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CHARACTERISTICS OF 30-CENTIMETER MERCURY ION THRUSTERS

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E-735

Abstract

The technology development of the 30-cm J-series mercury ion thruster for prime propulsion application in Solar Electric Propulsion Systems (SEPS) has been conducted at NASA-Lewis Research Center. This development included the Fabrication and Testing of the 30-cm thruster. The present J-series thruster design is the result of an intensive effort to eliminate real and potential design deficiencies that were uncovered during initial endurance, structural, and performance tests. A standardized set of test and data recording procedure was formulated to allow for the characterization of the J-series thruster. This paper will briefly review the design of the J-series thruster and will present a compilation of recent test results that define the J-series thruster characteristics.

Introduction

In order to enable the future development of a Solar Electric Propulsion Stage (SEPS), the NASA Office of Aeronautics and Space Technology has sponsored a technology program managed by the Lewis Research Center (LeRC) to develop an ion thruster for prime propulsion applications in SEPS.[1] In support of this technology program, Hughes Aircraft Company has participated in the development, fabrication, and testing of 30-cm mercury ion thrusters under contract to NASA's LeRC.[2-6] The latest version of this thruster is known as the J-series thruster.[7] The J-series thruster is the result of an intensive effort to eliminate real and potential design deficiencies that were uncovered during early endurance, structural, and performance tests.[6]

SEPS mission planners have great interest in the most recent performance data available on the J-series thruster. This paper will briefly review the design of the J-series thruster and will present test results (performance data) that were obtained at the Hughes Research Laboratories (HRL) and NASA LeRC.

The J-series thruster operates at a nominal specific impulse (I_{sp}) of 3100 sec at a thrust level of 130 mN with a thruster input power (P_t) of 2650 W and total efficiency of approximately 73 percent. The thruster dry mass is 10.4 kg. Testing of the 30-cm thruster so far has defined no parameters that would prevent a lifetime of least 15,000 hours at the maximum power level required for a 2.0 amp ion beam current. Since the number of ions and the fraction of double charged ions (which cause errosion of discharge chamber components) are reduced at lower beam currents, the lifetime of a 30-cm thruster would be longer (based on optics screen wear rate) when operated at a lower beam current. The thrust level can be varied from 130 mN to 36 mN. Other failure modes, which may prevent a lifetime of 15,000 hours or longer, have not been defined to date.

A standardized set of test and data-recording procedures was formulated in an effort to methodically document the J-series thruster characteristics. After each thruster was assembled, it was subjected to the acceptance test which consists of taking data at ten test points over a thrust level range of 36 to 130 mN.

With the completion of the testing of the 30-cm thruster, as reported in this paper, LeRC has completed its SEPS technology program. The technology program for flying a SEPS is now being managed by the NASA-Marshall Space Flight Center.

Background

The need for electric propulsion for possible future space missions was first recognized by Dr. R. H. Goddard in 1906. Professor Hermann Obeath, a German rocket pioneer described a possible electric rocket design in a 1929 text book.[8] But, it was not until 1959 that the first electron-bombardment thruster was conceived and tested by member of the staff of NASA LeRC. The ability of a mercury electron-bombardment thruster to produce thrust and to neutralize the exhaust beam in the space environment was successfully demonstrated on the SERT I spacecraft in 1964. The SERT II spacecraft, launched in February 1970, demonstrated ion thruster life operating in space with a flight-type power source.

After SERT II, mission planners both at the Jet Propulsion Lab (JPL) and at MSFC began to seriously consider ion thrusters for prime propulsion application. In an effort to meet future propulsion requirements the NASA Office of Aeronautics and Space Technology has sponsored a technology program managed by the Lewis Research Center to develop the 30-cm ion thruster for prime propulsion applications. In support of this technology program, Hughes Research Laboratories (HRL) has participated in the development, fabrication, and testing of 30-cm mercury ion thrusters since the early 70's under contract to NASA's LeRC. Figure 1 shows the series development, listing the design changes for each series, of the 30-cm thruster to the present J-series design.

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J-Series Thrusters

Figures 2 and 3 show the present J-series 30-cm mercury ion thruster. Figure 4 is a thruster cross section view listing the key components of the 30-cm thruster. The key features (which distinguish the J-series from the previous 30-cm thruster series) are briefly described as follows[5]:

(1) Ion optics with SHAG grids and modified mounting rings (Fig. 5). SHAG is an acronym for small hole accelerator grid. In order to decrease the amount of discharge chamber erosion (as experienced during S/N 701 and S/N 901 thruster endurance testing), it was desirable to reduce the discharge voltage without loss of thruster efficiency. This required an accelerator grid with smaller aperatures (permitting the trade of less lost neutral mercury for reduced ionization efficiency at the lower discharge voltage).

The grids' support rings are made from molybdenum (same material as the grids) while the mounting ring (Fig. 6) is titanium with slots cut adjacent to the screen grid's mounting points. This design resulted in the titanium mounting ring with the slots becoming the less rigid structural element (for radial stress) of the optic assembly, consequently eliminating the distortion of the molybdenum electrodes (grids) under thermal stress.

(2) Isolator Vaporizer (IV) assemblies, Fig. 7, which control propellant flow by heating the liquid mercury to produce mercury vapor, contain a phase separator. This phase separator is a of sintered porous tungsten disk which is electron beam welded into a tantalum tube. Due to thermal stress at the weld point between the porous tungsten and the tantalum tube during operation, the 300 series design IV developed cracks in the weld allowing liquid mercury to flow into the isolator. The 900 series design (Fig. 7) accomodates the differences in thermal expansion between the porous tungsten and tantalum tube and also provides a more direct thermal path from the heaters to the porous tungsten plug.

(3) In order to reduce discharge - chamber erosion two approaches were taken. (a) Erosion sites within the discharge chamber were covered with tantalum (experimentally, a more sputter resistant material). (b) The dimensions of the baffle support were changed in order to reduce the percentage of doubly charged ions (source of erosion) created within the discharge chamber.

(4) In order to reduce spalling of sputter-deposited material, the surfaces on which sputtered material was deposited were either grit blasted or covered with a fine stainless-steel wire mesh.

Facilities/Apparatus/Instrumentation

All of the J-series thrusters assembled to date have undergone testing and evaluation at HRL. In a parallel effort, in order to evaluate and verify test results, LeRC maintained an active 30-cm thruster program in which thrusters J-4, J-5, and J-6 were tested. Testing at LeRC also resulted in the confirming that 30-cm thruster are operational (obtain like results) in different facilities and in the definition of an accurate propellant flow measurement technique.

HRL Test Facility

The J-series thruster acceptance test were performed at HRL in a 2.7 meter by 5.5 meter long vacuum chamber. The chamber uses an oil diffusion pump and a liquid nitrogen cooled liner. The pressure range during the test was 10^{-6} to 10^{-7} torr. Figure 8 shows a cross-section of the vacuum chamber and a block diagram of the instrumentation, power processing unit and control unit. Thruster set points are controlled and electrical parameters are measured from these units.

Mercury flow rates to the thruster are measured with glass burrettes by recording the change in levels in the burrettes as a function of time.

LeRC Test Facility

Testing of the J-series thrusters at LeRC was conducted inside the LeRC's 7.6 meter in diameter by 21.3 meter long vacuum chamber as shown in Fig. 9. The vacuum capability of this chamber during the duration of this test was approximately 8.6×10^{-7} torr with one 30-cm thruster running and 1.2×10^{-6} torr with two 30-cm thrusters running. A general diagram of the vacuum facility and associated equipment is shown in Fig. 10.

During testing the J-series thrusters were controlled by power, data, and control system which consisted of:

1. A power source which supplies 28 volts dc and 200-400 volts dc to the functional model power processing units (FM/PPU).

2. FM/PPU which provides the required regulated power (from 12 different power supplies) needed to satisfy the thruster operating requirements. Applicable document NASA TM-79191 gives a description of the FM/PPU.

3. A "Thruster Controller" (a Hewlett Packer 21 MX Series Computer) which senses the thruster parameters and commands the thruster set points through the FM/PPU.

4. A meter panel and strip chart for monitoring thruster parameters and recording data.

To ensure accurate determination of thruster electrical efficiency all instrumentation was calibrated. Circuit resistances of the different thruster heater circuits were also obtained.

Propellant flow rates were measured by reading changes in the mercury level of calibrated flow tubes at 10 minute intervals for at least an hour. Prior to making valid flow measurements, a "hard fill" of the mercury feed system is needed. Compression in the flow tubes must be less than 2 mm when 10 psig is applied.

Test Thruster Configuration

Thruster Test

This report presents test results for the J-series thrusters J-2 through J-7. Thrusters

J-6, 9, and 10 are to be tested early in 1981 and should provide further documentation of the J-series thruster. Thruster J-1 through J-7 were tested at HRL while J-1, J-4, J-5, and J-6 have in addition been tested at LeRC. Table I gives the test history and critical component serial numbers for each J-series thruster. A serial number "800" indicates that a part or component is of the 800 series ventage, while a 900 number indicates a part is of the J-series design.

Test Plan

A standardized set of test and data recording procedures was formulated in an effort to document the J-series thruster's characteristics. Each J-series thruster was tested according to the "30-cm Thruster Acceptance Test Procedure" which is presented in NASA CR-165233.

This test procedure establishes the sequence and the procedures for performing acceptance tests that are used to prepare an acceptance test report for a 30-cm thruster. The purpose of the thruster acceptance test is to verify the characteristics, capabilities, and performance of the thruster. Towards this end, this acceptance test provides 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.

From experience gained in running 30-cm thrusters both at HRL and LeRC it has been learned that a thruster has to be conditioned (run after being exposed to the atmosphere) for approximately 20 to 40 hr before stable characteristics of the thruster can be obtained.

Measured Characteristics

The characteristics of each thruster measured during the acceptance testing are:

(a) The magnetic baffle characterization which includes the determination of the minimum magnetic baffle current, J_{mb}, at which the thruster will run stably for each test point and the variation of cathode keeper voltage (V_{CK}) as a function of J_{MB}. The magnetic baffle characterization is the first measurement made on a thruster for each test point.

(b) The neutralizer characterization which is the determination of the operating voltage, V_{NK}, that will permit the neutralizer vaporizer power processor control loop to perform without losing control. This characterization also results in determining of the V_{NK} verses neutralizer vaporizer temperature characteristic curve.

(c) Perveance which is a measurement of the minimum extraction voltage at which the optics assembly can effectively extract and focus an ion beam of a specified current value.

(d) The minimum eV/ion (power per beam current) measurement which is a determination of the minimum discharge chamber power at which a specific value of beam current can be maintained.

(e) The electrical and propellant utilization efficiency measurements.

Data Summary Sheet

An "Acceptance Test Data/Performance Summary" was filled out for each thruster (Fig. 11 is the summary sheet for thruster J-2). The summary sheets obtained for each thruster run at HRL and LeRC form the data base used to characterize the 30-cm ion thruster. Only HRL has the instrumentation for making the single and double ion measurements which are used for determining performance correction factors that account for doubly charged ions and beam divergence. Hence, the summary sheet for data taken at LeRC does not show correction factors or a corrected total thruster efficiency.

Performance Characteristics/Data

In order to obtain stable measurement of thruster efficiencies, the set points that ensure stable running must be determined first. These controlled set points are the magnetic baffle current, neutralizer keeper voltage, extraction voltage, discharge current. The criteria for selection of the controlled set points are defined in the HRL operating procedure No. 138 "30-cm Thruster Acceptance Test Procedure." Any one measured characteristic of a thruster could be affected by any number or combination of physical (mechanical/thermal) parameters. Also, the physical parameters between thrusters will vary within the machinery and assembly tolerances. These two factors alone will cause a spread in any characteristic data taken on different 30-cm thrusters. With this in mind the characteristic data, obtained during acceptance testing of thrusters J-2, 3, 4, 5, 6, and 7, will be presented.

Magnetic Baffle Characteristic

Figure 12 presents the selected (obtained during acceptance testing) magnetic baffle currents for each of the six J-series 30-cm thruster assemble at HRL.[5] Only a few select data points obtained at LeRC are presented in order to preclude the graph from being cluttered (since the data was closely repeatable) with data points. Figure 12 shows that there was some variation between the selected values of J_{MB} obtained by HRL and LeRC. Tests conducted at LeRC showed that a variation of 0.8 A in J_{MB} (other parameters held constant) will cause 0.35 percent variation in the measured (uncorrected) Propellant Efficiency. The magnetic baffle current is a function of the properties of the cathode insert, geometry of the magnetic pole piece, and possibly location of the magnetic coil (magnetic field). These physical conditions could have a greater impact when the thruster is run at full power (2 amp beam current).

The delta between data obtained at HRL and LeRC on thruster J-4 can be attributed to J-4 not being subjected to the required 20-40 hr conditioning prior to testing at HRL. Testing of the J-series thruster has shown that the cathode does

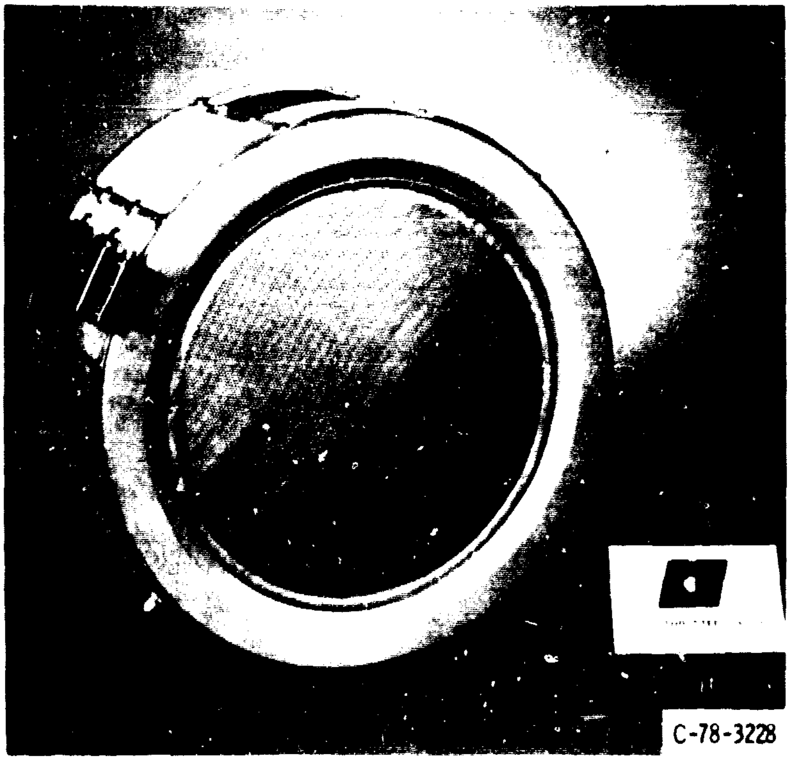

Figure 2. - Thruster-exhaust side.

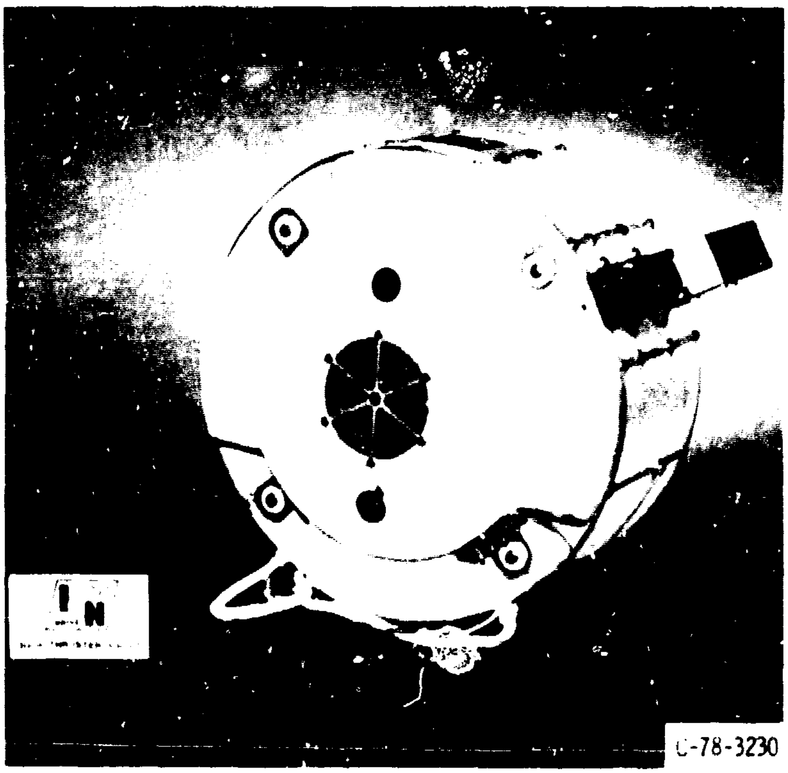

Figure 3. - Thruster-rearside

shown in Fig. 18) at HRL. The flow data taken at HRL on the first J-series thruster (J-3, 4, and 6) were taken within couple of hours from start of running. Hence there (inferred from Fig. 18) is an error of 1.5 to 2 percent "delta" in the initial flow measurements. Another source of error in flow measurements was found to be air or gas trapped within the propellant supply lines. Figure 19 shows the "delta" in utilization efficiency data obtained (on the same thruster run under identical conditions) with a good fill (no or little gas trapped in the feed system) and a poor fill. The delta difference in measured utilization efficiency as shown in Fig. 19 is 1.8 percent maximum. If the possibly 2 percent delta in flow efficiency caused by not being at thermal equilibrium and the possible error (1.8 percent) due to a poor fill are added and the initial data taken at HRL is corrected by this sum, all of the utilization efficiencies of all the thrusters would closely agree.

Summary of Thruster Performance

Mission planners need to know the total thruster efficiency, total thruster input power (P_t), and specific impulse (I_{SP}) for designing an electric propulsion system. Table V presents summary of 30-cm ion thruster performance parameters for the five principle throttle points. As seen from Table V the total thruster input power does not vary much from thruster to thruster over the principle throttle points. However there is a nominal variation in total thruster efficiency of 5 percent between thrusters. Table V also presents thruster J-5 performance results after J-5 was subjected to a life test at 0.75 amp beam for 5,000 hours. Comparison of J-5 results prior and post life test indicates that thruster J-5's performance decreased slightly over the period (5,000 hr) of life testing. Further life testing of other thrusters is needed to verify if this is a "true" thruster characteristic.

Development Status

Initial Testing Difficulties

Initial testing of several J-series thrusters indicated difficulties with the performance of the ion optic assemblies, isolator-vaporier assemblies, and vaporizer and cathode heater failures. A redesign of the optics assemblies and of all the isolator-vaporizer assemblies and a revision of the fabrication procedures resulted in components that successfully completed the acceptance testing. The heater failures were traced to poor quality control of the materials used, of tip welds, and of the required annealing process. Tighter R&QA control on the heater manufacturing process has resulted in reliable heaters. Having resolved these obstacles, retrofit modification of several J-series 30-cm thrusters was completed, acceptance tests were performed, and in the Spring of 1980 the design and test specifications were considered to be stabilized. The go ahead to fabricate three additional thrusters (J-8, 9, and 10) incorporating this design and test specifications was given.

Acceptance Test Results

All of the 30-cm thrusters retrofitted to J-series design have successfully undergone the acceptance testing. Results of these tests have illustrated the need for a required breaking-in-period (20 to 40 hr) before stable (reproducible) data can be obtained. The J-series retrofitted thrusters have performed within specifications.[6] The only exception is that the main and cathode vaporizer of the redesign (Fig. 7) operates approximately 40° C higher then specified. The impact on a system design (e.g., effect on the feed system operating pressure range) and on the isolator-vaporizer assembly's lifetime must be addressed.

The performance data presented in this report (allowing for errors due to a poor fill of the propellant feed system or the thruster not being at equilibrium during initial tests) indicate that all the thrusters' measured characteristics fall within a reasonable band of each other and are reproducible from one facility to another. Completion of the life tests (presently underway) is necessary in order to accurately assess the J-series 30-cm thruster's ability to meet a 15,000 hr lifetime goal. Test results presented in this report reveal no potential trouble areas that could preclude the J-series thruster from meeting the 15,000 hr lifetime goal.

Conclusion

The present J-series thruster design is the result of an intensive effort to eliminate real and potential design deficiencies that were uncovered during initial endurance, structural, and performance tests. Several thrusters of the J-series design have been successfully acceptance tested. The results of these acceptance tests have been compiled defining the characteristics of the J-series thruster. The successful acceptance testing (and repeating of acceptance testing at another facility on some of the thrusters) of several J-series thrusters has demonstrated that it is possible to operate them over a wide range of operating parameters. No operational instabilities were noted over the range of values in this test.

Symbols, Definitions, and Equations

Directly Measured Parameters

Symbol	Description
V_{MV}	Main Vaporizer Voltage
V_{CH}	Cathode Heater Voltage
V_{NV}	Neutralizer Vaporizer Voltage
V_{NK}	Neutralizer Keeper Voltage
V_{CK}	Cathode Keeper Voltage
V_D	Discharge Chamber Voltage
V_{Accel}	Accelerator Potential
V_S	Screen Supply Voltage
V_b	Beam (Net Accelerating) Potential
V_{MB}	Magnetic Baffle Voltage
V_G	Neutralizer to Ground Coupling Voltage

V_T	Total Accelerating Voltage
J_{NK}	Neutralizer Keeper Current
J_{CK}	Cathode Keeper Current
J_E	Cathode Emission Current
J_D	Discharge (Anode) Current
J_{Accel}	Accelerator Drain or Impingement Current
J_b	Beam Current
J_{MB}	Magnetic Baffle Current
T_{MV}	Main Vaporizer Temperature
T_{CV}	Cathode Vaporizer Temperature
T_{NV}	Neutralizer Vaporizer Temperature

Values Obtained From EXB Probe at Hughes Research Labs

α	Thrust reduction factor due to doubly charged ions
F_T	Thrust reduction factor due to non-axial ion trajectories
J_b^+	Singly charged ion beam current
J_b^{++}	Doubly charged ion beam current

Directly Measured Propellant Flow Rates

$\dot{m}_{MV}$	Main Propellant Flow Rate
$\dot{m}_{CV}$	Cathode Propellant Flow Rate
$\dot{m}_{NV}$	Neutralizer Propellant Flow Rate

Powers

P_b = Beam Power

P_D = Discharge Power

P_N = Neutralizer Power

P_V = Vaporizer Power

P_t = Total Input Power

Performance Calculations

γ = total thrust reduction factor = αF_T

β = discharge chamber utilization correct factor $= \left[\frac{\gamma}{F_T}\left(1 + \frac{\sqrt{2}}{2}\right) - \frac{\sqrt{2}}{2}\right]$

$\dot{m}_t$ = total propellant flow rate $= \dot{m}_{MV} + \dot{m}_{CV} + \dot{m}_{NV}$, A eq.

$\eta_{mD(unc)}$ = uncorrected discharge propellant utilization $= \frac{J_b}{\dot{m}_{MV} + \dot{m}_{CV}} \times 100$, %

η_{mD} = corrected discharge propellant utilization $= \beta\,\eta_{mD}(unc)$, %

$\eta_{m(unc)}$ = uncorrected total propellant utilization $= \frac{J_b}{\dot{m}_t} \times 100$, %

η_e = electrical efficiency $= \left(\frac{J_b V_b}{P_t} \times 100\right)$, %

η_T = corrected total thruster efficiency $= \gamma^2 \frac{\eta_e \eta_{m(unc)}}{100}$, %

F = corrected thrust = $2.0391\,\gamma\, J_b \sqrt{V_b}$, mN

I_{SP} = corrected specific impulse $= 100.98\,\gamma\,\frac{J_b}{\dot{m}_t}\sqrt{V_b}$, sec

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TABLE I. - THRUSTER TESTING STATUS

Serial no.	Testing history	Components serial number					
		NIV	CIV	MIV	Pole piece	Grids	Mtg. ring
J-1	9/78 performance tested at LeRC 12/78 4,000 hr life tested at EOS 10/79 performance tested at LeRC 11/79 disassembled for diagnosis 2/80 post diagnosis performance tested at LeRC 3/80 Bimod/P&F support	903	814	806	---	(LeRC S/N 41)	
J-2	9/80 acceptance tested at HRL 10/80 delivered to EOS for MPLT - HI cathode flow	815	903	901	817	902	907
J-3	11/79 acceptance tested at HRL 8/80 started 15,000 hr MPLT at EOS (Test terminated because of CIV isolator leak)	917	825	805	819	901	912
J-4	6/79 acceptance tested at HRL 6/79 delivered to EOS for MPLT - developed arcing problems 12/79 delivered to HRL for analysis 4/80 re-acceptance tested at HRL 5/80 magnetic moments measurements at TRW 7/80 acceptance tested at LeRC 9/80 Bimod/P&F support	907	819	807	814	837	901
J-5	8/79 acceptance tested at HRL 11/79 re-acceptance tested at LeRC 1/80 5000 hr at 0.75 A test at EOS 8/80 post life test at EOS	906	821	817	815	834	902
J-6	1/80 acceptance tested at HRL 2/80 EOS - CIV intruded 8/80 replace CIV, reacceptance tested at HRL 9/80 pre-vib tested at LeRC 9/80 vib tested at LeRC 10/80 post-vib tested at LeRC	919	811	814	816	903	908
J-7	8/80 acceptance tested at HRL 8/80 MPLT - 34 V at EOS (Test terminated due to flakes causing shorting between electrode)	920	901	902	822	904	910
J-8	12/80 scheduled assembly	901	907	903	---	905	919
J-9	11/80 scheduled assembly	902	904	909	---	911	920
J-10	12/80 scheduled assembly	903	908	904	---	913	921
702	-----------------------------------						
802	-----------------------------------						

TABLE II. - NEUTRALIZER CHARACTERIZATION

J_b, A	"max Δ"	HRL Data						LeRC Data		
		Thruster								
		J-2	J-3	J-4	J-5	J-6	J-7	J-4	J-5	J-6
		Minimum, V_{NK}, V								
2	3	11.31	12.6	11.1	12.5	13.1	14.15	11.7	12.95	12.2
1.6	3	11.5	12.9	11.0	12.8	13.0	13.98	11.0	13.3	12.4
1.3	3	11.33	13.2	11.1	12.9	----	14.14	11.0	13.65	12.5
1.0	3.5	11.83	13.6	11.1	13.3	13.5	14.49	11.1	13.6	13.3
.75	3.2	11.63	14.0	12.6	13.4	12.8	14.88	11.6	14.35	----
Chamber pressure range, torr		1.1×10^{7} to 7.8×10^{-7}	1.6×10^{-7} to 1.5×10^{-6}	3.5^{-7} to 1.4^{-6}	5.2^{-7} to 1×10^{-6}	3.9^{-7} to 1×10^{-6}	4.6×10^{-7} to 1.0×10^{-6}	1.2×10^{-6} to 2.5×10^{-6}	4×10^{-6} to 5.3×10^{-6}	3.7×10^{-7} to 3.6×10^{-6}

TABLE III. - MINIMUM eV/Ion, E_I

J_b, A	HRL Data						LeRC Data		
	Thruster								
	J-2	J-3	J-4	J-5	J-6	J-7	J-4	J-5	J-6
	Minimum ev/ion, (amp-V)/amp								
2	166.8	172.5	170	[a]190	174	170	-----	187	172
1.6	167.0	169.5	179	[a]197	168	168	181.5		174
1.3	168.3	176.0	175.7	[a]192	175	169.5	181	188	180
1.0	173.9	182.2	179.8		181	168.1	181.5	192	184
.75	177.6	193.0	186.2	[a]186	185	185.9	189	193	192

[a]Estimated.

TABLE IV. - MEASURED THRUSTER ELECTRICAL EFFICIENCY

J_b, A	HRL Data						LeRC Data		
	Thruster								
	J-2	J-3	J-4	J-5	J-6	J-7	J-4	J-5	J-6
	Electrical efficiency, percent								
2	83.	83.1	83.1	82.8	83.3	82.7	83.0	82.9	82.9
1.6	79.6	79.7	79.8	79.6	81.6	83.1	79.4	79.7	79.7
1.3	76.3	76.	75.7	76.4	76.4	75.8	71.2	76.4	76.0
1.0	71.3	71.0	71.4	71.4	71.7	70.9	71.2	71.0	71.0
.75	65.2	64.8	66.1	65.2	65.6	64.8	65.4	64.9	65.1

TABLE V. - SUMMARY OF J-SERIES THRUSTER PERFORMANCE

[α denotes thrust reduction factor due to doubly charge ions; F_T thrust reduction factor due to nonaxial ion trajectories; η_T correct total thruster efficiency; F corrected thrust; I_{SP} corrected specific inpulse.]

Thruster	V_b = 600 V; J_b = 0.75 amp						V_b = 700 V; J_b = 1 amp						V_b = 820; J_b = 1.30					
(a)	P_T, W	α	F_T	η_T, %	F, mN	I_{SP}, sec	P_T, W	α	F_T	η_T, %	F, mN	I_{SP}, sec	P_T, W	α	F_T	η_T, %	F, mN	I_{SP}, sec
2	692	0.999	0.988	54.7	37.1	2085	982	0.995	0.988	61.4	53	2320	1397	0.991	0.989	68.7	74.5	2630
3	691	.99	.98	51.3	36.3	1993	480	.984	.984	58.4	52	2249	1394	.978	.986	64.8	72.9	2531
4	681	.99	.977	50.7	35.6	1941	978	.983	.977	59.6	51.7	2251	1406	.978	.978	67.6	72.6	2510
5	696	.98	.983	50.3	36.16	1977	977	.97	.982	55.3	51.5	2142	1398	.967	.982	61.9	72.2	2447
6	691	.99	.984	50.2	36.7	1926	978	.988	.984	62.8	52.6	2390	1394	.976	.985	64.7	73.0	2511.2
7	694	.99	.99	52.7	36.7	2035	982	.98	.986	59.9	52.	2306	1399	.973	.983	63.6	72.4	2510
b5	696	0.99	0.974	48.4	36.1	1897	987	0.988	0.974	54.7	51.8	2127	1397	0.988	0.974	60.9	72.7	2388
	V_b = 920; J_b = 1.6						V_b = 1100 V; J_b = 2.0 amp											
2	1874	0.985	0.988	71.7	96.8	2833	2647	0.977	0.988	74.6	130.5	3091						
3	1877	.975	.987	69.2	96.3	2771	2661	.966	.986	73.1	129.3	3066						
4	1890	.972	.977	68.1	95.1	2764	2663	.964	.982	72.2	128.5	3049						
5	1889	.945	.983	65	93	2695	2626	.967	.982	72.5	127.7	3043						
6	1861	.972	.986	70.9	96.6	2824	2658	.982	.986	77	131.3	3179						
7	1890	.972	.985	73.3	95.8	2828	2664	.958	.989	73.1	128.5	3094						
b5	1894	0.984	0.974	64.9	96	2612	----	-----	----	-----	----	----						

[a]Prelife test data unless otherwise noted.
[b]Postlife test data.

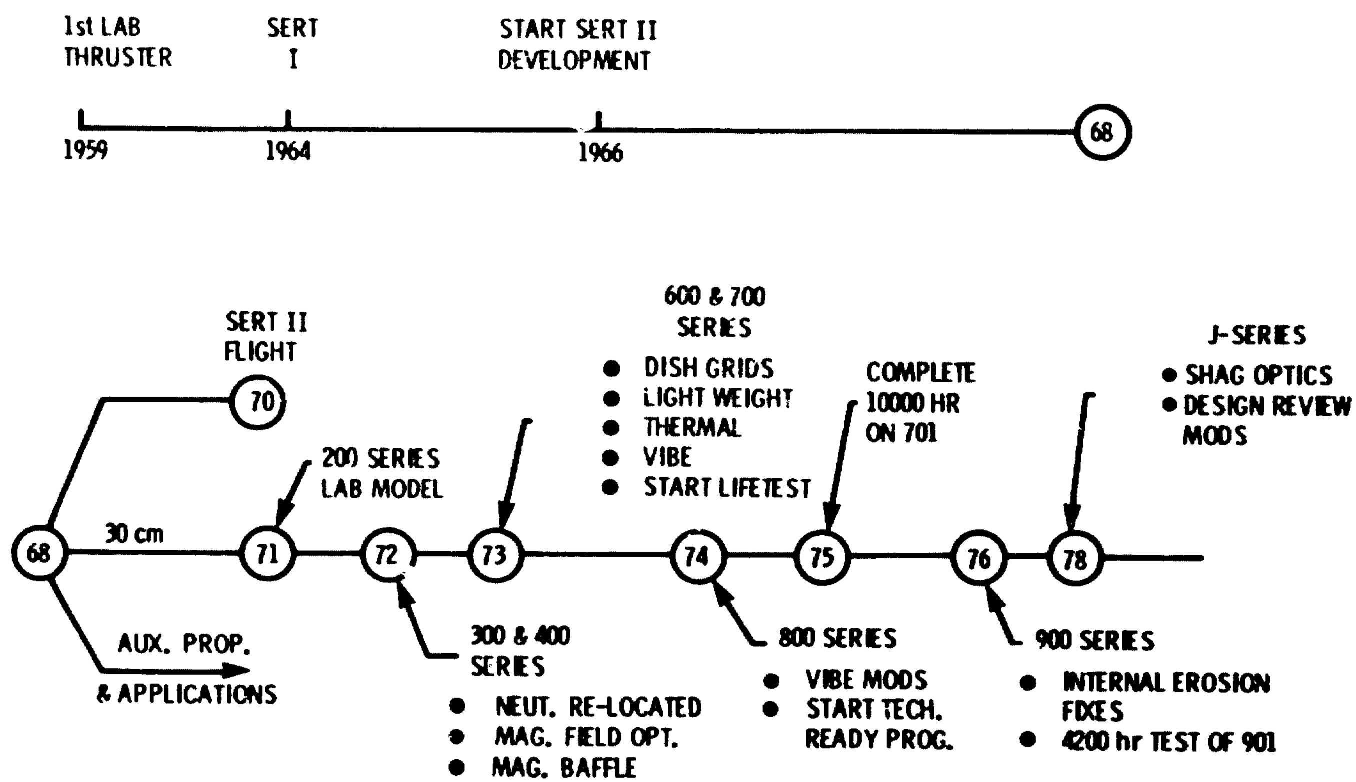

Figure 1. - 30-cm thruster - history of development.

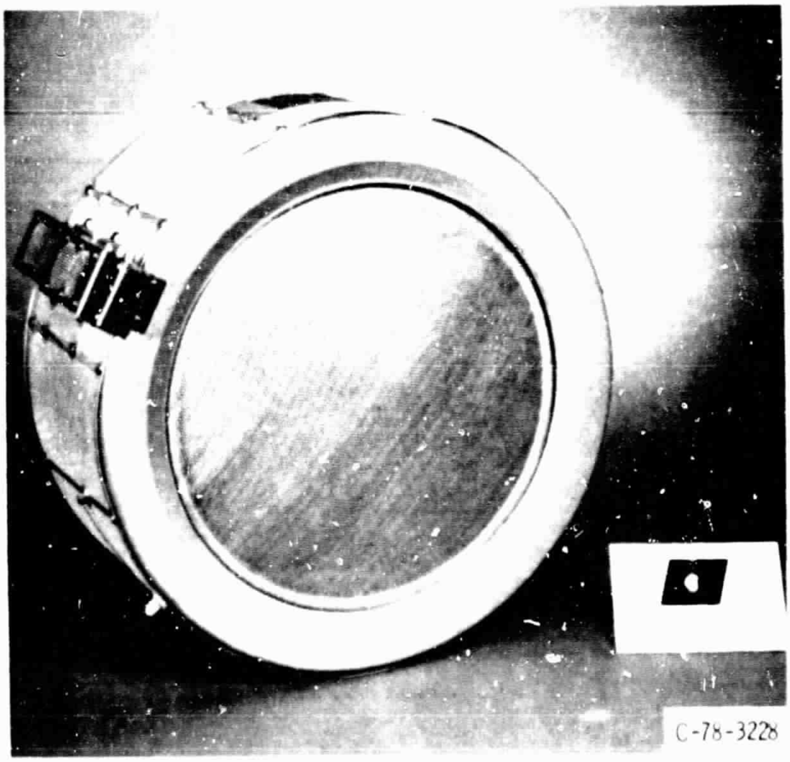

Figure 2. - Thruster-exhaust side.

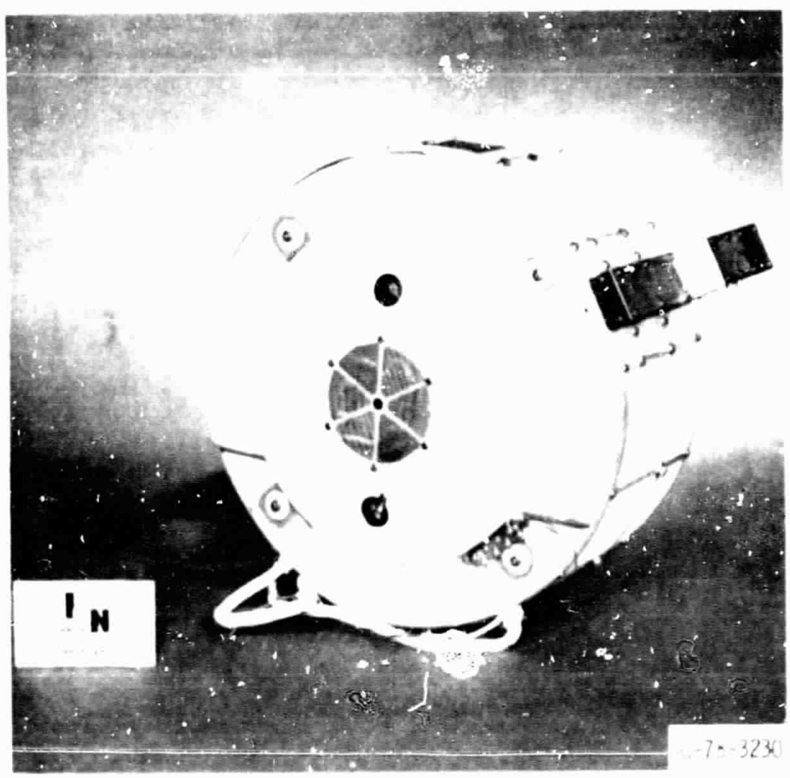

Figure 3. - Thruster-rear side.

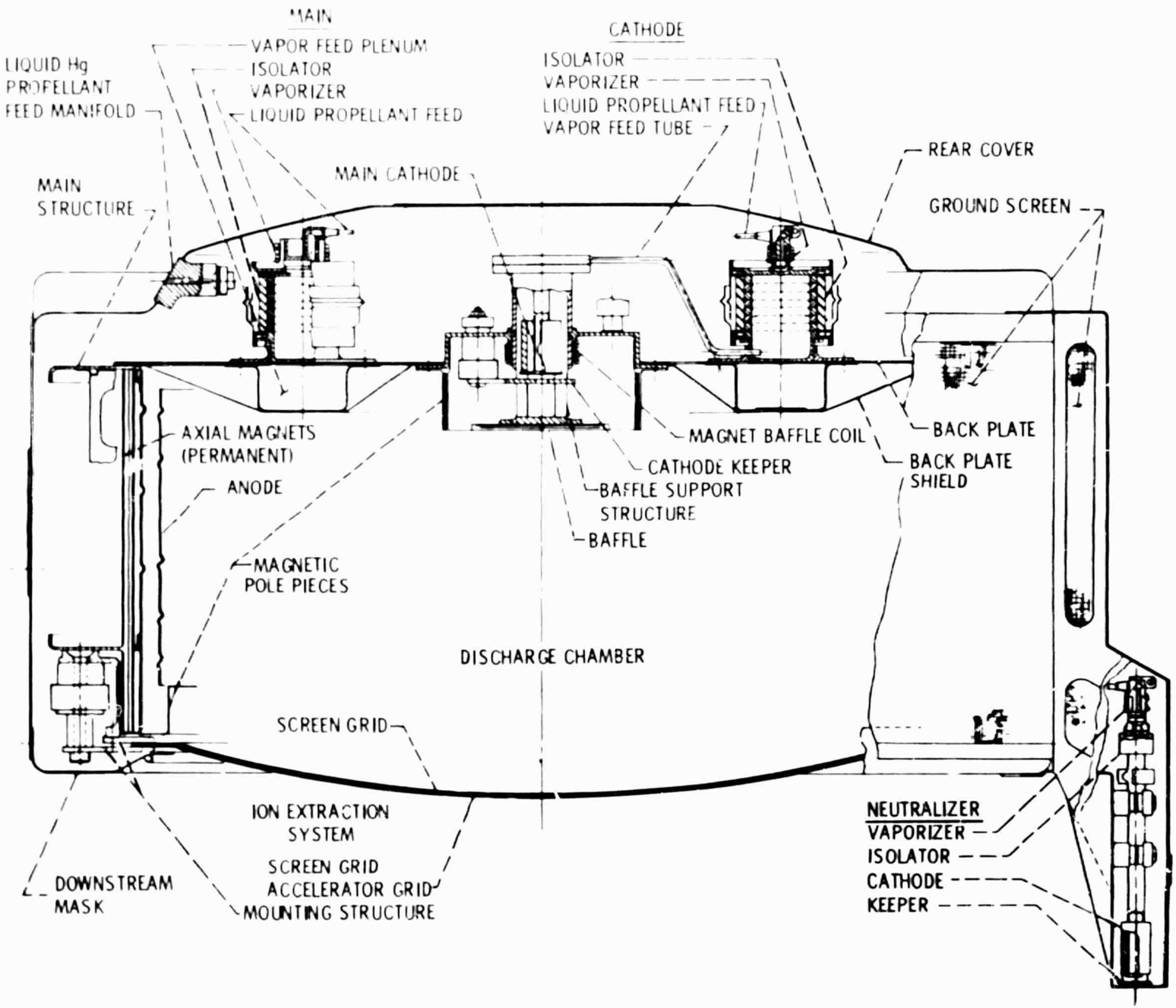

Figure 4. - Thruster cross section.

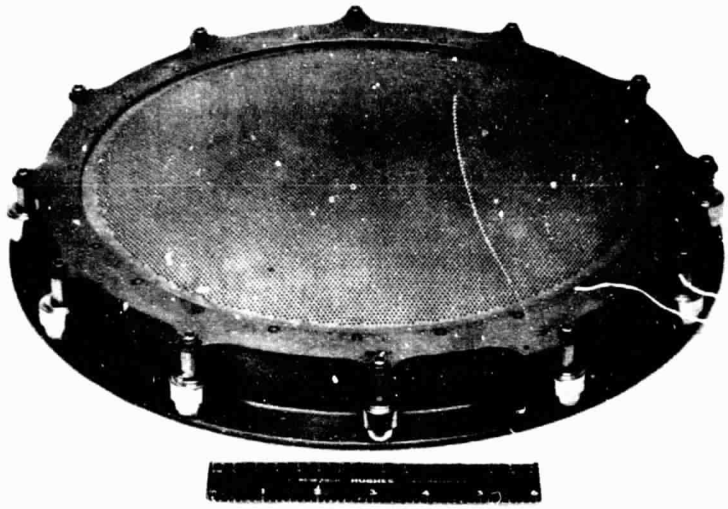

Figure 5. - Ion optic assembly.

Figure 6. - Ion optics mounting ring.

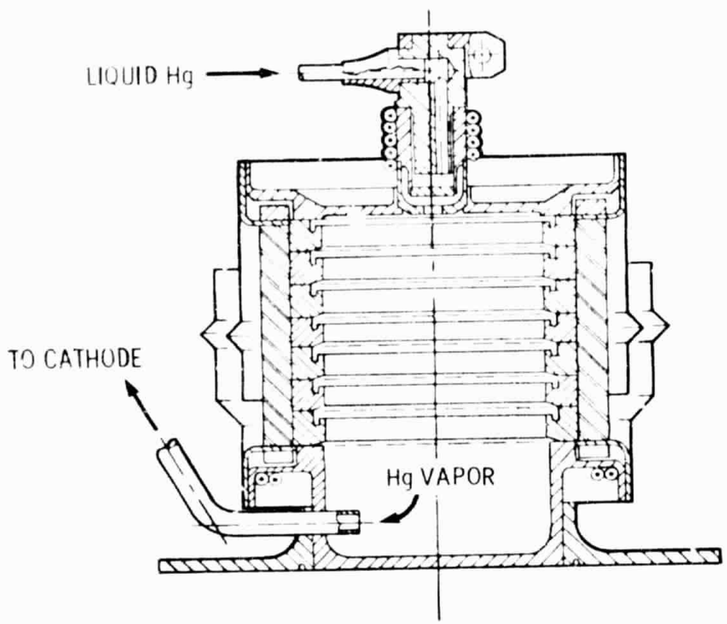

Figure 7. - New CIV vaporizer - isolator design.

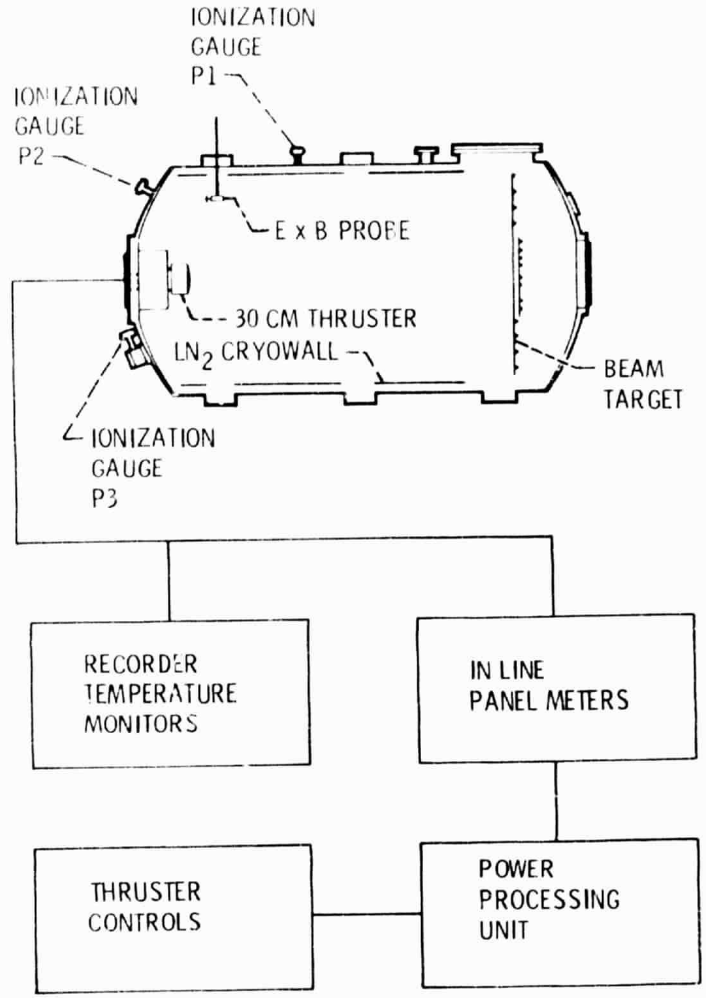

Figure 8. - Cross-section of HRL vacuum facility and block diagram of instrumentation. Power processing unit, and controller.

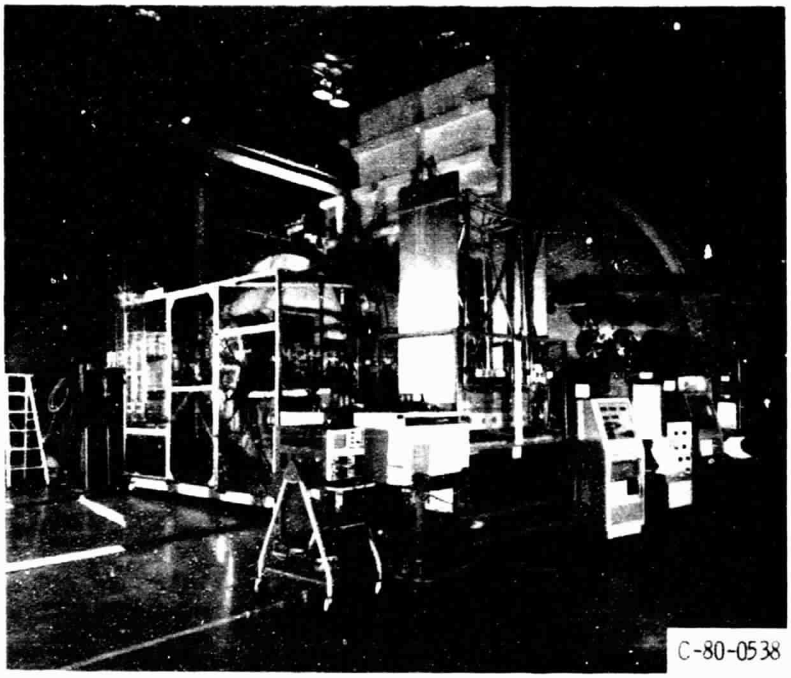

Figure 9. - Lewis' thruster testing/vacuum chamber.

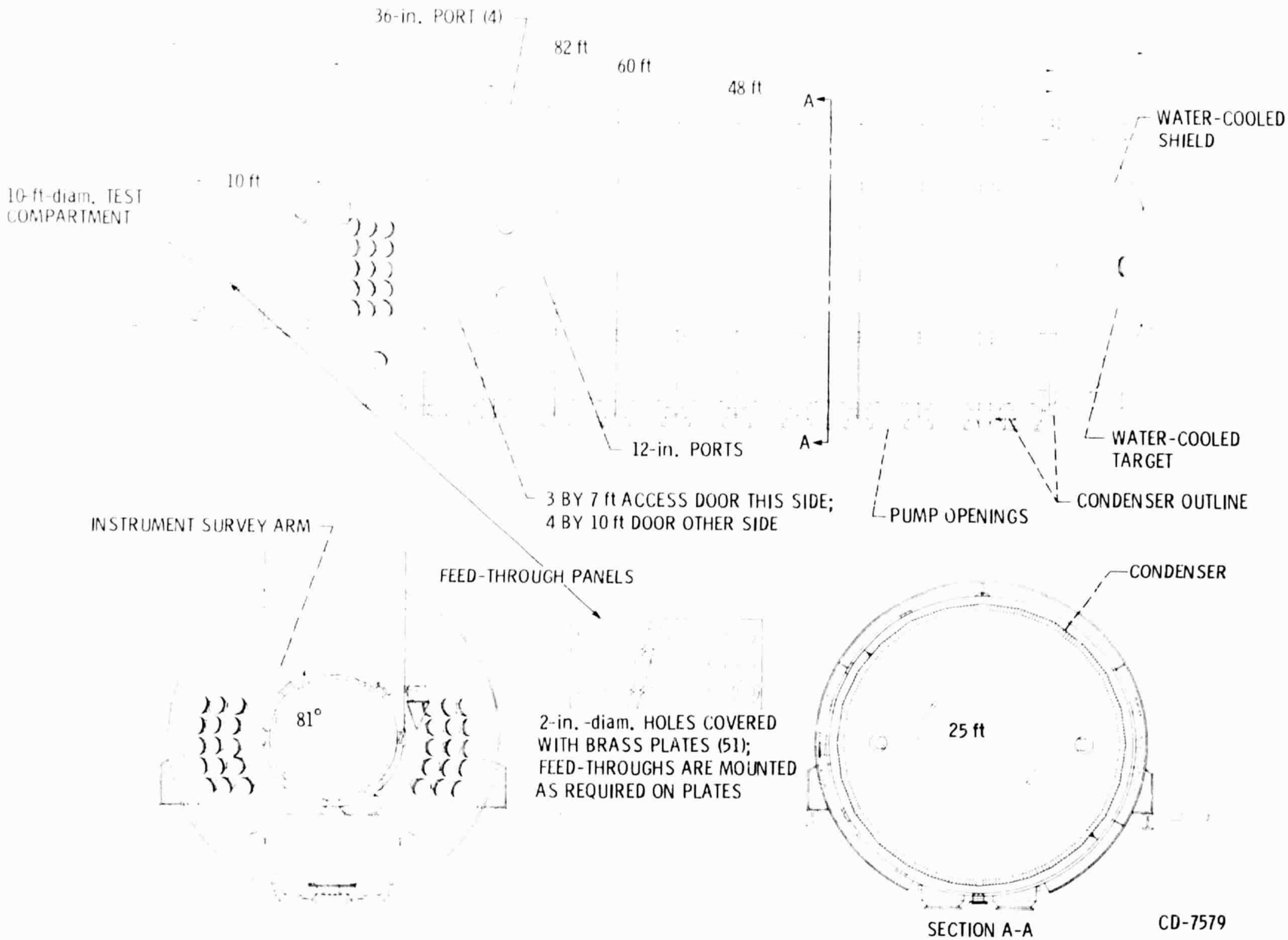

Figure 10. - Drawing of electric propulsion laboratory - tank 6.

	TEST POINT		1	2	3	4	5	6	7	8	9	10
OPERATING PARAMETERS	V_b	V	1100	1100	1099	936	1101	819	700	1101	600	600
	J_b	A	1.998	1.997	1.995	1.594	1.303	1.302	1.000	0.751	0.752	0.752
	V_D	V	32.01	30.97	32.02	32.05	32.02	32.00	32.00	31.98	31.98	31.00
	J_D	A	14.0	14.0	13.4	11.59	9.8	9.8	8.0	6.51	6.52	6.49
	J_E	A	12.0	12.0	11.4	10.0	8.5	8.5	7.0	5.76	5.76	5.74
	J_{MB}	A	2.50	2.60	2.6	2.90	3.10	3.10	3.30	3.30	3.30	3.30
	V_{CK}	V	3.92	3.90	4.06	4.62	4.97	4.88	5.72	6.58	6.55	6.64
	J_{CK}	A	1.02	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
	V_{Accel}	V	-308	-307	-308	-304	-306	-301	-299	-304	-296	-296
	J_{Accel}	mA	3.31	3.57	3.50	2.49	1.93	2.17	1.57	1.80	1.24	1.31
	V_{NK}	V	13.38	13.43	13.40	13.49	13.31	13.33	13.89	13.70	13.70	13.71
	J_{NK}	A	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80	1.80
	V_G	V	9.47	9.47	9.46	9.38	9.35	9.28	9.16	9.18	9.02	9.06
FLOWS	T_{MV}	^oC	349	349	349	340	332	333	322	311	311	312
	T_{CV}	^oC	335	337	333	350	347	345	352	355	355	357
	T_{NV}	^oC	291	291	289	298	297	298	298	302	303	303
	$\dot{m}_{MV}$	EQ. A	1.993	1.995	1.986	1.572	1.305	1.322	1.015	0.764	0.759	0.781
	$\dot{m}_{CV}$	EQ. A	0.056	0.060	0.053	0.078	0.072	0.065	0.080	0.086	0.084	0.087
	$\dot{m}_{NV}$	EQ. A	0.023	0.024	0.023	0.027	0.027	0.023	0.027	0.031	0.030	0.031
	$\dot{m}_t$	EQ. A	2.072	2.079	2.062	1.677	1.404	1.390	1.122	0.881	0.873	0.899
	η_{mD} (unc)	%	97.5	97.2	97.8	96.6	94.6	95.5	91.3	88.4	89.2	86.6
	η_{mD}	%	93.7	94.1	94.4	94.4	93.2	93.8	90.5	88.1	88.3	86.4
	η_m (unc)	%	96.4	96.1	96.8	95.1	92.8	93.7	89.1	85.2	86.1	83.6
POWER	P_b	W	2198	2197	2193	1492	1435	1066	700	827	451	451
	P_V	W	12.41	13.00	12.30	13.64	13.98	13.88	14.36	15.53	15.53	15.34
	P_t	W	2647	2634	2623	1874	1766	1397	982	1070	692	686
	η_e	%	83.0	83.4	83.6	79.6	81.3	76.3	71.3	77.3	65.2	65.7
BEAM	α		0.9773	0.9814	0.9796	0.9855	0.9911	0.9909	0.9951	0.9981	0.9944	0.9985
	F_T		0.9880	0.9880	0.9884	0.9878	0.9893	0.9893	0.9879	0.9877	0.9881	0.9883
	γ		0.9656	0.9696	0.9682	0.9735	0.9805	0.9803	0.9831	0.9858	0.9875	0.9868
	β		0.9611	0.9681	0.9650	0.9771	0.9847	0.9858	0.9917	0.9968	0.9992	0.9975
	J_b^{++}/J_b^{+}		0.0848	0.0686	0.0759	0.0424	0.0321	0.0254	0.0169	0.0063	0.0013	0.0050
MISC.	η_T	%	74.6	75.3	75.9	71.7	72.5	68.7	61.4	64.0	54.7	53.5
	F	mN	130.5	130.0	130.6	96.8	86.4	74.5	53.0	50.1	37.1	37.1
	I_{sp}	s	3091	3091	3108	2833	3022	2630	2320	2791	2085	2024
	P_{tank}	pa	8.6^{-5}	1.18^{-4}	1.18^{-4}	1.02^{-4}	1.26^{-4}	6.0^{-5}	1.46^{-5}	4.79^{-5}	4.39^{-5}	4.26^{-5}

Figure 11. - Acceptance test data/performance summary.

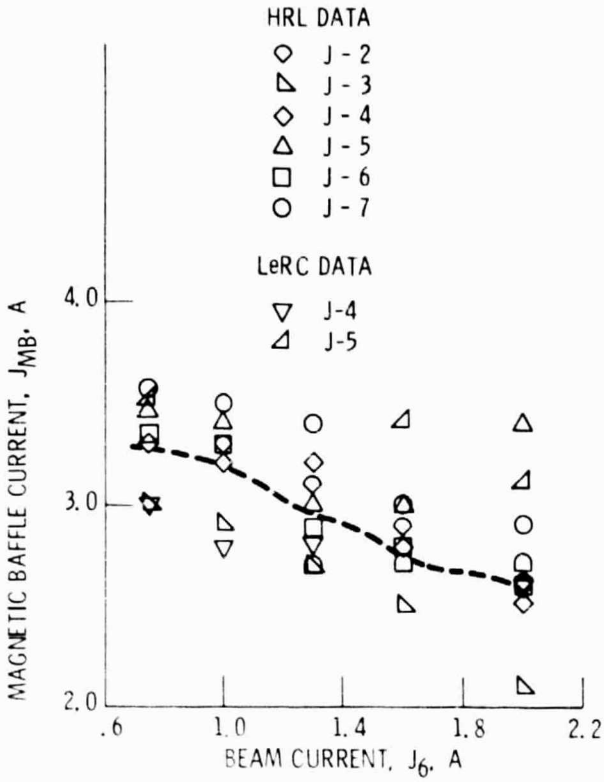

Figure 12. - Selected magnetic baffle currents.

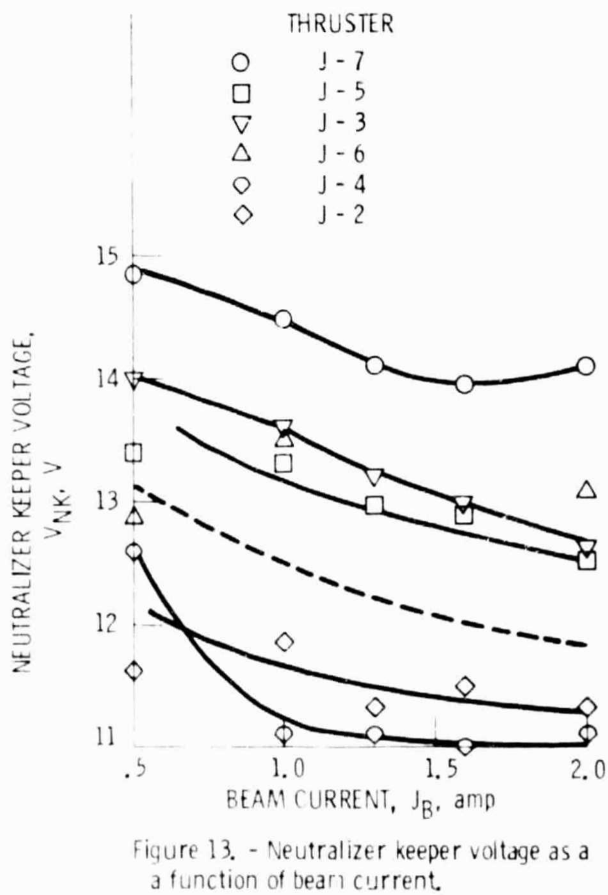

Figure 13. - Neutralizer keeper voltage as a a function of beam current.

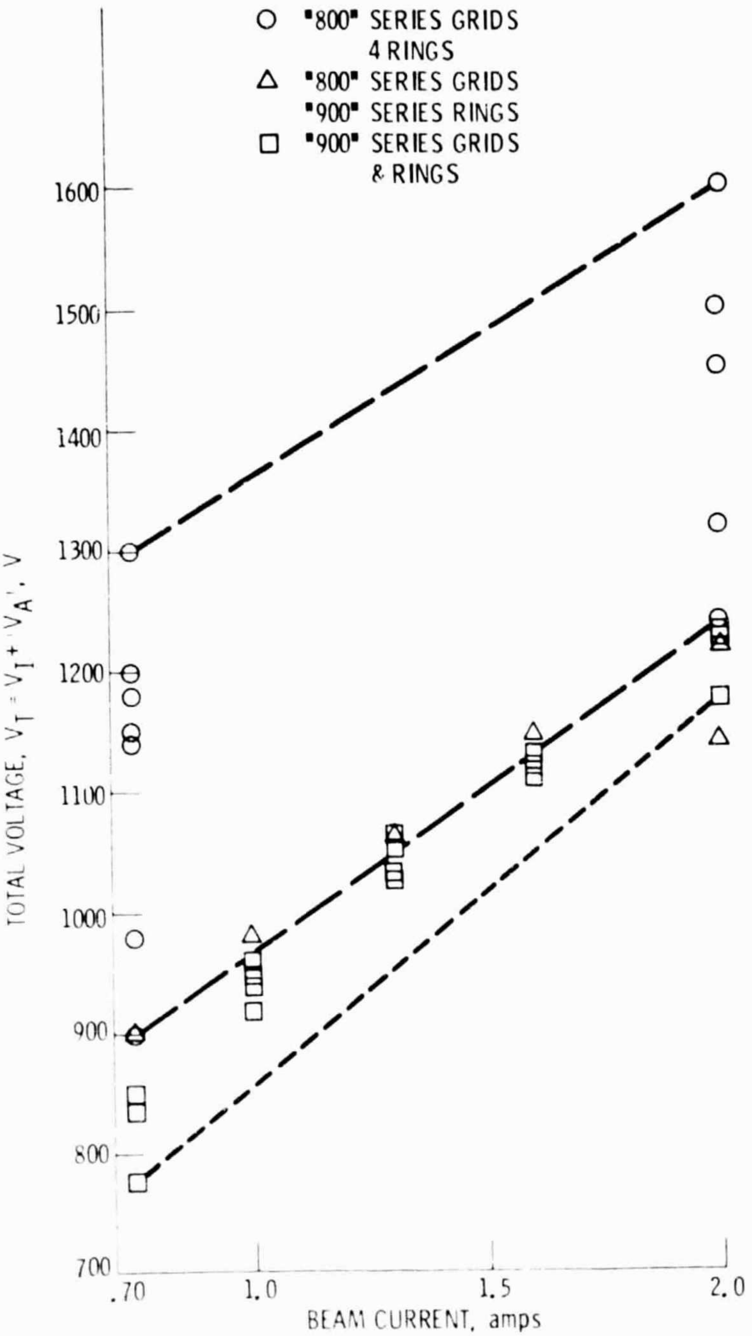

Figure 14. - Ion optics pervance

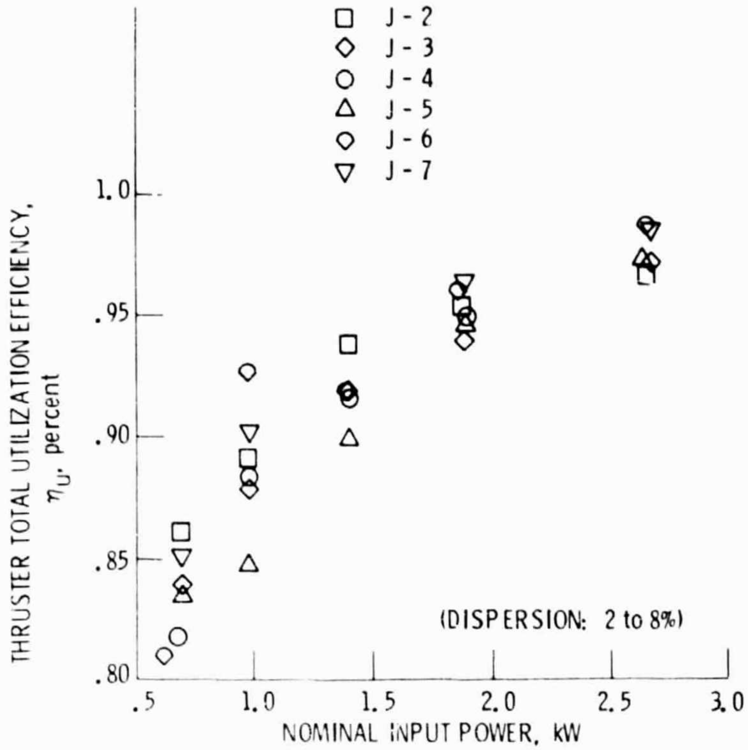

Figure 15. - Summary of J-Series mercury flows measured at HRL (uncorrected for doubly charge ions non-axial ion trajectories).

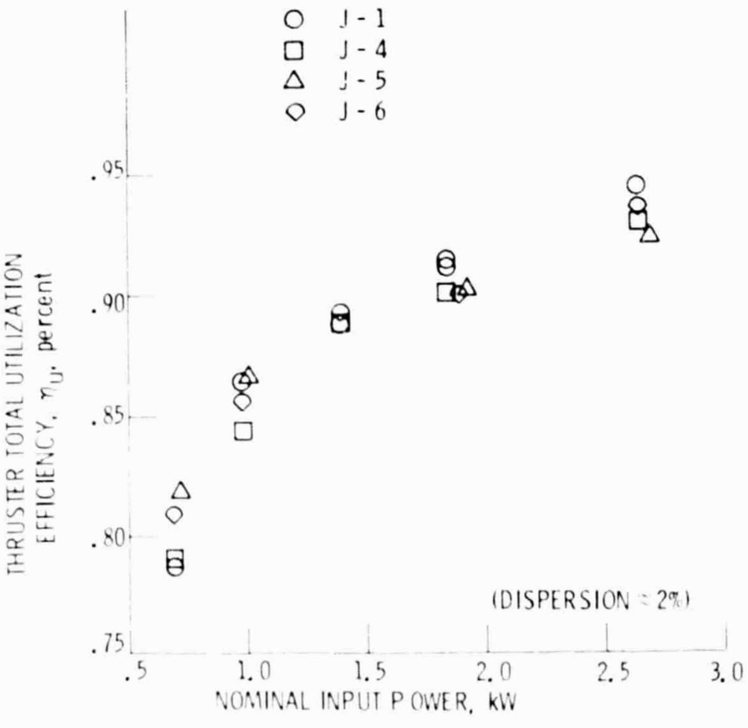

Figure 16. - Summary of J-Series mercury flows measured at LeRC (uncorrected).

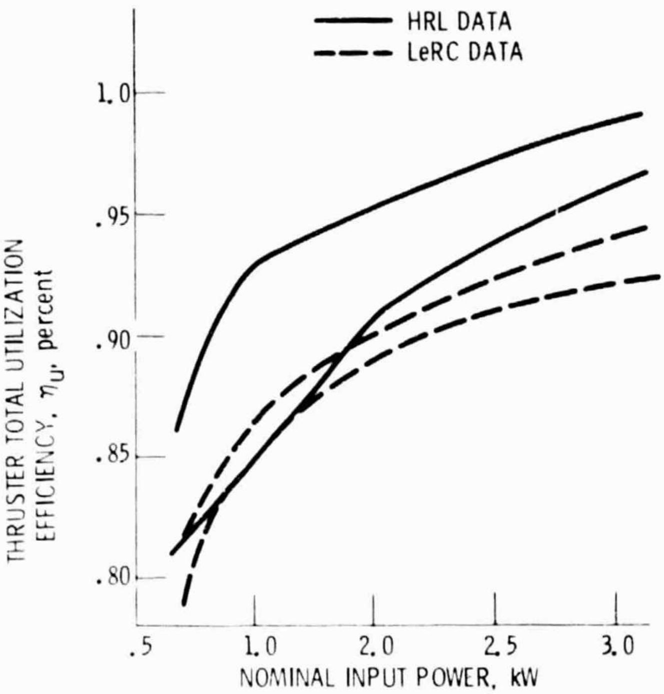

Figure 17. - Comparison of flow data obtained at LeRC and HRL (uncorrected).

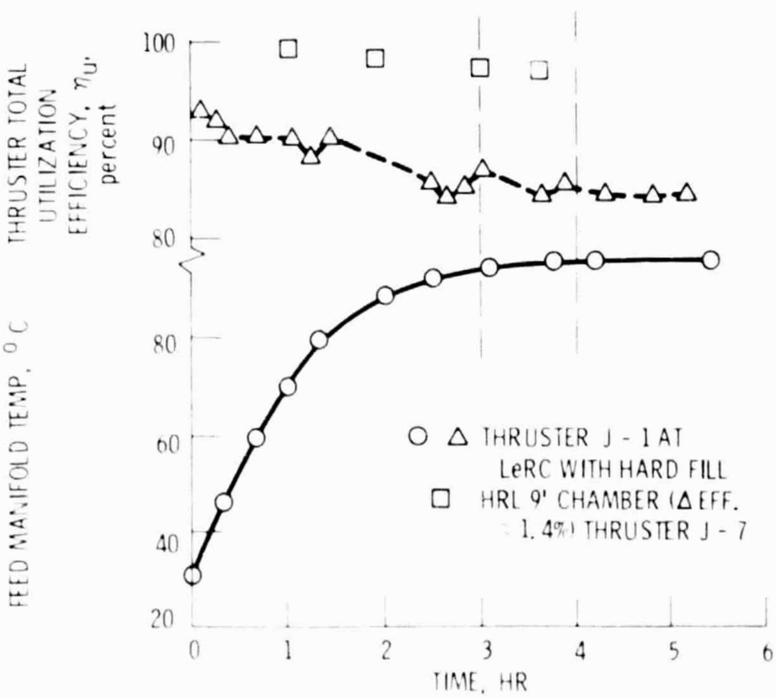

Figure 18. - Required time to reach equilibrium for accurate flow measurement.