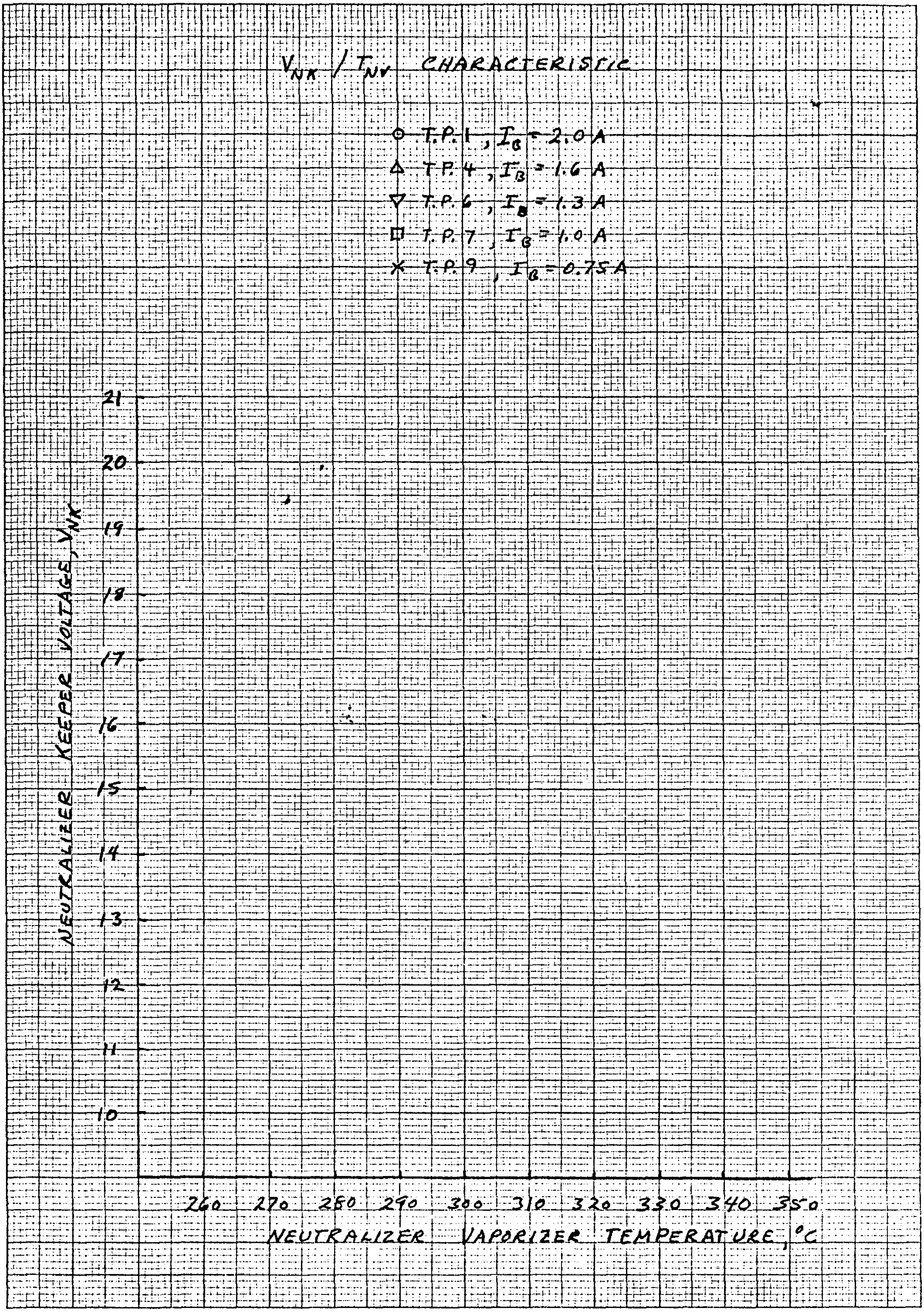
I_E Test Plan A	I_E Measured A	I_{CV} A	I_{MB} A	I_{MV} A	I_A mA	COMMENTS
7.0						Test Point No. 7, Table 5.1
6.6						
6.2						
5.8						
5.4						
5.2						
5.0						
5.75						Test Point No. 9, Table 5.1
5.4						
5.0						
4.6						
4.2						
4.0						
3.8						
3.6						

MAGNETIC-BAFFLE/DISCHARGE CHARACTERIZATION

Procedure Para. 4.5, IPD-PR-138

DATE ____________ THRUSTER ________________ Page 1 of ____

Time of Day	Test Point	I_{MB} A	T_{CV} ^oC	T_{MV} ^oC	I_A mA	V_{CK}	COMMENTS



V_NK / T_NV CHARACTERISTIC
○ T.P. 1, I_B = 2.0 A
△ T.P. 4, I_B = 1.6 A
▽ T.P. 6, I_B = 1.3 A
□ T.P. 7, I_B = 1.0 A
× T.P. 9, I_B = 0.75 A
NEUTRALIZER KEEPER VOLTAGE, V_NK
21
20
19
18
17
16
15
14
13
12
11
10
260
270
280
290
300
310
320
330
340
350
NEUTRALIZER VAPORIZER TEMPERATURE, °C

NEUTRALIZER CHARACTERIZATION DATA

Test Point ________

I_B = ____________ I_D = ____________ I_{MB} = ____________

V_B = ____________ V_D = ____________ I_{NK} = ____________

Test Point V_{NK}	Measured V_{NK}	Time of Day	T_{NV}	I_{NV}	V_{NV}	P_{NV}	Comment
15.5							
15.0							
14.5							
14.0							
13.5							
13.0							
13.5							
12.0							
12.5							
11.0							
15.5							
16.0							
16.5							
17.0							
17.5							
18.0							

APPENDIX B

ANALYSIS OF CORRECTION FACTORS FOR BEAM DIVERGENCE AND DOUBLY CHARGED IONS THAT WERE OBTAINED IN CHARACTERIZATION TESTING OF THRUSTER SN J3

The analysis of correction factors reproduced here was performed by Mr. R.T. Bechtel of NASA's Lewis Research Center. Only the symbols have been changed to conform to those used in this report.

Summary of Beam Divergence Thrust Loss Reduction Factor, F_T

All values of F_T measured for thruster J3 are shown in Tables B1 through B5 for the throttling points shown in Figure B1. Initial examination shows no uniform, monotonic variation of F_T with J_{MB}, J_E, V_D, or V_b at a given beam current. There does however appear to be a consistent decrease in F_T as V_{Accel} is increased to 528 V. This variation is not unexpected since high V_{Accel} tends to cause over focusing of ions.

If it is assumed that the variation in all data at a given J_b is due to data error rather than the variation of J_{MB}, J_E, V_D, or V_b (V_{Accel} will be discussed separately), then the average value and the standard deviation for each beam current can be calculated. This is shown in Table B6. Note the deviation is less than 1.56×10^{-3} (∿0.16% of average) and the range of values for a given J_b is typically 0.0022 or less. The single exception appears to be the 0.75 A J_b, where the maximum value of 0.9867 appears to be an anomalous reading. If the data for V_{Accel} variation is also included the deviations generally increase at each J_b. However, for purposes of a total efficiency calculation, the average values probably are within the accuracy of the measurement technique. The average values of F_T within and without V_A data are plotted in Figure B2.

Table B7 shows the average of all data at all values of J_b. Note that excluding all or part of the V_A data or J_b = 0.5 A data affects the average only in the 4th decimal place. The standard deviation is less than 2.34×10^{-3} and the maximum deviation from the average is less than 0.0005. Thus it appears that either an average value of 0.985 for any value of J_b (from 2.0 to 0.5 A) or the value taken from the

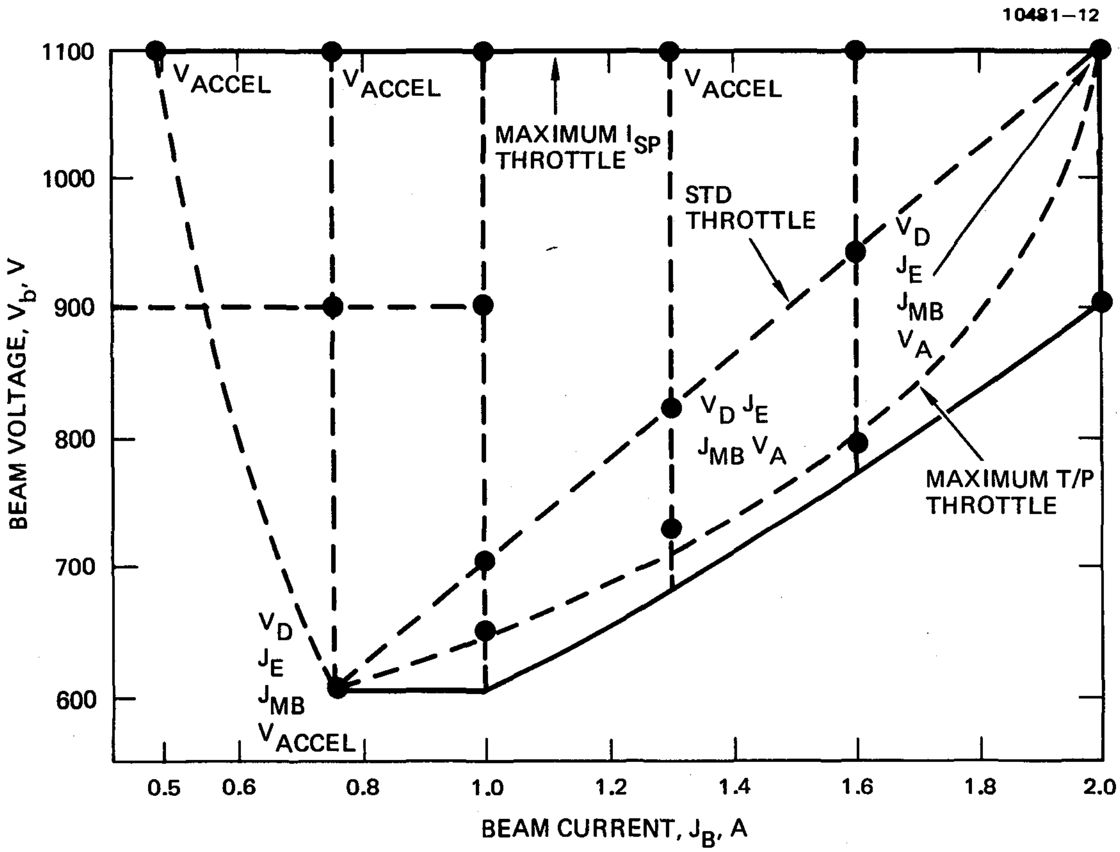


Figure B1. Throttling points for 30 cm J-series thruster.

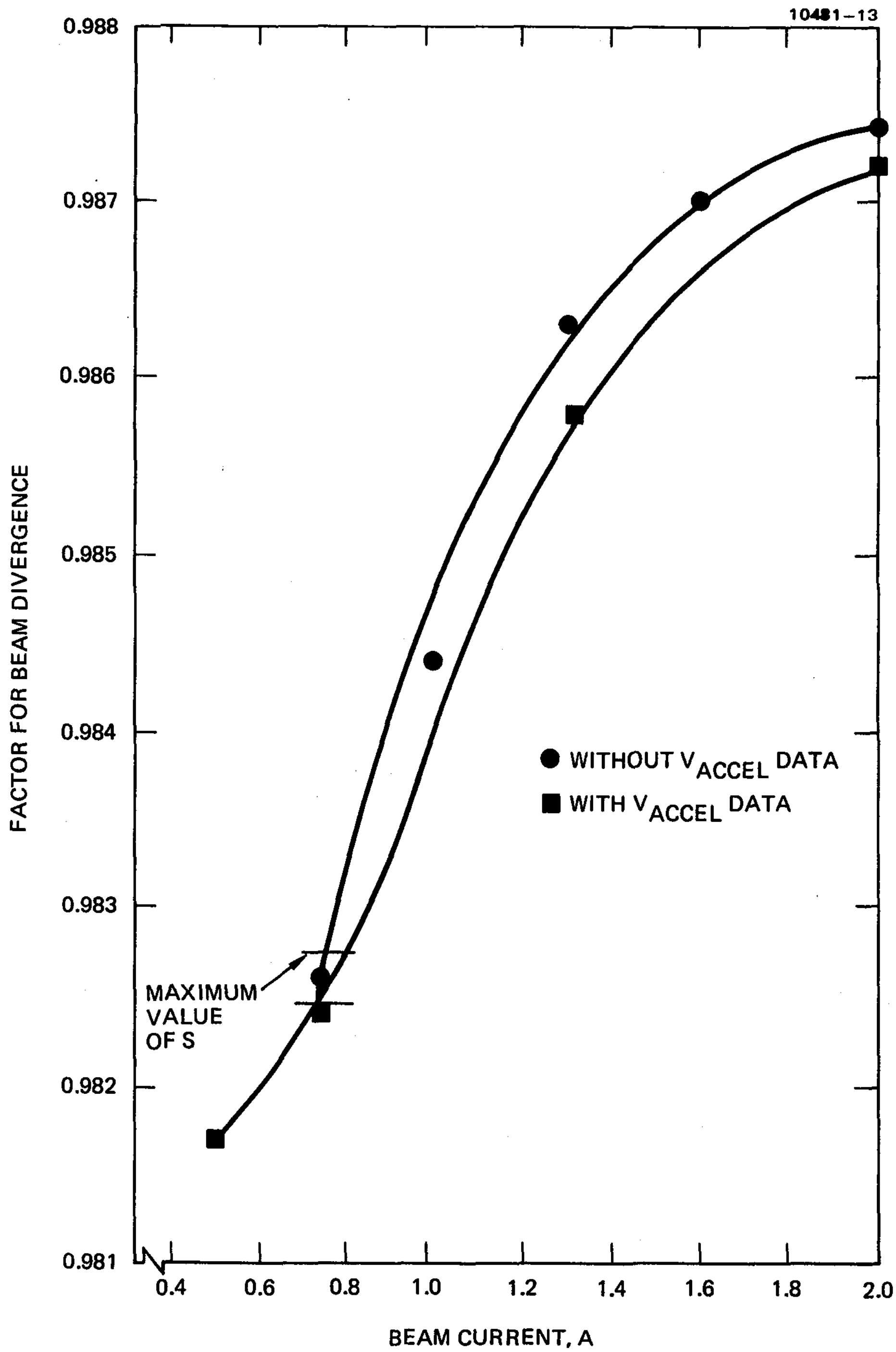


Figure B2. Factor for beam divergence, F_T, as a function of beam current.

curve of Figure B2 should not significantly affect a total efficiency calculation.

Summary of Doubly Charged Ion Thrust Loss Reduction Factor, α

Tables B1 through B5 show that α is not a strong function of V_b, J_{M_B}, or V_{Accel} at a given beam current. The variation caused by including the effect of J_E is only slightly greater, but the effect of variation of V_D is much more significant. The variation with V_b appears to be random with no definite trend established by the data for all J_b. The effect of J_{MB} is extremely small, in the fourth decimal place, and appears to be constant over the range of J_{MB} at each J_b. The effect of V_{Accel} is the same as for V_b variations. No definite trend is apparent. At some J_b, α increases with V_A, but at other J_b, α will decrease.

The effect of increasing J_E is to decrease α (more double ions formed) as shown in Table B8; the magnitude of this effect is small, but the variation is established.

These data are shown in Figure B3. Note that the value of α appears to level off as J_E is increased sufficiently beyond the standard operating point. The effect of increasing V_D is shown in Table B8 and Figure B3. The decrease in α with increasing V_D is large especially at the higher J_b. As J_b is lowered, the effect, although still present, is reduced.

A summary curve of all V_D = 32 V data is shown in Figure B4. To a first order, this curve is accurate with a standard deviation of less than 1.8×10^{-3} (<0.2% of average). This curve does treat the variation of α with J_E as data error, which is probably not accurate, but the variation is small enough that significant errors are not introduced. The effect of V_D is more pronounced and should be evaluated using the data of Figure B3.

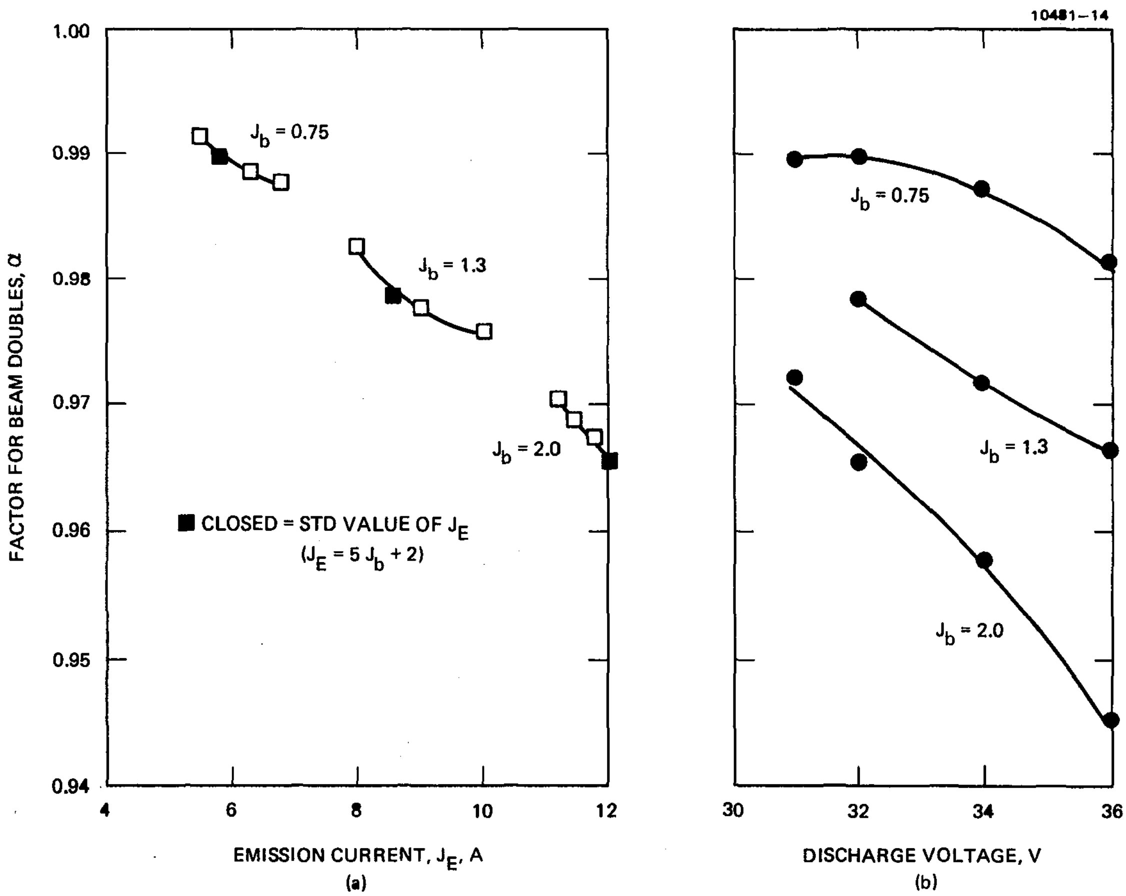


Figure B3. Factor for beam doubles, α, as a function of (a) beam current and (b) discharge voltage.

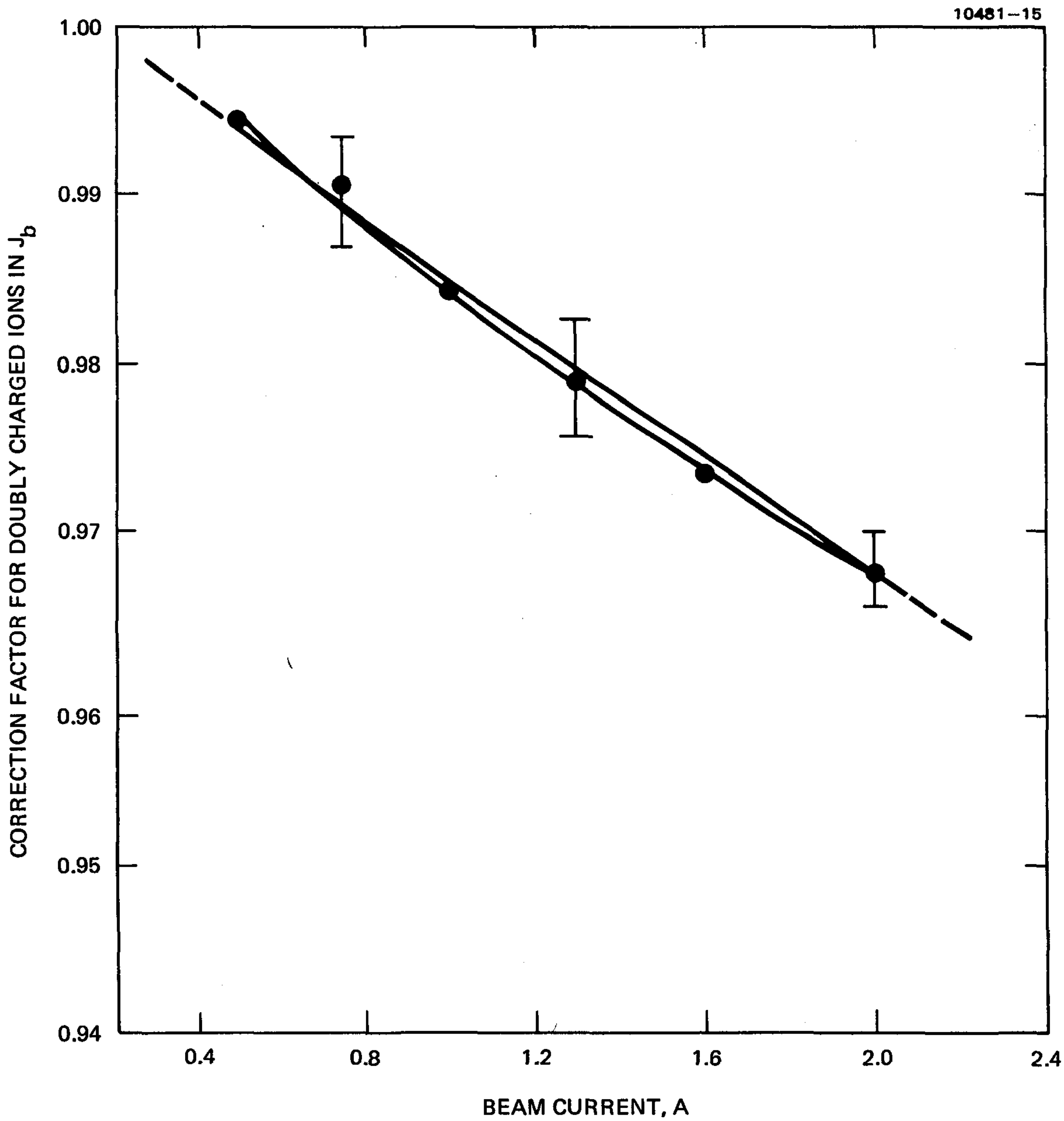


Figure B4. α as a function of J_b for V_D = 32 V (data of Table B8).

Summary of Total Thrust Reduction Factor

The total thrust reduction factor is $\gamma = F_T$. Table B9 summarizes the variation of γ as a function of J_B using the average values of Tables B3 and B4 and Figures B2 and B4. The effect of V_D on the value of α is not included in this curve. These data are plotted in Figures B5 for γ (thrust reduction) and γ^2 (total efficiency reduction).

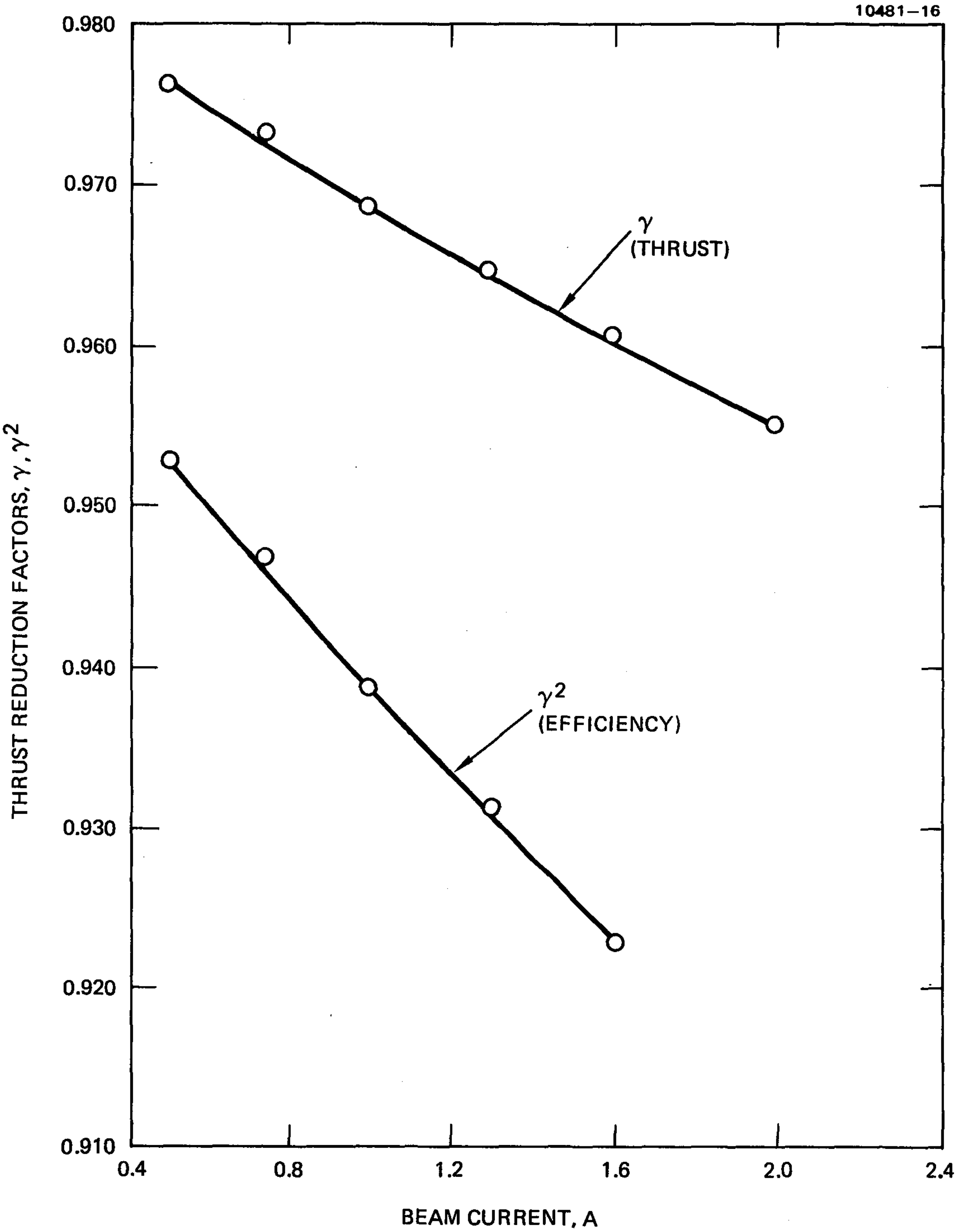


Figure B5. Thrust correction factors γ and γ^2 as functions of beam current for "standard" operating conditions.

Table B1. Effect of V_b (J_E, J_{MB} = STD, V_D = 32 V, V_{Accel} = 340 V)

J_b	V_b	α	F_T
2.0	1100	0.9657	0.9860
	900	0.9692	0.9868
1.6	1100	0.9707	0.9868
	940	0.9747	0.9874
	695	0.9750	0.9868
1.3	1100	0.9785	0.9877
	820	0.9785	0.9857
	731	0.9818	0.9861
1.0	1100	0.9850	0.9843
	900	0.9841	0.9848
	700	0.9838	0.9841
	647	0.9844	0.9845
0.75	1100	0.9909	0.9851
	900	0.9878	0.9830
	600	0.9898	0.9816

Table B2. Effect of J_{MB} (V_b, J_E = STD; V_D = 32 V; V_{Accel} = 340 V)

J_b	J_{MB}	α	F_T
2.0	2.0	0.9653	0.9875
	2.1	0.9657	0.9860
	2.3	0.9660	0.9881
	2.4	0.9669	0.9882
	2.6	0.9671	0.9876
1.3	2.2	0.9786	0.9865
	2.4	0.9788	0.9865
	2.7	0.9785	0.9857
	3.2	0.9789	0.9860
	3.4	0.9782	0.9862
0.75	2.4	0.9917	0.9823
	2.8	0.9918	0.9820
	3.0	0.9898	0.9816
	3.2	0.9917	0.9815
	3.4	0.9903	0.9822

Table B3. Effect of V_D (V_b, J_{MB}, J_E = STD; V_{Accel} = 340 V)

J_b	V_D	α	F_T
2.0	31	0.9721	0.9877
	32	0.9657	0.9860
	34	0.9580	0.9876
	36	0.9452	0.9866
1.3	32	0.9785	0.9857
	34	0.9718	0.9867
	36	0.9660	0.9867
0.75	31	0.9893	0.9867
	32	0.9898	0.9816
	34	0.9873	0.9815
	36	0.9815	0.9824

Table B4. Effect of J_E (V_b, J_{MB} = STD, V_D = 32 V, V_{Accel} = 340 V

J_b	J_E	α	F_T
2.0	12.0	0.9657	0.9860
	11.75	0.9675	0.9876
	11.4	0.9689	0.9874
	11.25	0.9708	0.9878
1.3	9.5	0.9757	0.9859
	9.0	0.9779	0.9858
	8.5	0.9785	0.9857
	8.0	0.9827	0.9860
0.75	5.5	0.9915	0.9826
	5.75	0.9898	0.9816
	6.25	0.9892	0.9823
	6.75	0.9876	0.9812

Table B5. Effect of V_A (J_E, J_{MB} = STD; V_D = 32 V)

J_b	V_b	V_{Accel}	α	F_T
2.0	1100	340	0.9657	0.9860
		528	0.9675	0.9853
1.3	1100	340	0.9785	0.9877
		387	0.9799	0.9856
		525	0.9790	0.9830
	820	340	0.9785	0.9857
		380	0.9780	0.9851
		518	0.9802	0.9831
0.75	1100	339	0.9909	0.9851
		383	0.9913	0.9815
		521	0.9889	0.9807
	600	328	0.9898	0.9816
		367	0.9938	0.9817
0.5	1100	306	0.9946	0.9828
		385	0.9952	0.9819
		521	0.9931	0.9806

Table B6. Summary of F_T at Various J_b

Parameter(s) Varied (V_{Accel} = 340 V)	J_b	# PTS	F_T AVG	S	Range
J_{MB}, J_E, V_D, V_b	2.0	(12)	0.9874	6.37^{-4}	0.9882 - 0.9860
V_b	1.6	(3)	0.9870	3.46^{-4}	0.9874 - 0.9868
J_{MB}, J_E, V_D, V_b	1.3	(12)	0.9863	5.52^{-4}	0.9877 - 0.9857
V_b	1.0	(4)	0.9844	2.99^{-4}	0.9848 - 0.9841
J_{MB}, J_E, V_D, V_b	0.75	(13)	0.9826	1.56^{-3}	0.9867 - 0.9812 (0.9824)
J_{MB}, J_E, V_D, V_A, V_b	2.0	(13)	0.9872	8.45^{-4}	0.9882 - 0.9853
V_b	1.6	—	—	—	—
J_{MB}, J_E, V_D, V_A, V_b	1.3	(16)	0.9858	1.22^{-3}	0.9877 - 0.9830
V_b	1.0	—	—	—	—
J_{MB}, J_E, V_D, V_A, V_b	0.75	(16)	0.9824	1.51^{-3}	0.9867 - 0.9807
V_{Accel}	0.5	(3)	0.9817	1.10^{-3}	0.9828 - 0.9806

Table B7. Summary of F_T at all J_B

	F_T(AVG)	S
All Data (55)	0.9849	2.43^{-3}
All Data Except $V_A \neq 340$ (44)	0.9854	2.19^{-3}
All Data Except $J_b = 0.5A$ (52)	0.9851	2.27^{-3}
All Data Except $V_A = 528$ (50)	0.9851	2.26^{-3}
NOTE: ( ) = No. of Data Points S = Standard Deviation		

Table B8. Summary of α at Various J_b

Parameters Varied	J_b	α(AVG)	S
V_b, J_{MB}, V_{Accel} (7)	2.0	0.9668	1.3^{-3}
V_b, J_{MB}, V_{Accel}, J_E (10)	2.0	0.9675	1.72^{-3}
V_b, J_{MB}, V_{Accel}, J_E, V_D (13)	2.0	0.9654	6.94^{-3}
V_b (3)	1.6	0.9734	2.4^{-3}
V_b, J_{MB}, V_{Accel} (13)	1.3	0.9790	1.03^{-3}
V_b, J_{MB}, V_{Accel}, J_E (16)	1.3	0.9789	1.61^{-3}
V_b, J_{MB}, V_{Accel}, J_E, V_D (18)	1.3	0.9778	3.72^{-3}
V_b (4)	1.0	0.9843	5.12^{-3}
V_b, J_{MB}, V_{Accel} (11)	0.75	0.9908	1.61^{-3}
V_b, J_{MB}, V_{Accel}, J_E (14)	0.75	0.9905	1.71^{-3}
V_b, J_{MB}, V_{Accel}, J_E, V_D (17)	0.75	0.9897	2.75^{-3}
V_{Accel}	0.5	0.9943	1.08^{-3}

NOTE: ( ) = No. of Data Points

S = Standard Deviation

Table B9. Summary of All Reduction Factors

J_b	α	F_T	γ	γ^2
2.0	0.9675	0.9872	0.9551	0.9122
1.6	0.9734	0.9870	0.9607	0.9230
1.3	0.9789	0.9858	0.9650	0.9312
1.0	0.9843	0.9844	0.9689	0.9389
0.75	0.9905	0.9824	0.9731	0.9469
0.5	0.9943	0.9817	0.9761	0.9528

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