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DEFINITION OF A
 RESISTOJET CONTROL SYSTEM FOR
 THE MANNED ORBITAL RESEARCH LABORATORY
 FINAL REPORT

ADDENDUM TO VOLUME V
 720 - HOUR RESISTOJET LIFE TEST

SEPTEMBER 1968

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Prepared under Contract No. NAS1-6702
 by Douglas Aircraft Company
 Missile and Space Systems Division
 Huntington Beach, California
 for
 NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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RESISTOJET CONTROL SYSTEM FOR
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FINAL REPORT**

**ADDENDUM TO VOLUME V
720 - HOUR RESISTOJET LIFE TEST**

SEPTEMBER 1968

**BY R.J. PAGE and R.A. SHORT
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Van Nuys, California
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Subcontract Technical Monitor
Douglas Aircraft Company**

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PREFACE

This report is submitted to the National Aeronautics and Space Administration's Langley Research Center (NASA-LRC), Langley AFB, Virginia. It has been prepared under Contract No. NAS1-6702 and describes the results of a detailed assessment of the use of a resistojet control system for the MORL.

The study results are documented in five volumes:

DAC-58130	I	Summary
DAC-58131	II	Resistojet Control System Analysis
DAC-58132	III	Biowaste Utilization
DAC-58133	IV	Ground and Flight Test Plan
DAC-58134	V	Resistojet Design and Development

Volume I is a summary report in which the significant results are presented. Volume II contains a detailed definition of the selected resistojet control system, the recommended orbit injection system, the supporting system analyses and integration, and comparative evaluation data. Volume III presents the biowaste utilization analysis. Volume IV details the ground and flight test program for a resistojet control system. Volume V presents the results of the resistojet design and development program. Life test data are provided in this separately bound addendum to Volume V.

Requests for further information concerning this report will be welcomed by the following Douglas representative:

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ABSTRACT

Six-10 mbf resistojet thrusters using the high-temperature (2400°K) rhenium technology have successfully undergone an initial 720-hour life test. Four units were tested on ammonia (NH₃) and two on hydrogen (H₂) at progressively increasing wall temperature from ~ 1800 to 2400°K.

The ammonia thrusters achieved a measured specific impulse of 320 sec. It is estimated that the measured value of 320 sec corresponds to at least 360 sec in space. An unknown cell-pressure effect, particular to the resistojet low Reynolds number nozzle, is believed to have caused the lower measured value.

The units operating on hydrogen did not achieve the specific impulse objective of 720 sec (on a measured basis) but did operate at the same wall temperature as the ammonia units. A measured specific impulse of 550 sec was achieved on hydrogen. It is believed that this measured value corresponds to at least 660 sec in space (for the reasons stated above).

Extended-duration life testing is in process under Contract No. NAS1-8090 to fully evaluate these thrusters.

FOREWORD

Units, abbreviations, and prefixes used in this report correspond to the International System of Units (SI) as prescribed by the Eleventh General Conference on Weights and Measures and presented in NASA Report SP-7012. The basic units for length, mass, and time are meter, kilogram, and second, respectively. Throughout the report, the English equivalent (foot, pound, and second) are presented for convenience.

The SI units, abbreviations, and prefixes most frequently used in this report are summarized below:

Basic Units

Length	meter	m
Mass	gram	g
Time	sec	s
Electric current	ampere	A
Temperature	degree Kelvin	°K

Supplementary Units

Plane angle	radian	rad
-------------	--------	-----

Derived Units

Area	square meter	m ²
Volume	cubic meter	m ³
Frequency	hertz	Hz (s ⁻¹)
Density	kilogram per cubic meter	kg/m ³
Velocity	meter per second	m/s
Angular velocity	radian per second	rad/s
Acceleration	meter per second squared	m/s ²
Angular acceleration	radian per second squared	rad/s ²
Force	newton	N (kg-m/s ²)
Pressure	newton per sq meter	N/m ²
Dynamic viscosity	newton-second per sq meter	N-s/m ²

Work, energy, quantity of heat	joule	J	(N-m)
Power	watt	W	(J/s)
Electric charge	coulomb	C	(A-s)
Voltage, potential difference, electromotive force	volt	V	(W/A)
Electric field strength	volt per meter	V/m	
Electric resistance	ohm	Ω	(V/A)
Electric capacitance	farad	F	(A-s/V)
Magnet flux	weber	Wb	(V-s)
Inductance	henry	H	(V-s/A)
Magnetic flux density	tesla	T	(Wb/m ²)
Magnetic field strength	ampere per meter	A/m	
Magnetomotive force	ampere	A	

Prefixes

Factor by which unit is multiplied	Prefix	Symbol
10 ⁶	mega	M
10 ³	kilo	k
10 ⁻²	centi	c
10 ⁻³	milli	m
10 ⁻⁶	micro	μ

DEFINITION OF A RESISTOJET CONTROL SYSTEM FOR
THE MANNED ORBITAL RESEARCH LABORATORY
FINAL REPORT
VOLUME V ADDENDUM--720-HOUR RESISTOJET LIFE TEST

By R. J. Page and R. A. Short

INTRODUCTION

This report, an addendum to Volume V (CR-56604), describes a 720-hour (30-day) life test on six 10-mlb resistojets (Model II), two operating on hydrogen (H_2) and four on ammonia (NH_3). This work was performed by the Marquardt Corporation under subcontract to the Douglas Aircraft Company, a component of the McDonnell Douglas Corporation. The reader is referred to Volume V (ref. 1) of this series for the description of the design and fabrication techniques of the life test thrusters.

The purposes of the life test were to (1) determine the life and life-governing mechanism of these thrusters as the measured specific impulse (I_{sp}) was progressively increased from 650 to 720 sec for H_2 and 280 to 320 sec for NH_3 , (2) discover any effects of thermal cycling (one half-hour on--one half-hour off), (3) measure any performance change with time, (4) determine any differences in thruster life resulting from the use of NH_3 and H_2 propellants (at the same chamber temperature and pressure).

All the thrusters were operational at the end of the 720-hour period. The life test was not of sufficient duration to evaluate thruster life, its governing mechanisms, the effects of cycling, or significant performance changes. The tests were extended one order of magnitude in duration (under Contract No. NAS1-8090 from the NASA Langley Research Center) and are currently in process. The ultimate answers to these questions await the conclusion of that program.

LIFE-TEST THRUSTOR FABRICATION

The fabrication process used was exactly that described in ref. 1. Figs. 1 through 3b describe the Model II (10-mlb) resistojet; a life-test thruster prior to the installation of thermal insulation; and two views of the six completed thrusters as fabricated, mounted, and ready for installation on the thrust dynamometer.

All parts and components of the life thrusters were inspected before the endurance test. (The data on the inner element assembly of thruster S-5 were not taken. Since the completed assembly was taken from development parts, such measurements were no longer possible.) The specific pretest description of the salient physical and mechanical characteristics follows.

Foldout FRAME 1

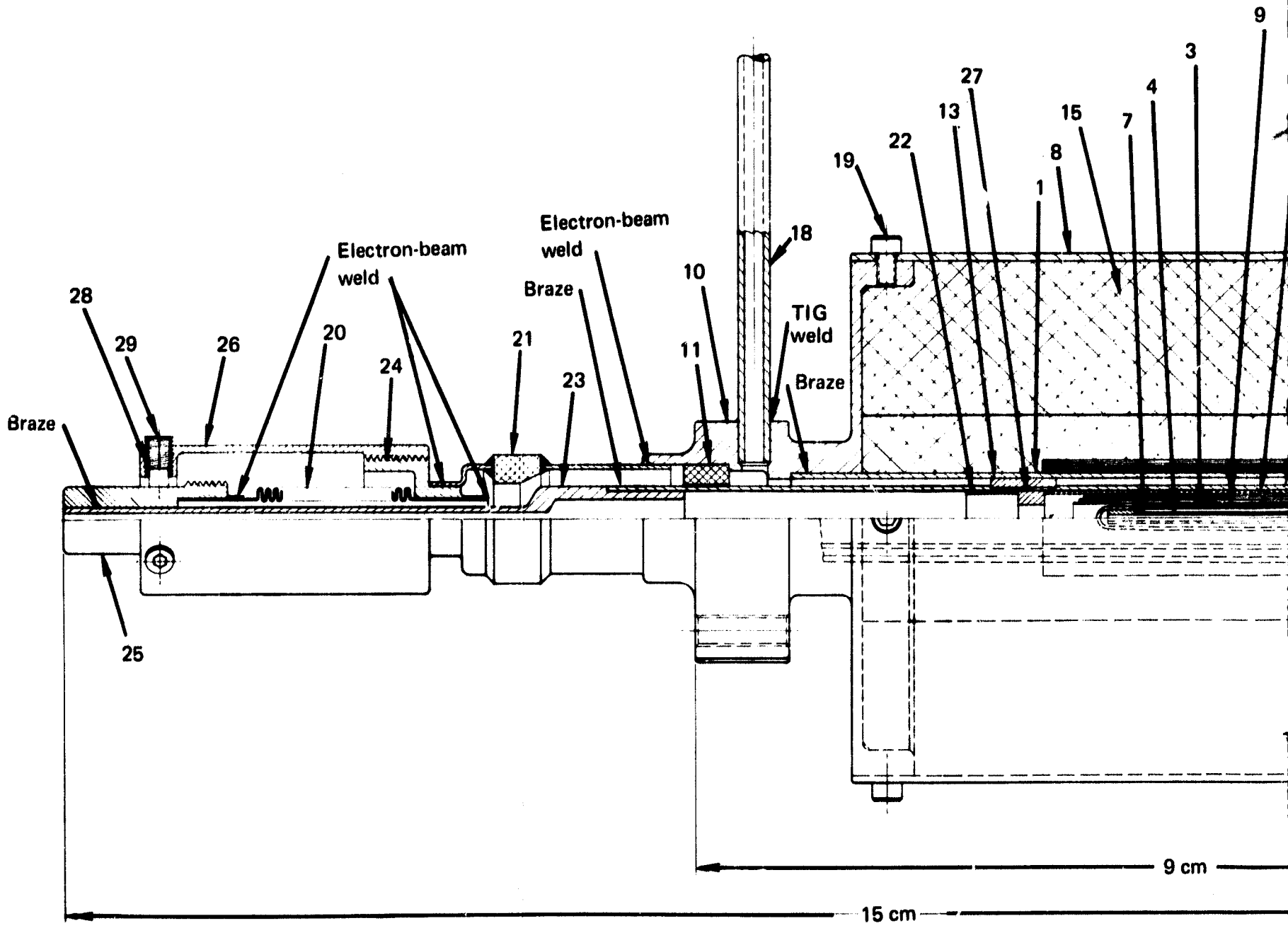
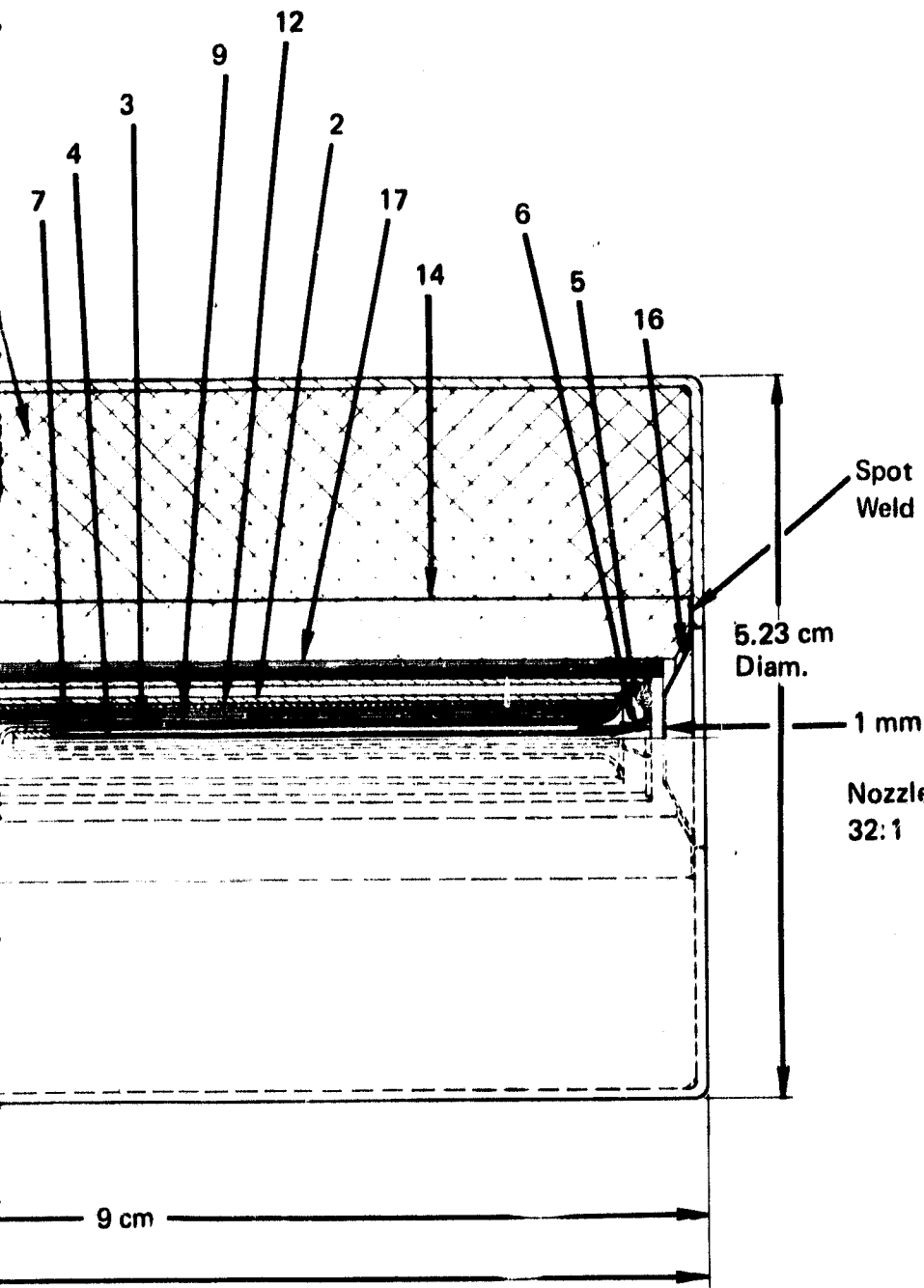


Figure 1. 10-mlbf Resistojet Model II

Foldout FRAME 2



- 1 Outer case
- 2 Inner case
- 3 Heater outer
- 4 Heater inner
- 5 Case cover
- 6 Nozzle
- 7 Strut connector
- 8 Housing
- 9 Radiation shield inner
- 10 Housing mount
- 11 Spacer ring
- 12 Electrical insulator
- 13 Spacer
- 14 Thermal insulation
- 15 Thermal insulation
- 16 Exit shield
- 17 Radiation shield outer
- 18 Tube
- 19 Screw
- 20 Bellows
- 21 Insulator fitting
- 22 Snap tube
- 23 Inner case stem
- 24 Fitting
- 25 Fitting
- 26 Guard
- 27 Electrical insulator
- 28 Guide pin
- 29 Set screw

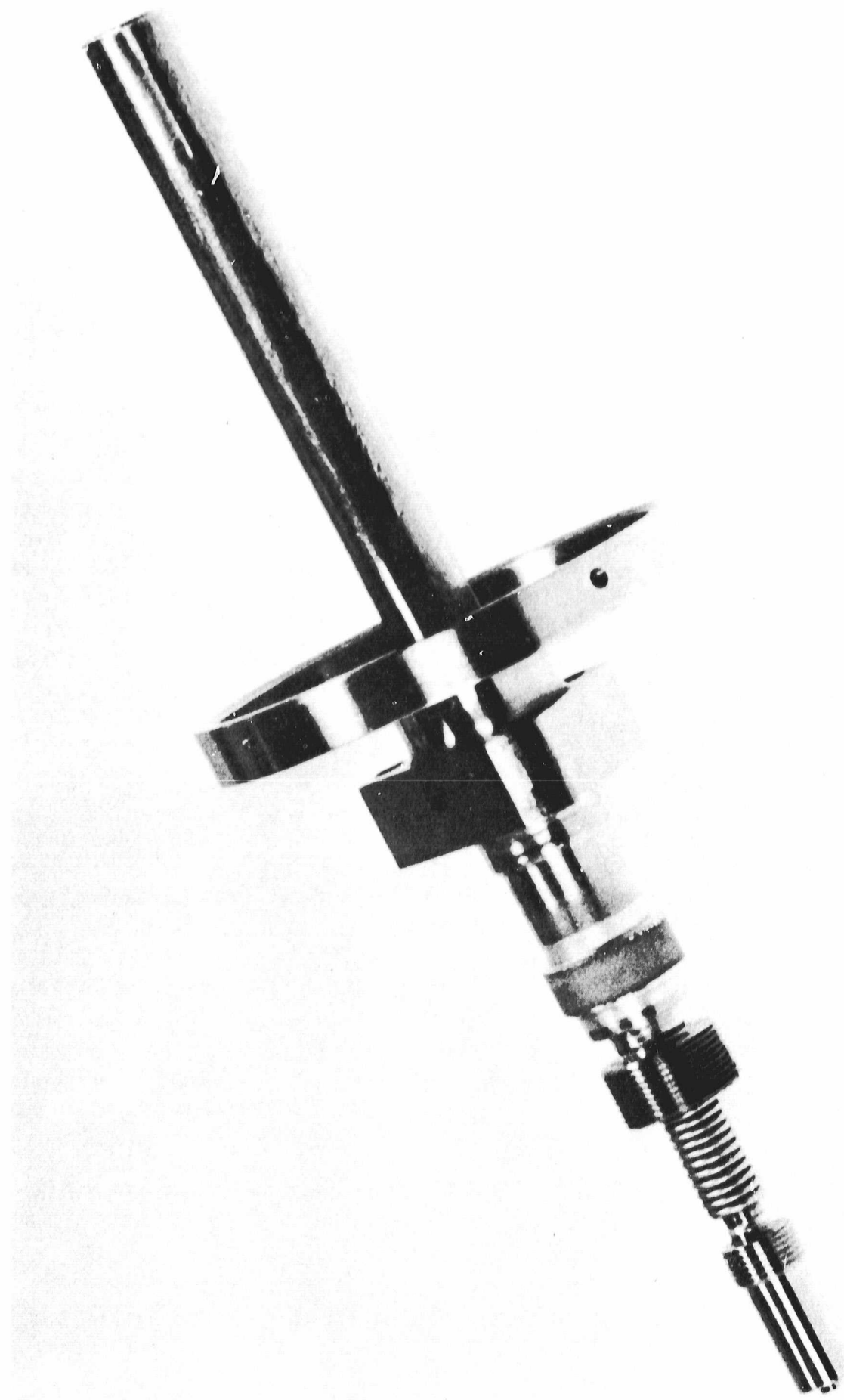


Figure 2. Model II After Welding and Brazing and Prior to Thermal Insulation

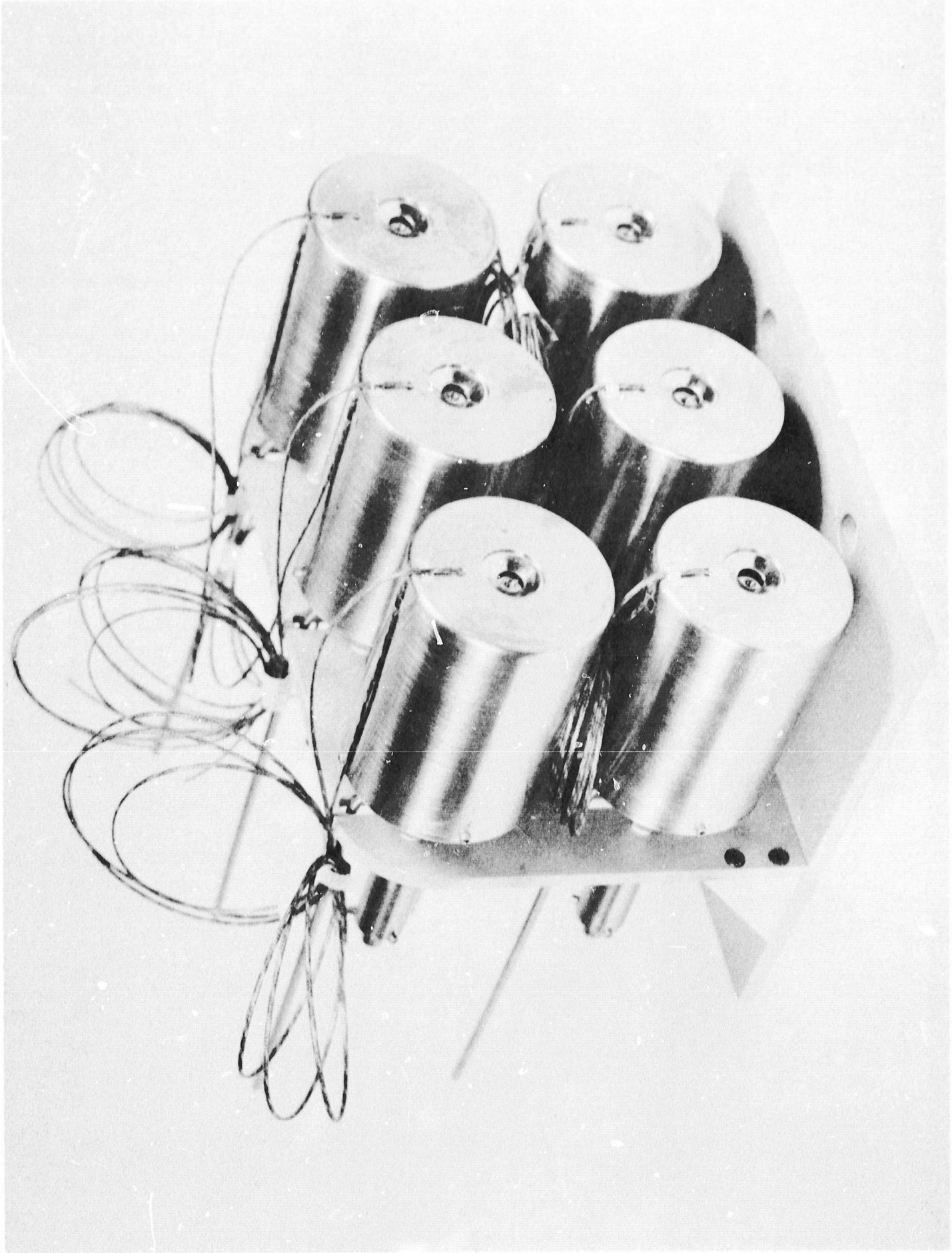


Figure 3A. Six 10-milbf Resistojet Thrusters in Life-Test Mounting Bracket (Nozzle End)

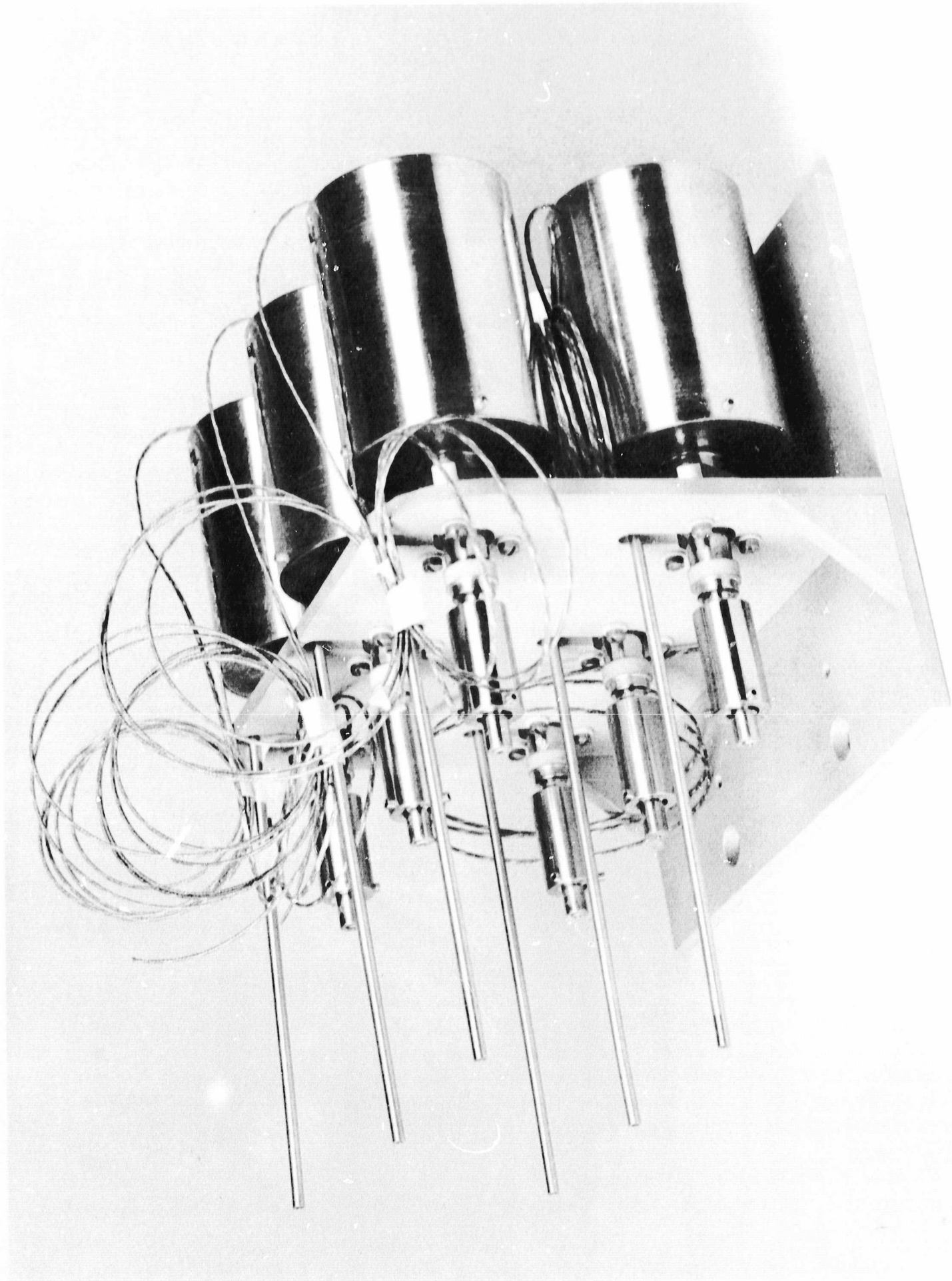


Figure 3B. Six 10-mlbf Resistojet Thrusters in Life-Test Mounting Bracket (Inlet End)

Dimensions

A tabulation of important dimensions of the thruster is given in table 1; reference values are provided for comparison. All other dimensions were to blueprint values or insignificantly different from them.

The nozzle-throat diameter measurements were made by precision pin gages. Any small lack of roundness of these sections, however, shows up as a larger effective flow area. (See the section on cold-flow check.) Future production quality control should rely on cold-flow checks or optical comparator measurements of the nozzle (Part No. 6 on fig. 1) prior to assembly. Diamond grinding of the throat should be considered for precise sizing.

In the future, the bellows (Part No. 20) should be checked by the direct measurement of its "extension" under design pressure. This would also confirm the measurement of the spring constant itself.

Masses

All elements of the thruster were individually weighed prior to assembly. The only purpose of weighing them on an individual basis was to verify consistency of the set of dimensional measurements. Post-test comparisons must be on a dimensional basis (after any sectioning) as the parts are permanently welded together by the electron-beam process. Table 2 compares these weighings with those calculated from the drawings considering a theoretical density of 21.02 g/cm^3 for the rhenium parts. The key rhenium parts were considered reasonably uniform in mass, particularly when the small wall thickness of the parts was considered. The inner elements (Part No. 4) averaged 0.2945 g with a maximum 3.7% deviation. The total thruster reference mass, including its propellant tube (Part No. 18) is 272.6 g (0.60 lbm).

Metallurgical Examination

Cutoffs of the parts used in the construction of the life-test thrusters have been carefully identified and saved so as to be compared with any post-metallurgical inspection. Similarly, spare parts and representative braze joints have been set aside.

One preexamination was done to solve a fabrication difficulty not experienced on the development thrusters. This involved cracking the inner element (Part No. 4) tube ends when they were swaged to match the nozzle inside diameter (i. d.) preparatory to electron-beam welding. The need for swaging was caused by the tube i. d. being 0.031 in. instead of the print 0.030 in. Since parts had been successfully swaged before, the cause was investigated.

Figure 4 shows the photomicrograph of a cross section (one hundred times size) of the inner heating element (Part No. 4) as received. Note the

TABLE 1
PRETEST DIMENSIONS
(cm)

Part number and name	Reference dimensions	Life-test thrusters					
		S-1	S-2	S-3	S-4	S-5	S-6
3. Outer heating element							
Forward i. d.	0.168 \pm 0.002 - 0	0.170	0.170	0.173	0.170	0.170	0.170
Forward o. d.	0.229 \pm 0.002 - 0.002	0.226	0.226	0.229	0.229	0.229	0.226
Rear i. d.	0.218 \pm 0.002 - 0	0.221	0.221	0.221	0.221	0.221	0.218
Rear o. d.	0.279 \pm 0.002 - 0.002	0.279	0.279	0.279	0.279	0.279	0.279
Flare o. d.	0.607 \pm 0.002	0.599	0.605	0.615	0.584	0.607	0.605
Flare thickness	0.030 \pm 0.002 - 0.002	0.030	0.033	0.033	0.028	0.033	0.028
Overall length	4.491 \pm 0.005	4.509	4.483	4.501	4.501	4.514	4.496
4. Inner heating element							
i. d.	0.076 \pm 0.0015	0.0805	0.080	0.0803	0.080	NA	0.0792
o. d.	0.107 \pm 0.005 - 0.005	0.1067	0.1087	0.1092	0.1092	NA	0.1092
5. Case cover							
i. d.	0.264 (snug fit)	0.264	0.264	0.264	0.264	0.264	0.264
o. d.	0.846 (snug fit)	0.846	0.846	0.846	0.846	0.846	0.846
Thickness	0.038 \pm 0.002 - 0	0.038	0.038	0.038	0.038	0.038	0.038

TABLE 1. - Concluded
PRETEST DIMENSIONS
(cm)

Part number and name	Reference dimension	Life-test thrusters					
		S-1	S-2	S-3	S-4	S-5	S-6
6. Nozzle	i. d.	0.0762	0.0765	0.0762	0.0765	NA	0.0772
	o. d.	0.1052	0.1067	0.1067	0.1067	NA	0.1067
	Throat diameter	0.0457	0.0450	0.0445	0.0475	NA	0.0457
	Exit diameter	0.2794	0.2705	0.2794	0.2692	NA	0.2794
	Nozzle cone angle	44°	44	44	44	NA	44
7. Strut connector	Element i. d.	0.0818	0.0762	0.0744	0.0813	NA	0.0813
	Element o. d.	0.1064	0.1064	0.1067	0.1067	NA	0.1067
	Strut length	0.244	0.254	0.257	0.244	NA	0.257
	Overall length	0.386	0.384	0.387	0.387	NA	0.387
	Strut width	0.0371	0.0381	0.0381	0.0376	NA	0.0401

TABLE 2
THRUSTOR ELEMENT MASSES
(Grams)

Part number and name	Reference mass	Life-test thrusters					
		S-1	S-2	S-3	S-4	S-5	S-6
1. Outer case	21.69	22.5739	22.1319	21.9612	22.8412	22.5534	22.0204
2. Inner case	18.73	19.1984	19.3506	19.0069	19.1771	19.0761	19.0565
3. Outer heater	2.109	1.6665	1.9160	1.9847	1.9275	1.8530	1.8750
4. Inner heater	0.3273	0.2918	0.2836	0.2929	0.3005	(a)	0.3040
5. Case cover	0.4252	0.3919	0.3757	0.3893	0.3868	0.3840	0.3788
6. Nozzle	0.1158	0.1126	0.1159	0.1281	0.1026	(a)	0.1093
7. Strut connector	0.0507	0.0435	0.0573	0.0626	0.0482	(a)	0.0552
8. Housing	81.87	77.5880	79.3421	78.1493	79.0607	77.9704	78.5109
9. Radiation shield, inner	1.619	1.7256	1.7685	1.6859	1.8107	1.8247	1.7240
10. Housing mount	62.3	61.9091	62.1660	62.0296	62.0787	61.3671	62.0385
11. Spacer ring	0.4790	0.4720	0.4768	0.4742	0.4786	0.4730	0.4736
12. Electrical insulator	0.4366	0.4863	0.4842	0.5154	0.5076	0.4933	0.4902
13. Spacers (3)	0.0750	0.072 ^b	0.072 ^b	0.072 ^b	0.072 ^b	0.072 ^b	0.072 ^b
14. Thermal insulation	3.231	2.7161	2.7092	2.8275	2.7605	2.5396	2.7714
15. Thermal insulation	39.15	34.9 ^b	34.9 ^b	34.9 ^b	34.9 ^b	34.9 ^b	34.9 ^b

^aThe data on the inner element assembly of thruster S-5 were not taken. Since the completed assembly was taken from development parts, such measurements were no longer possible.

^bThe materials from which these parts are made are such that some material is often lost during assembly operations. All the parts were weighed before assembly and an average taken. This is an approximation and applies to all engines.

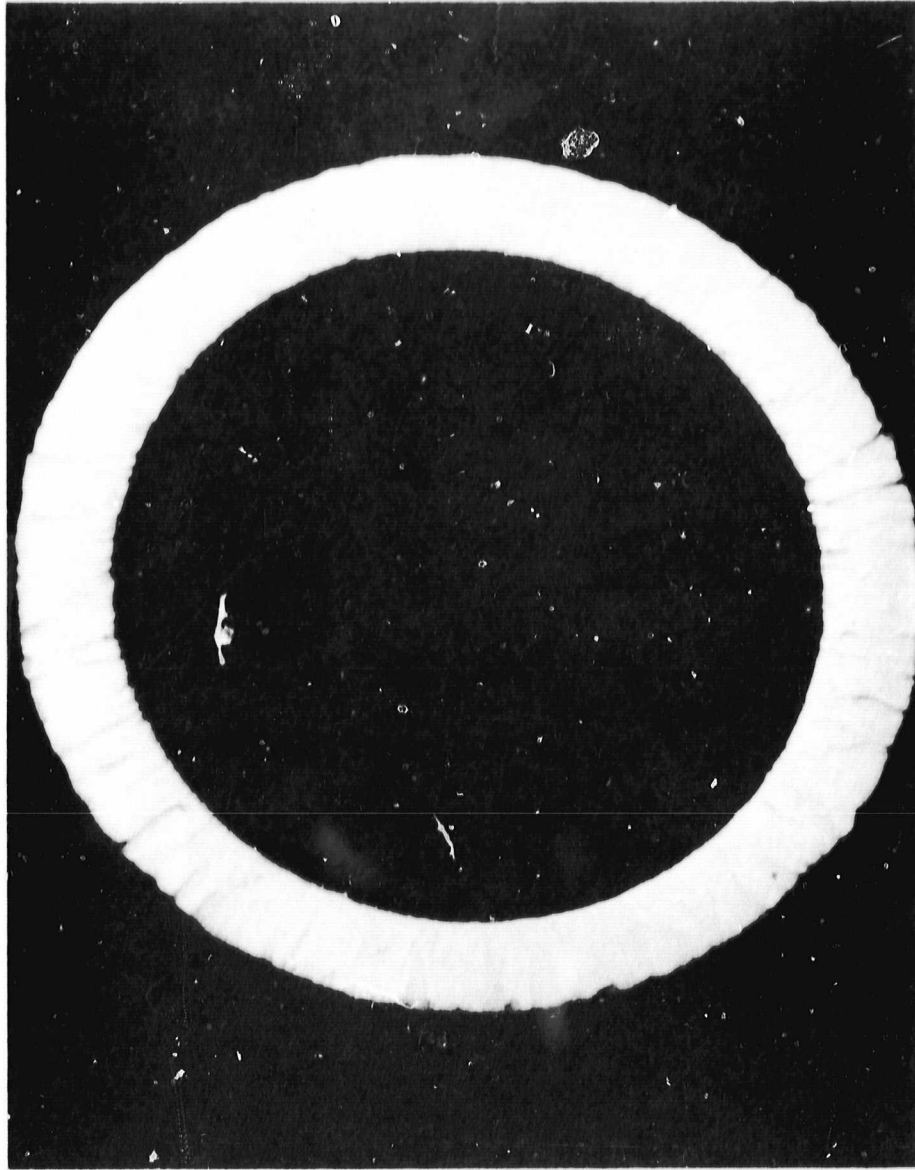
TABLE 2. - Concluded
THRUSTOR ELEMENT MASSES
(Grams)

Part number and name	Reference mass	Life-test thrusters					
		S-1	S-2	S-3	S-4	S-5	S-6
16. Exit shield	0.7822	0.8067	0.7935	0.8159	0.8248	0.8087	0.8033
17. Radiation shield, outer	3.811	3.9189	3.8703	4.0059	3.9536	3.7898	3.9685
18. Propellant tube	8.343 (15-cm long) ^c	---	---	---	---	---	---
19. Screws (4)	0.4676	0.4676 ^d	0.4676 ^d	0.4676 ^d	0.4676 ^d	0.4676 ^d	0.4676 ^d
20. Bellows	0.5805	0.5746	0.5732	0.5819	0.5742	0.5856	0.5956
21. Insulator fitting	3.755	3.8973	3.8759	3.8138	3.9419	3.8824	3.8437
22. Snap tube	0.5650	0.5745	0.5688	0.5648	0.5748	0.5507	0.5444
23. Inner case stem	4.057	4.0171	3.9606	4.0419	4.0380	4.0552	4.1698
24. Fitting	3.245	3.2638	3.2691	3.2785	3.1676	3.1598	3.2008
25. Fitting	3.769	3.6626	3.6489	3.6261	3.6362	3.6757	3.6613
26. Guard	10.25	10.3103	10.2127	10.2880	10.2311	10.1750	10.2081
27. Electrical insulator	0.0915	0.0887	0.0919	0.0914	0.0901	0.0896	0.0900
28. Guide pins (3)	0.0705	0.0705 ^b	0.0705 ^b	0.0705 ^b	0.0705 ^b	0.0705 ^b	0.0705 ^b
29. Set screws (3)	0.2449	0.2449 ^d	0.2449 ^d	0.2449 ^d	0.2449 ^d	0.2449 ^d	0.2449 ^d
Total	264.3	256.0	257.8	256.4	258.3	e	256.6

^cPart No. 18 variable not included in totals.

^dAverage masses were used for the two sets of screws used on each engine rather than to assign specific screws to each engine.

^eThe data on the inner element assembly of thruster S-5 were not taken. Since the completed assembly was taken from development parts, such measurements were no longer possible.



I.D. = 0.0800 cm
Wall = 0.0145 cm

Figure 4. Rhenium Inner Heating Element – Photomacrographic Cross Section

columnar grain structure typical of the vapor deposition process. These elements were found to have been made using ReF_6 gas rather than the ReCl_5 used earlier. The microhardness (Knoop) using a 100-g load was 400 to 410 which "converts" to a 35.0 to 36.0 Rockwell-C hardness. Successful swaging of ReF_6 elements required annealing in a vacuum furnace for 1 hr at 1650°C .

Since no failures occurred and the life tests have been extended, no post-test metallographic examination has been performed. Metallographic comparisons will be provided upon completion of the extended-duration test.

Leak Checks

A Veeco helium leak detector (Model MS-9, a mass spectrometer) was used to verify the integrity of each thruster joint during assembly and as a completed thruster. No leakage was detected in the completed assemblies.

These tests will be repeated for each thruster at test completion to assist in determining any degradation of braze joints and welds and any porosity of materials.

The life-test facility propellant system, including thrusters, was leak checked by the method of pressure decay with time in a known volume. The total leakage found was less than 0.1% of design mass flow.

Flow Checks

The cold-flow check of the assembled thruster was made to determine the effective size of the nozzle throat and, hence, thrust level at design pressure. The resultant specific impulse serves as a check on the overall thruster integrity.

Table 3 compares the geometric throat diameter (pin gage measurement), cold-flow rate (H_2 at two supply pressures), specific impulse, and cold-terminal resistance of the Design Verification Test (DVT) thruster (B-2), and the life-test thrusters.

These data support the recommendation that the nozzle (Part No. 6) be cold-flow checked and/or optically measured to establish the actual throat measurement.

Electrical Checks

The terminal resistances of all units were measured (table 3) under a light electrical load of approximately 1 W. The average was 0.0347 ohms, the maximum variation from average was +5%. Table 1 shows the dimensions which influence resistance and require close quality control.

TABLE 3
HYDROGEN COLD-FLOW CHECKS--INITIAL

Thruster no.	Throat diameter pin gage (cm)	Geometric throat area (cm ²)	Supply pressure (psia)	Thrust (g)	Mass flow (g/sec)	Specific impulse (sec)	Throat mass flux (geometric) (m/A*g) (g/cm ² /sec)	Cold resistance (Ω)
B-2	0.0473	1.75 x 10 ⁻³	34.7 51.0	4.58 7.24	0.0187 0.0293	245 246	10.7 16.7	0.0333
S-1	0.0457	1.64 x 10 ⁻³	35 50	4.16 6.54	0.0181 0.0269	230 243	11.0 16.4	0.0340
S-2	0.0450	1.59 x 10 ⁻³	35 50	4.25 6.33	0.0178 0.0263	238 241	11.2 16.5	0.0340
S-3	0.0445	1.55 x 10 ⁻³	35 50	3.60 5.52	0.0156 0.0225	230 246	10.1 14.5	0.0338
S-4	0.0475	1.77 x 10 ⁻³	35 50	4.39 6.47	0.0184 0.0273	238 237	10.4 15.4	0.0339
S-5	a	a	35 50	3.98 6.02	0.0172 0.0250	232 241	NA NA	0.0361
S-6	0.0457	1.64 x 10 ⁻³	35 50	3.60 5.42	0.0158 0.0225	228 240	9.6 13.7	0.0364

a. The parts originally scheduled for the S-5 engine nozzle-heating element assembly were damaged and replaced with parts that had already been assembled. When the engines had undergone tests for some time, it was discovered that measurements of these parts had not been taken. However they were known to fall within the tolerances because of a previous inspection.

INSTRUMENTATION AND EQUIPMENT

Life Test Facility

Table 4 lists the instruments used in the 720 hour-test along with their ranges and accuracies. A Photograph of the life-test facility at the Marquardt Corporation, Van Nuys, and the system schematic are shown in Figs. 5 and 6. The cycling of the thrusters is automatic. The operating point of each thruster is set by fixed values of terminal voltage and propellant supply pressure as selected for the MORL studies. A current limiter is provided but does not control at the operating point. A time-cycle controller (Switchmaster Model 300-72-12) alternately selects one of two sets of thrusters for a half-hour operation each. Each set consists of one H₂ and two NH₃ thrusters. The controller has cam-actuated microswitches for energizing relays and solenoids.

The H₂ thrusters alternately share a Sorenson DCR-20-125A power supply and propellant supply and metering system. For example, the S-1 thruster is started as follows. The timer selects S-1 first by actuating relay R₇ and then propellant solenoid V₁. As propellant pressure increases, the pressure switch is actuated, which in turn energizes R₁. The shut down starts with interruption of power by R₇, followed by de-energizing solenoid V₁ by two separate timer cams. Manual-override select switches are provided to allow for single engine calibration.

The two NH₃ systems are identical to the H₂ system described above.

In the event of cell pressure exceeding 500 μ m Hg (such as by vacuum system power interruption), the Magnevac-gage pressure switch initiates complete system shut down.

Measurement Methods

The instrument range and nominal accuracy are called out in Table 4 for the measurements described below.

Thrusts. -- The thrusts of the 10-mlbf resistojets were measured by a sensitive floatation-type dynamometer with a linear-variable-differential-transformer displacement transducer. The dynamometer is completely described in ref. 2. The output of the transducer was demodulated and measured with a precision potentiometer-recorder. The six thrusters, mounted

FRAME 1

TABL
INSTRUMENTATI

Measurement	Instrument
1. Thrust	Thrust systems Model 128 dynamometer Robinson-Halpern 70 - 3101 LVDT and 201B exciter demodulator Honeywell Electronic 15 potentiometer
2. Propellant flow, low range (H_2)	Brooks Model 1110 rotameter
3. Propellant flow, high range (H_2)	Brooks Model 1110 rotameter
4. Propellant flow, low range (NH_3)	Brooks Model 1110 rotameter
5. Propellant flow, high range (NH_3)	Brooks Model 1110 rotameter
6. Thrustor voltage	Kintel digital voltmeter
7. Thrustor current	Kintel digital voltmeter
8. Thrustor supply pressure, H_2	Heise pressure gauges
9. Thrustor supply pressure, NH_3	Heise pressure gauges
10. Propellant temperature	United Systems Digitec digital thermometer
11. Test chamber pressure	CVC Magnevac gauge
12. Thrustor temperatures	Honeywell Electronic 15 multipoint potentiometer and chromel-alumel thermocouples
13. Element temperature	Photomatic automatic optical pyrometer Pyrometer Instrument Company

FRAME 2

TABLE 4

IDENTIFICATION SUMMARY

	Serial No.	Range	Nominal accuracy
Barometer with VDT and Datronic	---	0.1 mlbf to 1.5 lbf	±1.0% at 10 mlbf
Potentiometer	---		
	NB6A41		
	V6805523001		0.25%
	6802-38657	0.0008 - 0.008 g/sec	1.0%
	6802-3856	0.0045 - 0.048 g/sec	1.0%
	6802-38659/1	0.0025 - 0.025 g/sec	1.0%
	6802-38659/2		
	6802-38658/2	0.010 - 0.116 g/sec	1.0%
	6802-38656/1		
	3232		0.1%
	3232		0.5%
	H13395	0 - 100 psia	0.2%
	H15613R	0 - 50 psia	0.1%
	H16584		
Thermometer	1574C	0 - 100°C	0.1%
	15054	1 μ to atmospheres	±5%
Point potentiometer couples	66B/5545	0 - 1200°C	±2°C
Pyrometer, any	A107	1450 - 5800°F	0.5%

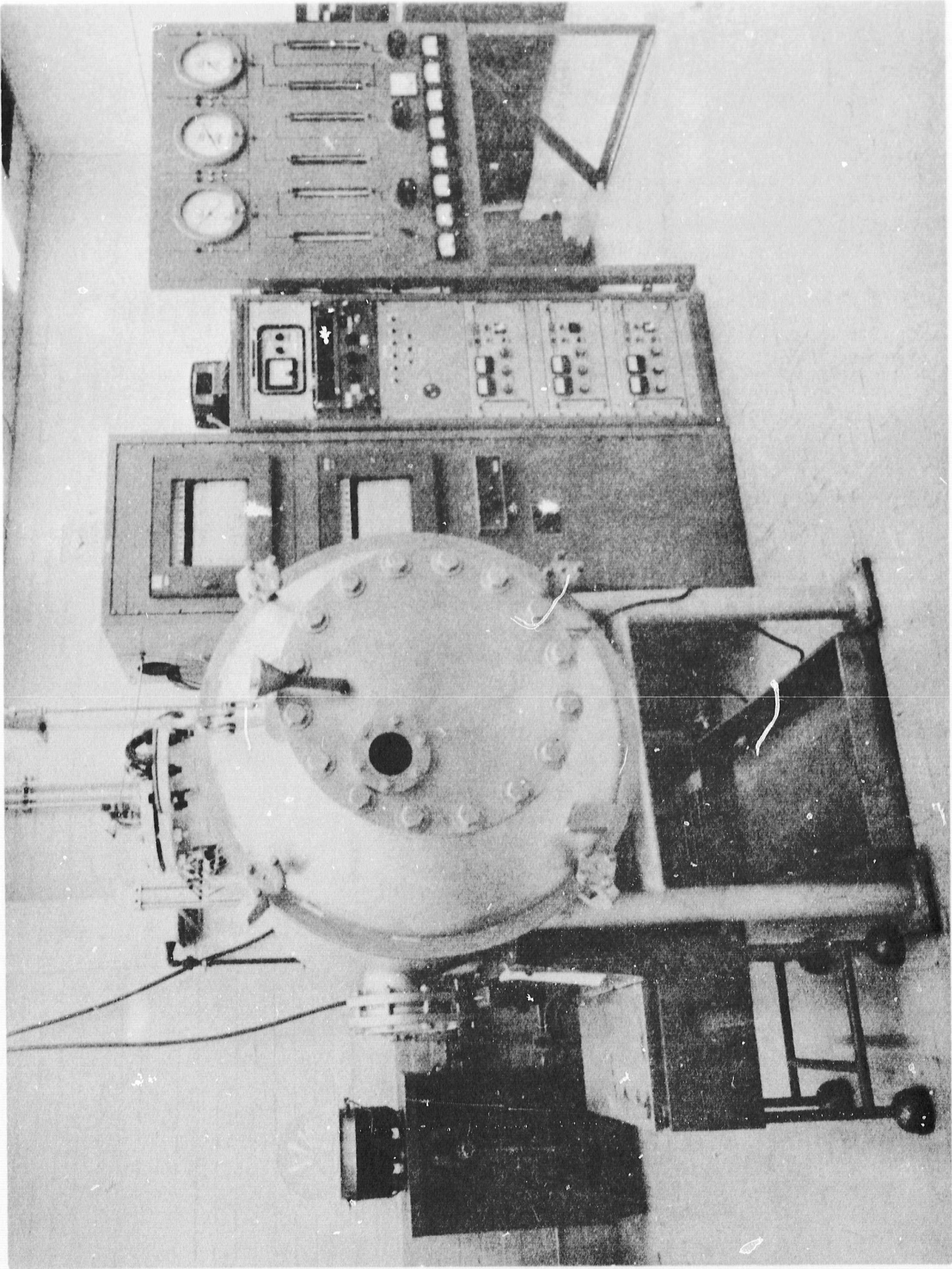


Figure 5. Resistojet Life-Test Facility

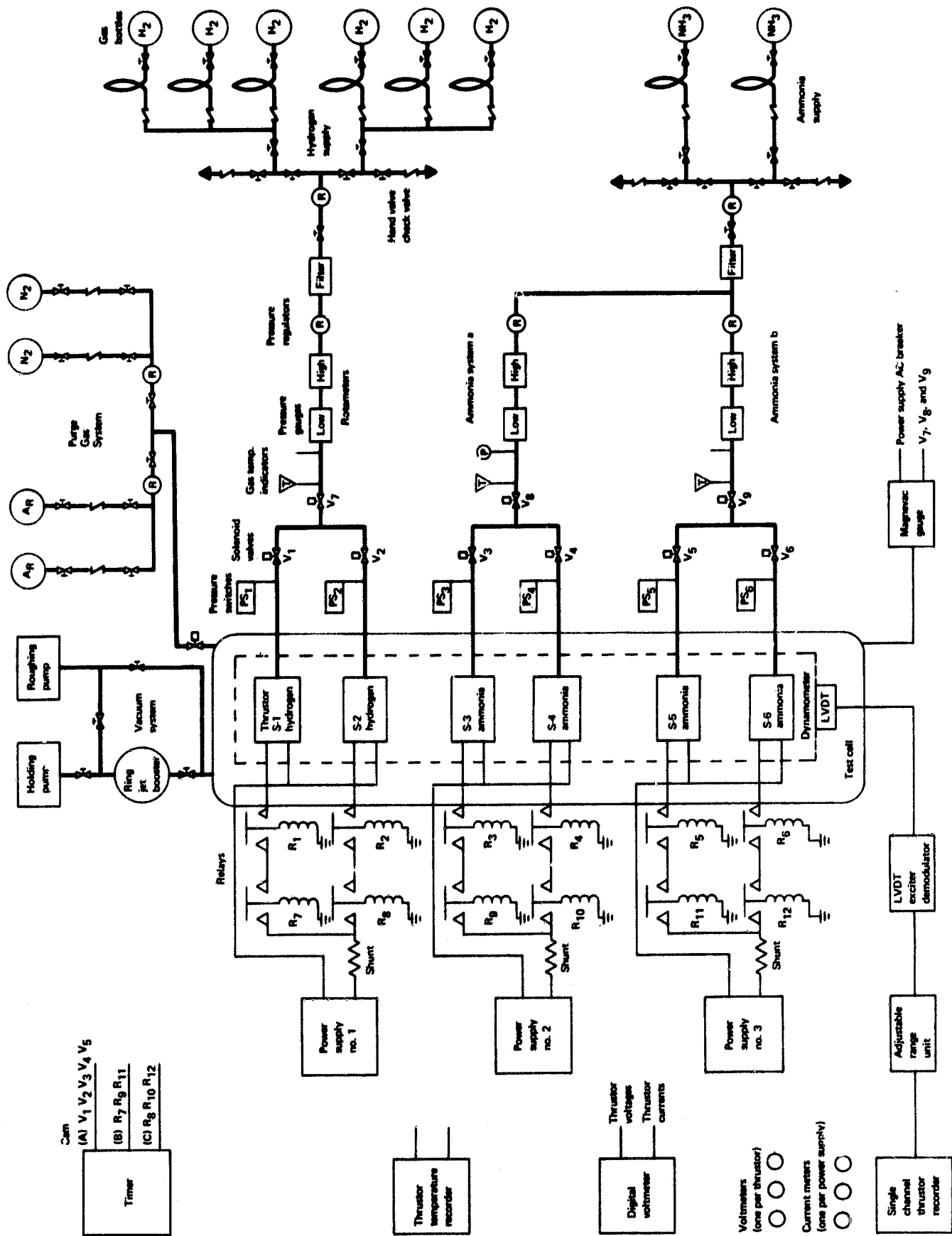


Figure 6. Resistojet Life-Test Facility Schematic

in the same thrust direction, are shown on the dynamometer in fig. 7. Three units fire at one time. To measure the thrust of an individual unit, the other two are stilled.

Flow. — The flow measurement was significantly improved over that used in the development testing (ref. 1). Two 25-cm flow meters in series were used (see table 4) as compared to a single 15-cm rotameter. These were calibrated at design pressure rather than by using the rotameter correction formula supplied by the manufacturer:

$$\dot{m} = \dot{m}_i \sqrt{\frac{T_c P_i}{T_i P_c}} \quad (1)$$

where

m = mass flow, T = gas temperature, P = pressure, and subscript "i" refers to "indicated" values and subscript "c" to "calibration" values. The formula supplied by the rotameter manufacturer can cause serious flow rate errors in the laminar-flow regime.

Temperature. — Two thermocouples are used to measure the temperature of the forward part of the engine pressure case (Part No. -2) and insulation cover (Part No. -8). These are used to estimate the thermal losses and to compare with the previous performance test data.

Cell pressure. — A gaseous conduction-type (Magnevac) gage is used to measure test cell pressure. In the continuing life test, a secondary McLeod gage comparator is being installed as a check. This redundant measurement capacity will provide more accurate data to define delivered specific impulse variation with cell pressure.

Measurement schedule. — The 720-hour cyclic life test was run continuously. The data shown in table 4 were taken manually once daily (excepting Saturdays and Sundays), with the notable exception of thrusts. Thrust measurements were taken once on Mondays, Wednesdays, and Fridays. These thrust data were taken by means of turning off all other thrusters. The reason for this procedure is to achieve minimum cell pressure, the importance of which is discussed later. Concurrent with each thrust measurement all the associated data, such as propellant mass flow, voltage, and current, were taken.

All thrusters were cycled on a 50% duty cycle, that is, 1800 sec on and 1800 sec off. The minimum performance data were taken relative to the last 400 sec of the "on" part of the cycle.

Calibrations

Instrument calibrations evidenced traceability of the performance of the end item to national standards. Calibration intervals have been established by the Marquardt Test Instrumentation Organization on the basis of stability, purpose, and degree of usage which were observed. Supplementing this, all

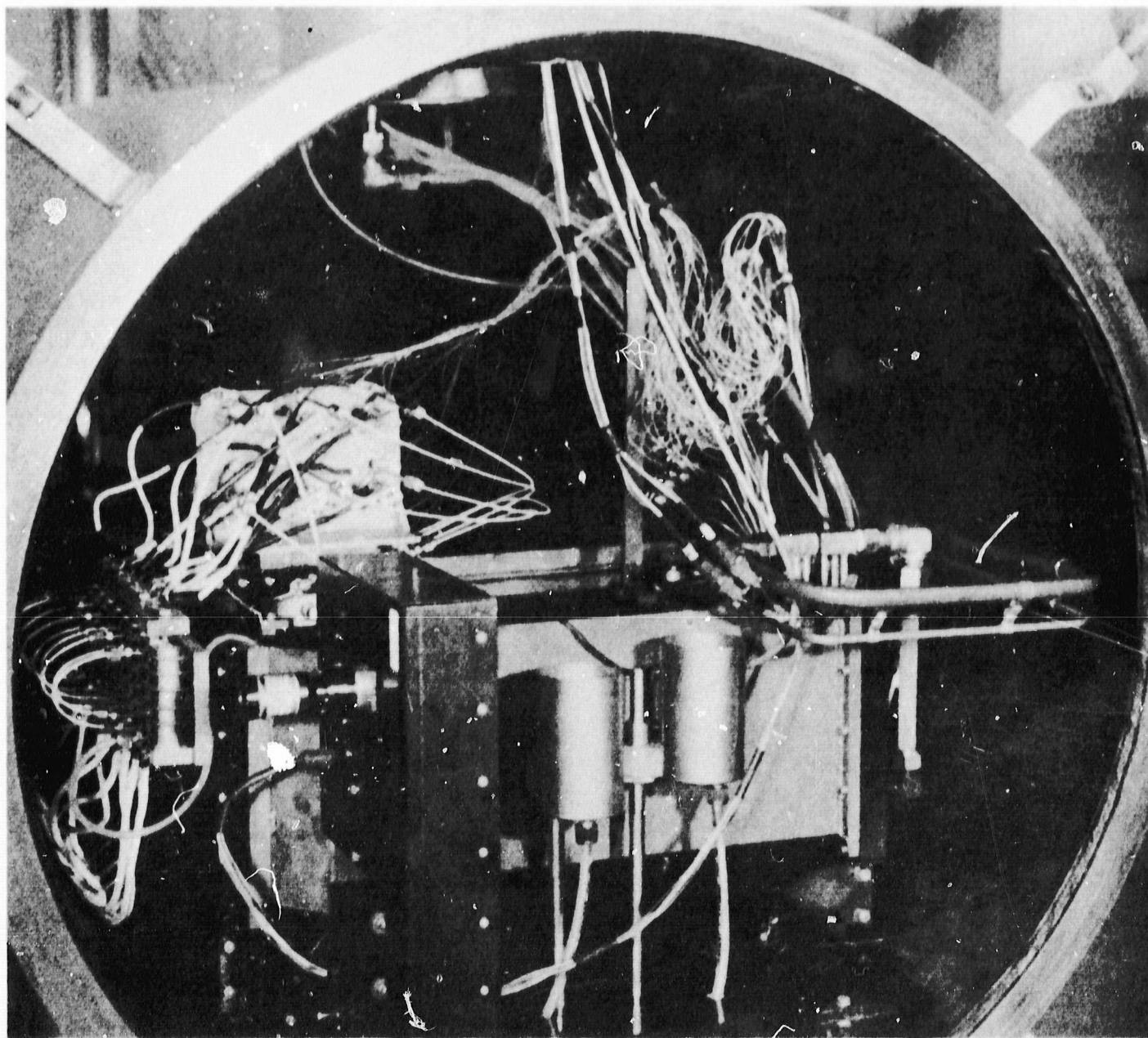


Figure 7. Six 10-mlbf Resistojets Mounted on the Dynamometer

instruments were calibrated before the endurance test. In the event of any shutdown caused by an instrumentation failure, the repaired instruments were calibrated.

Thrust stand, - A remote calibrator was used so that weights could be remotely added to or removed from the dynamometer. Such a calibration procedure was conducted immediately before each major start-up and at the final shutdown. Fig. 8 shows a typical calibration curve. This calibration was made while the test cell was at vacuum conditions. The normal time of calibration was any day thrust data were recorded at the conclusion of thrust measurements.

Documentation, - All instrumentation calibrations were documented in an instrumentation log which also contains make, model, serial number, functional use, range, and accuracy for each instrument used in the life test. Table 4 contains this information.

The dynamometer calibration log is shown in table 5. It contains the (1) date and time of day (local standard) of calibration, (2) the reading recorded for each calibration, and (3) the calibration weights used.

The variation in recorder scale reading (table 5) at a particular calibration mass is caused by changes in the dynamometer temperature and the varying condition of the mercury pool surfaces. These changes occur over long periods of time compared to the interval of a few minutes between thrust measurements and dynamometer calibration. The effect on accuracy, therefore, is small.

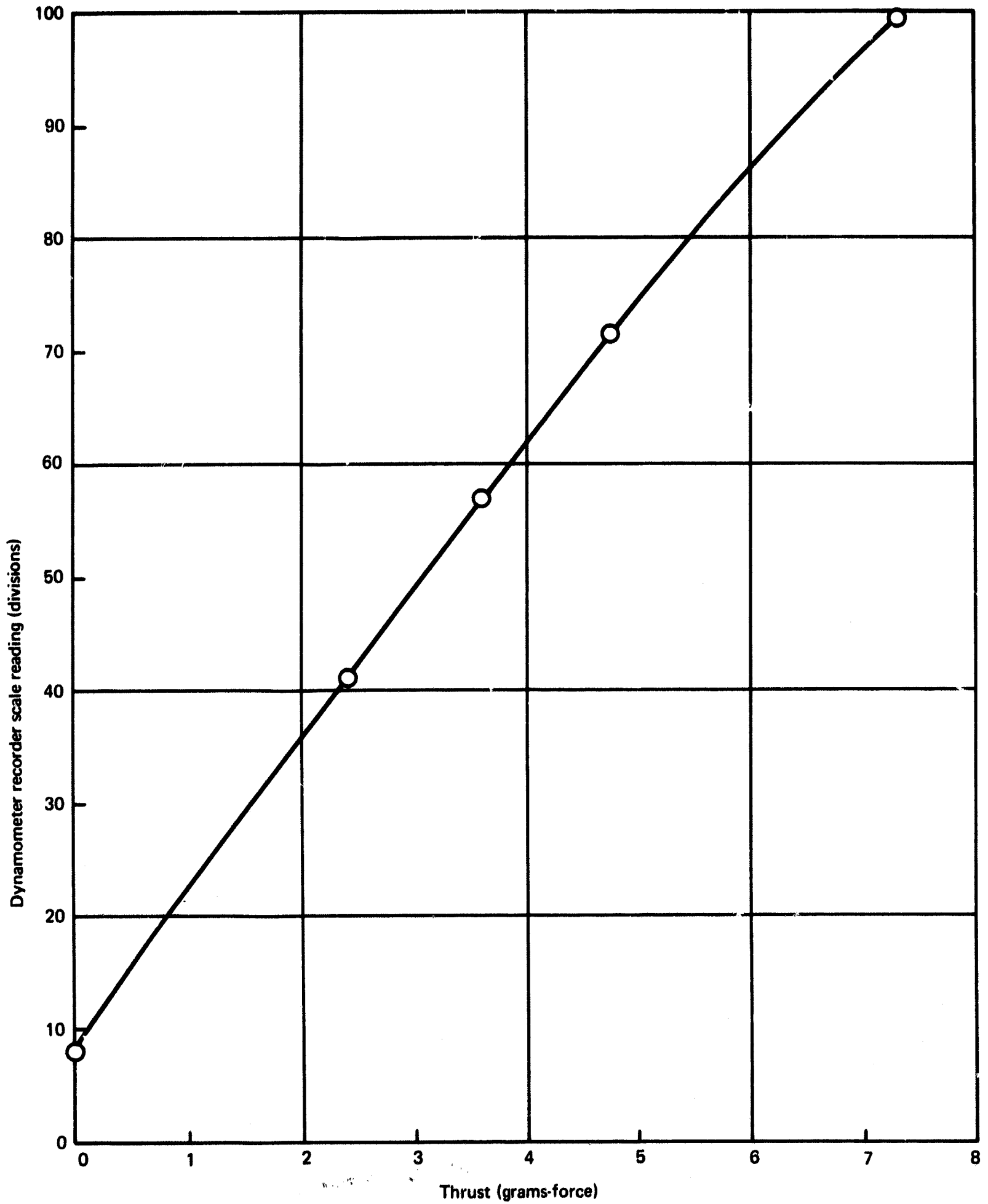


Figure 8. Thrust Dynamometer Calibration Using Remote Calibration Unit

TABLE 5
DYNAMOMETER CALIBRATION LOG

Remote calibrator mass (grams)		Recorder scale readings				
		0	2.41	3.60	4.77	7.32
<u>Date</u>	<u>Time</u>					
4-2-68	1100	6.8	39.2	---	66.8	94.0
4-3-68	1711	9.2	42.8	55.5	71.7	99.6
4-5-68	1245	8.6	41.4	56.8	71.4	100.2
4-8-68	1240	10.1	43.5	59.3	73.4	101.4
4-15-68	900	9.1	42.1	55.9	70.2	97.6
4-17-68	1615	11.0	40.8	53.8	67.0	94.2
4-19-68	1800	---	41.6	56.7	70.5	95.7
4-24-68	1630	20.5	43.5	55.0	67.6	101.5
4-26-68	1653	11.9	45.1	60.3	75.0	101.9
4-29-68	1610	11.8	45.3	60.4	75.2	102.6
5-1-68	1430	11.5	45.0	60.8	75.6	104.3
5-3-68	1413	11.9	46.0	60.9	75.9	105.0
5-6-68	1225	12.4	46.3	61.3	76.3	105.3
5-9-68	1600	12.8	46.6	61.7	76.5	104.9
5-17-68	1402	12.9	46.9	61.5	76.4	103.5
5-20-68	1230	12.9	46.7	61.6	76.4	104.2
5-22-68	1420	13.0	46.6	61.5	76.4	104.9
5-24-68	1446	13.0	46.8	61.8	76.5	104.5
5-27-68	1300	12.9	46.7	61.7	76.7	105.5

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LIFE TEST PLAN

Conditions

Fig. 9 summarizes the planned specific impulse schedule with time. The specific impulse of the ammonia engines was to be increased in steps to 320 sec. In like manner, the hydrogen engines were to be moved up to 720 sec. This was to give some preliminary indication of the effect of specific impulse on thruster life.

The thruster Set A consisted of units S-2 (H₂), S-4 (NH₃), and S-6 (NH₃), and Set B of units S-1 (H₂), S-3 (NH₃), and S-5 (NH₃). Sets A and B were alternately fired on a half-hour basis.

The test chamber conditions were to be minimum cell pressure but no greater than 1000 μ m H_g and a wall chamber temperature between 294 and 316°K. During thrust measurement the cell pressure was expected to be 12 μ m H_g. The propellant was to be supplied to the thruster as a gas at ambient temperature.

Endurance Time Accrual

Endurance time was accrued when single thruster measurements indicated that the thruster operated within the following tolerances of "reference" conditions. The "reference" operating conditions were established from performance tests at a thrust of 10 mlbf prior to the endurance running at the specific impulse level under test. (See section on life-test unit calibration.) Further, it was necessary that between thrust measurements no data observed on the remaining variables fell outside the tolerances given in table 6.

If the cell pressure during a thrust measurement was higher than that of the reference calibration, then the cell pressure correction to thrust was to be applied.

Restrictions and Allowances

During the course of the endurance tests, the following applied:

- (1) A failure was considered to have occurred if, during the test, maintenance, repairs, or adjustments to the thruster itself were required.
- (2) If during the testing of a thruster the thruster performance failed to meet that specified, it was at the discretion of the Contracting Officer's Technical Representative as to whether testing should continue on that thruster.

Performance		Specific impulse (sec)			
Gas	No. of units	Level	(1)	(2)	(3)
H ₂	2		650	680	720
NH ₃	4		280	300	320

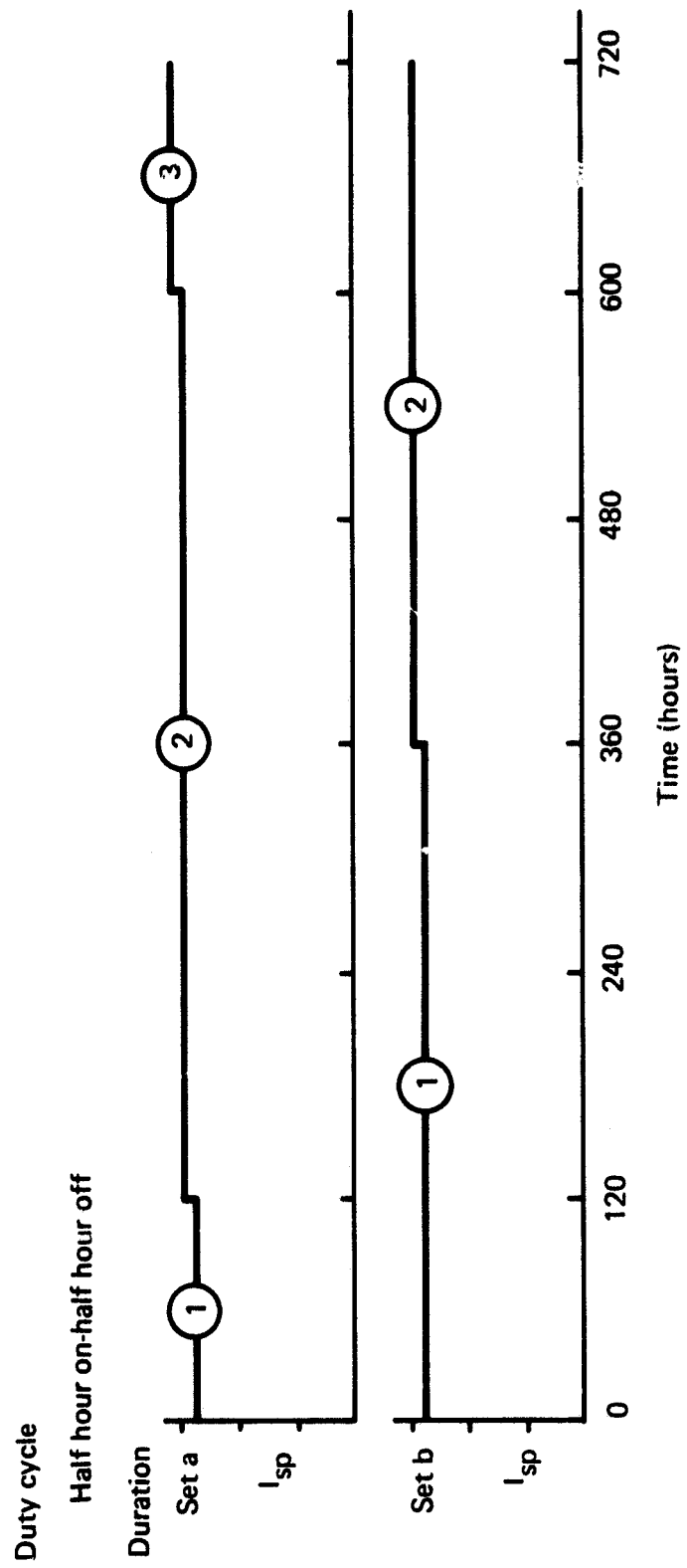


Figure 9. Life-Test Plan

TABLE 6
REFERENCE OPERATING CONDITIONS

(1) Input power:	$\pm 3\%$
(2) Mass flow:	$\pm 4\%$
(3) Thrustor supply pressure:	$\pm 5\%$
(4) Vacuum tank pressure:	less than 1000 μ m H _g
(5) Thrust:	$\pm 7\%$
(6) Specific impulse:	$\pm 8\%$

(3) Stops and starts were permitted to repair facility or instrumentation failures, to provide propellant storage resupply, to maintain equipment, or to conduct the test economically.

(4) System adjustments were logged when made. These adjustments specifically include propellant system supply pressure and electric voltage levels.

Thrustor Life Definition

Total thrustor life was defined as:

(1) The time required to reduce the assembled heater weight or individual element thickness to 90% of its initial fabricated measurement.

(2) The actual or estimated time before either the input power, thrust, or specific impulse could not be maintained to within the following percentage of their reference values less the tolerance of the measurement: (A) input electric power - $\pm 3\%$, (B) thrust - $\pm 7\%$, and (C) specific impulse - $\pm 8\%$.

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LIFE TEST

Design Verification Unit Recalibration

The B-2 thruster was retested during March 1968 to serve as a comparison between the development and the life-test facility instrumentation. It was tested from zero to full electric power on both NH_3 and H_2 . The primary difference occurred in mass flow metering (See the section on measurement). After this correction was applied to the original data, the remaining differences were small. Any remaining differences are believed to be the result of changes in cell pressure caused by a slow deterioration in vacuum system performance. These cell pressure effects can manifest themselves in thrust, mass flow, and temperature distribution changes as is discussed.

Ammonia. — Fig. 10 shows the specific impulse versus gas temperature as predicted in ref. 1. Also shown is the gas temperature determined on the basis of an energy balance. These are compared with wall temperature measurements made on the rear of the outer heating element (Part No. 3) by means of a pyrometer. The latter was sighted through the inner case stem (Part No. 23). These comparisons show that at the 320 sec measured specific impulse condition that the wall to gas temperature difference is approximately 300°K . Note further that the inferred gas temperature is higher by approximately 150°K than that predicted. This difference, as will be discussed in the section to follow, is caused by an unknown cell pressure effect on a viscous nozzle. It is interesting to note that, at intermediate temperatures, the performance is substantially better than that predicted. This is believed to be caused by the uncertainty of temperature values found from enthalpy measurement and gas property data in the region of ammonia dissociation. The exact state of the gas is not accurately known. These data indicate that the space performance (I_{sp}) will be about 360 sec staying within the temperature limitation of 2400°K .

The power distribution as a function of measured specific impulse level is summarized in fig. 11. The definitions of the performance parameters are given in Appendix A. The total power represents the sum of the initial power in the propellant gas and the applied electric power. Note that the losses can be measurably reduced by the addition of more thermal insulation. These losses represent the performance of a single thruster. They do not include the reduction in losses that would be brought about by the additional thermal insulation as in a multiple thruster module. The thermal insulation is the same for the NH_3 as for the H_2 data presented. These data are for constant supply pressure operation at 44 psia. The thrust level at cold flow (zero electric power) is 7.1 g and at design (320 sec) is 4.6 g (10 mlbf).

At a specific impulse of 320 sec, the efficiencies which correspond to the power performance above are as shown in fig. 12. The heater efficiency is

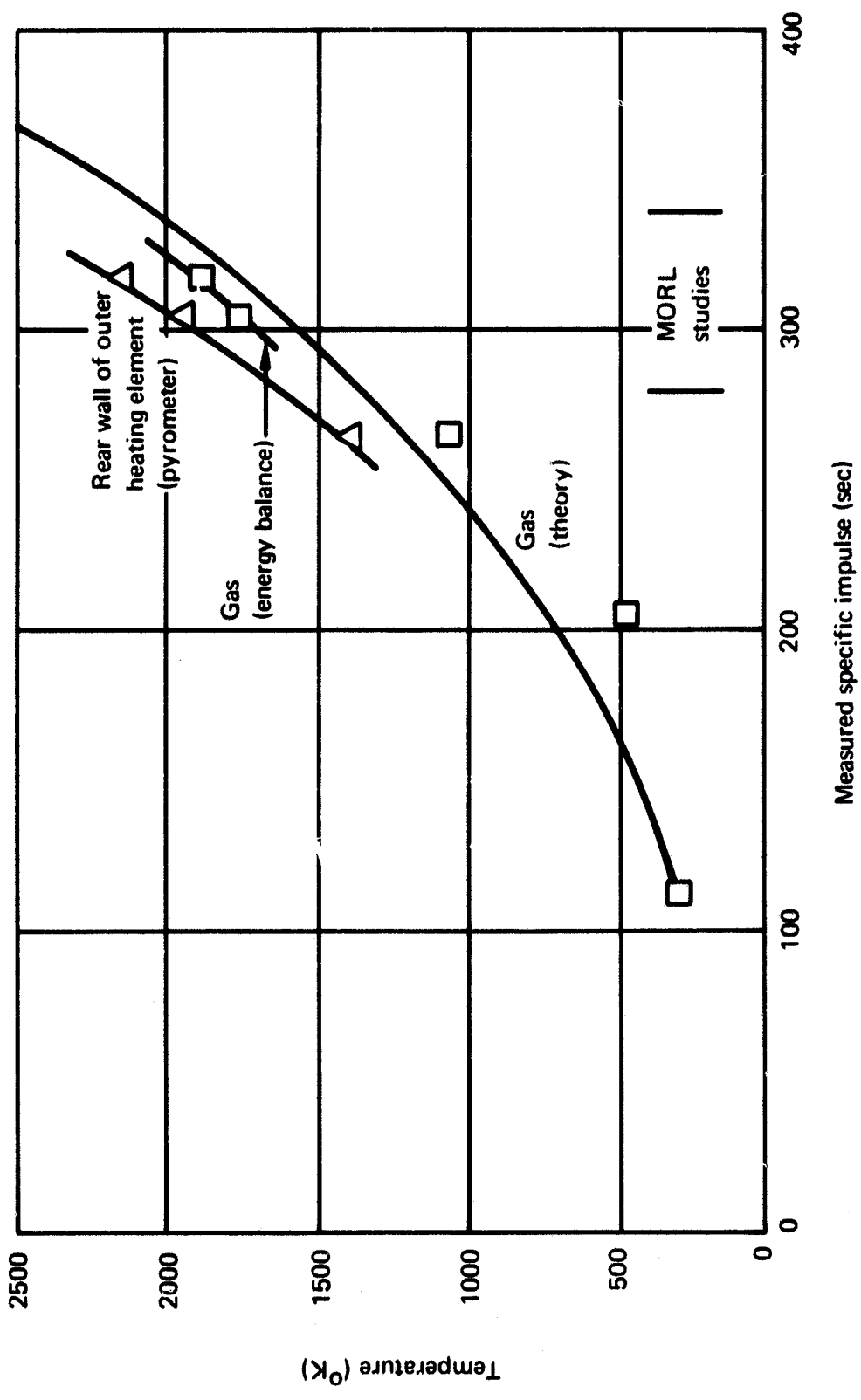


Figure 10. Temperature Comparisons with Theory - 10-mlbf Ammonia Resistojet

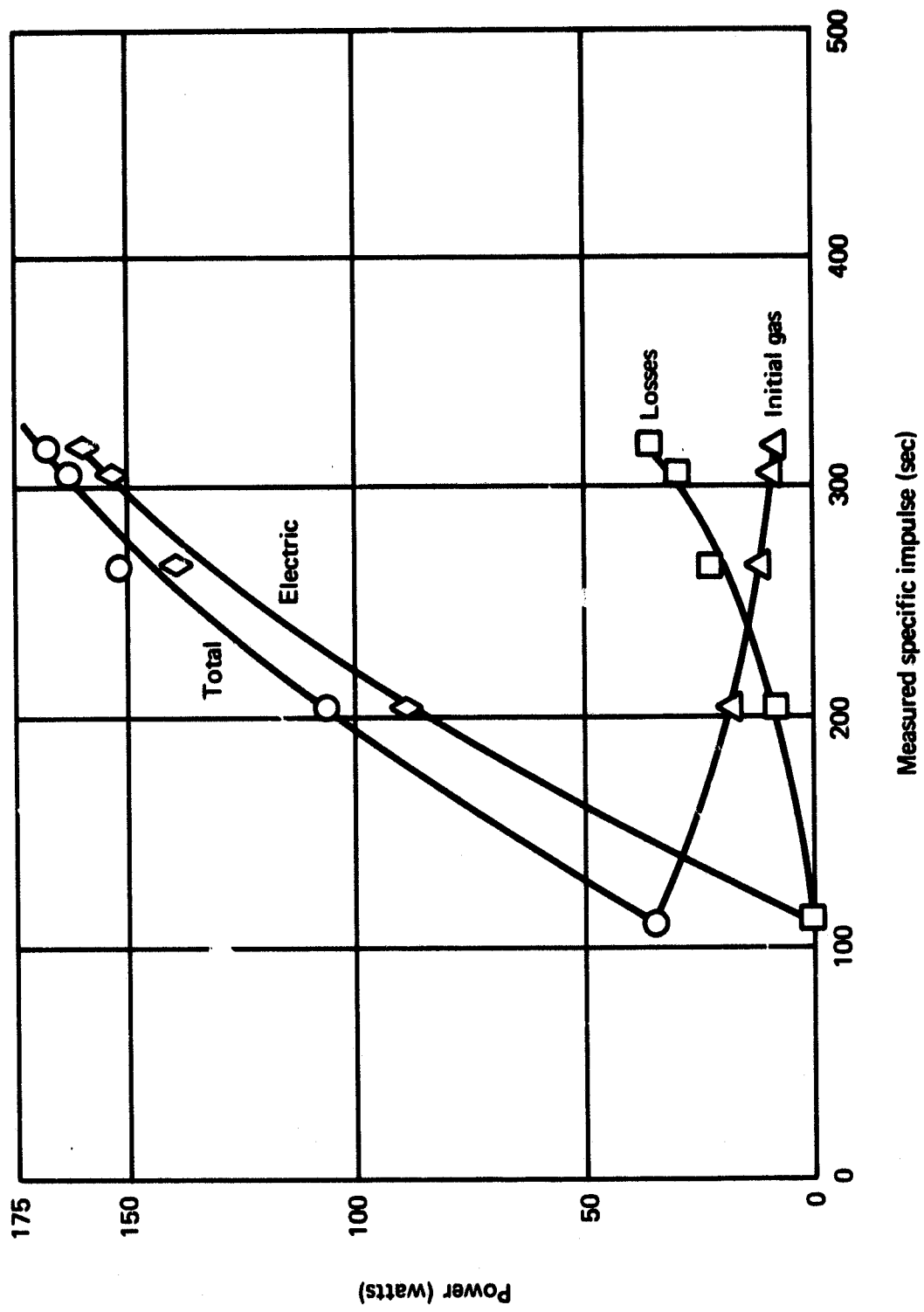


Figure 11. Power Summary – 10-mlbf Ammonia Resistojet

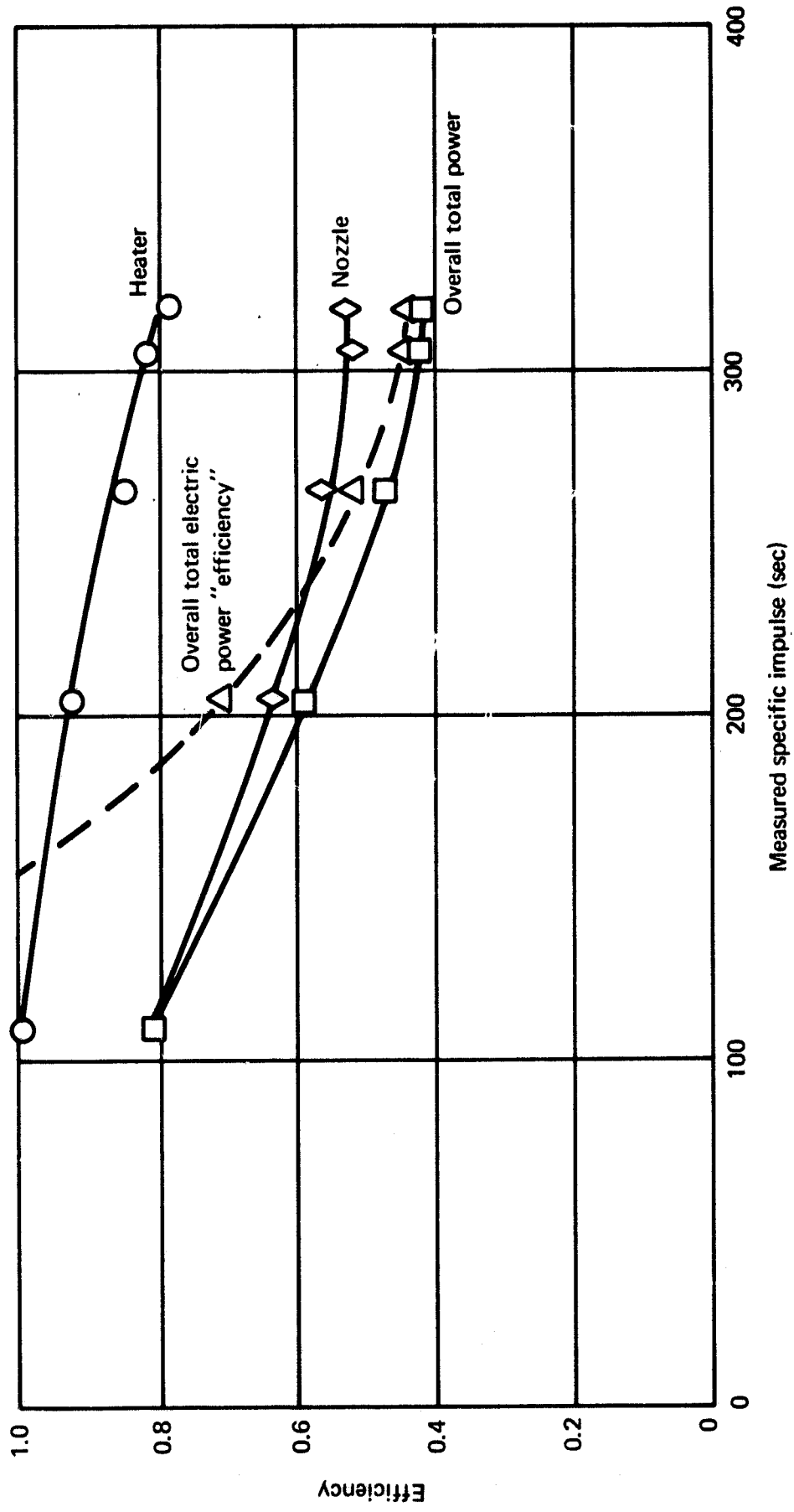


Figure 12. Efficiency Summary – 10-mlbf Ammonia Resistojet

approximately 80% and the nozzle efficiency $\sim 53\%$ giving an overall efficiency of about 42%. Better insulation could improve the heater efficiency to 95%. This, with the same nozzle performance, would produce an overall efficiency of approximately 50%. Electric power efficiency is a parameter often used in electric propulsion. However, since it does not take into account the power in the gas before it enters the resistojet, this parameter becomes infinite at zero electric power. (See Appendix A.) In effect, it is not a true efficiency.

Fig. 13 summarizes the temperature distribution through the thruster while operating on NH_3 . Note that the exterior envelope is relatively uniform at approximately 500°K .

Hydrogen. — The corresponding performance of the B-2 thruster on H_2 is summarized in the following figures. Fig. 14 shows the temperature comparison with theory as a function of measured specific impulse. Note that very small temperature differences are present from wall to gas (approximately 70°K). The deficiency in specific impulse (thrust) for the same gas temperature is due to cell pressure effect.

This reduced specific impulse as a function of cell pressure is better illustrated in fig. 15. A similar curve can be plotted for NH_3 . This effect was briefly discussed in ref. 1. The influence of cell vacuum pressure on a nozzle in the low Reynolds number regime is not currently understood. To gas dynamicists it is fundamental that no influencing pressure signal will propagate upstream in the fully expanded supersonic nozzle. Contrary to this, several investigators (refs. 1, 4 through 7) have recently found serious cell pressure effects both on thrust and throat performance at low Reynolds number (even at pressure ratios several orders of magnitude lower than that required to fully expand a nozzle in inviscid flow). As shown in fig. 15, the thrust performance suddenly and dramatically improves with reduced cell pressure. These data are currently limited to pressures above approximately 10 microns because of the capacity limitations of present pumping facilities. Very large pumping stations are required to pump these low molecular weight resistojet propellants a few orders of magnitude lower in pressure than this. It has been suggested by several investigators recently that cell pressures of the order of a tenth of a micron of mercury would be adequate to develop the theoretical performance of hydrogen as representative in space. Note that the performance is constant at cell pressures of the order of 60 microns and above for this particular H_2 data. This portion of the curve almost corresponds to the theoretical inviscid performance of a choked throat, that is no nozzle divergent section at all. Data taken on the life-test thrusters as a function of cell pressure show all the thrusters were essentially operating in this region. Substantial higher specific impulses would probably be attained in space. The performance uncorrected is still attractive compared to contemporary resistojets.

The electric power summary for H_2 is shown in fig. 16, and the corresponding efficiencies versus measured specific impulse are shown on fig. 17. Note that the heater efficiency of 92% and the relatively low thermal losses compared to the NH_3 case. Fig. 18 shows the temperature distribution summary. The envelope temperature is approximately 450°K . This is cooler than that for the NH_3 case.

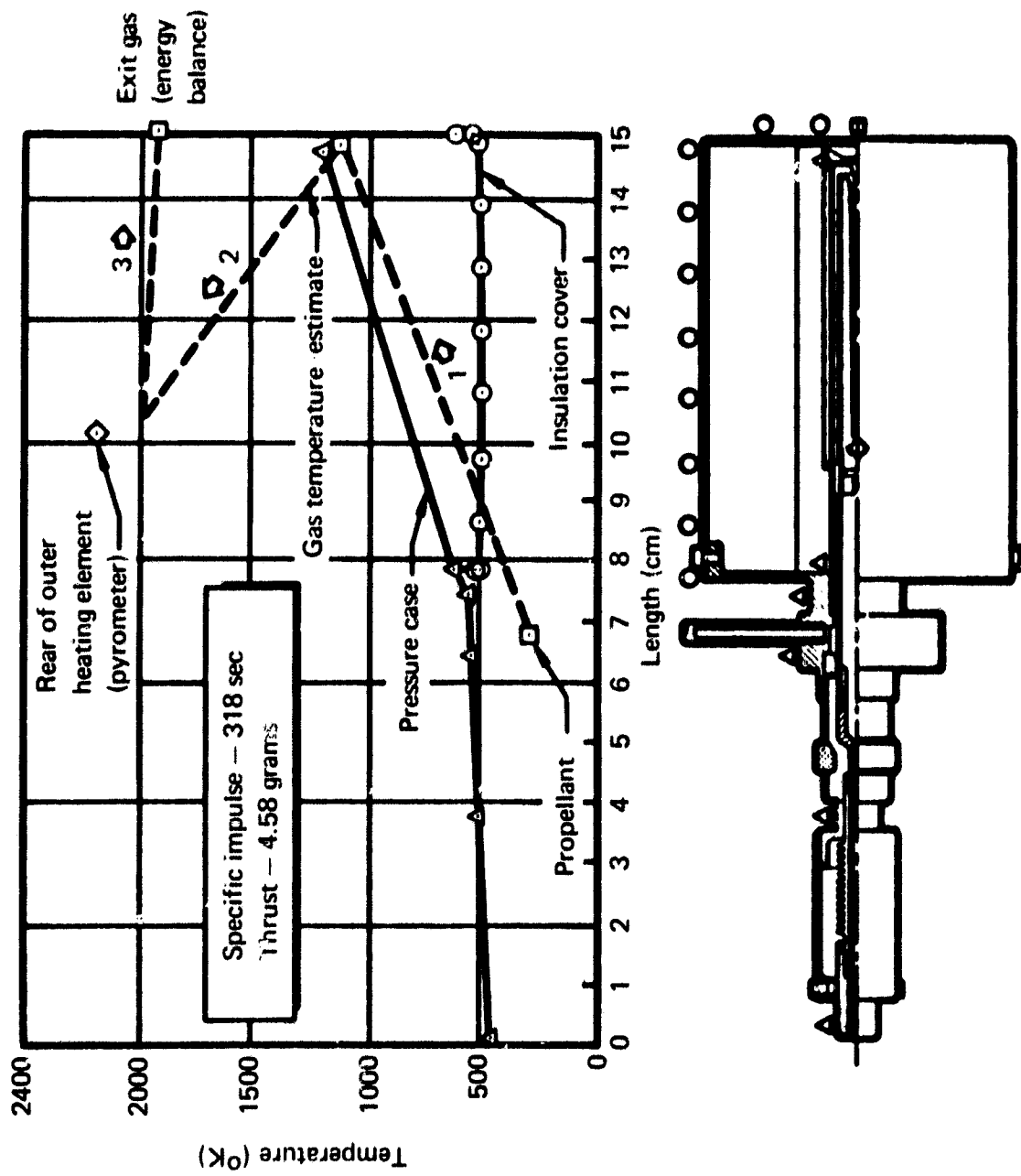


Figure 13. Temperature Distribution - 10-mibf Ammonia Resistojet

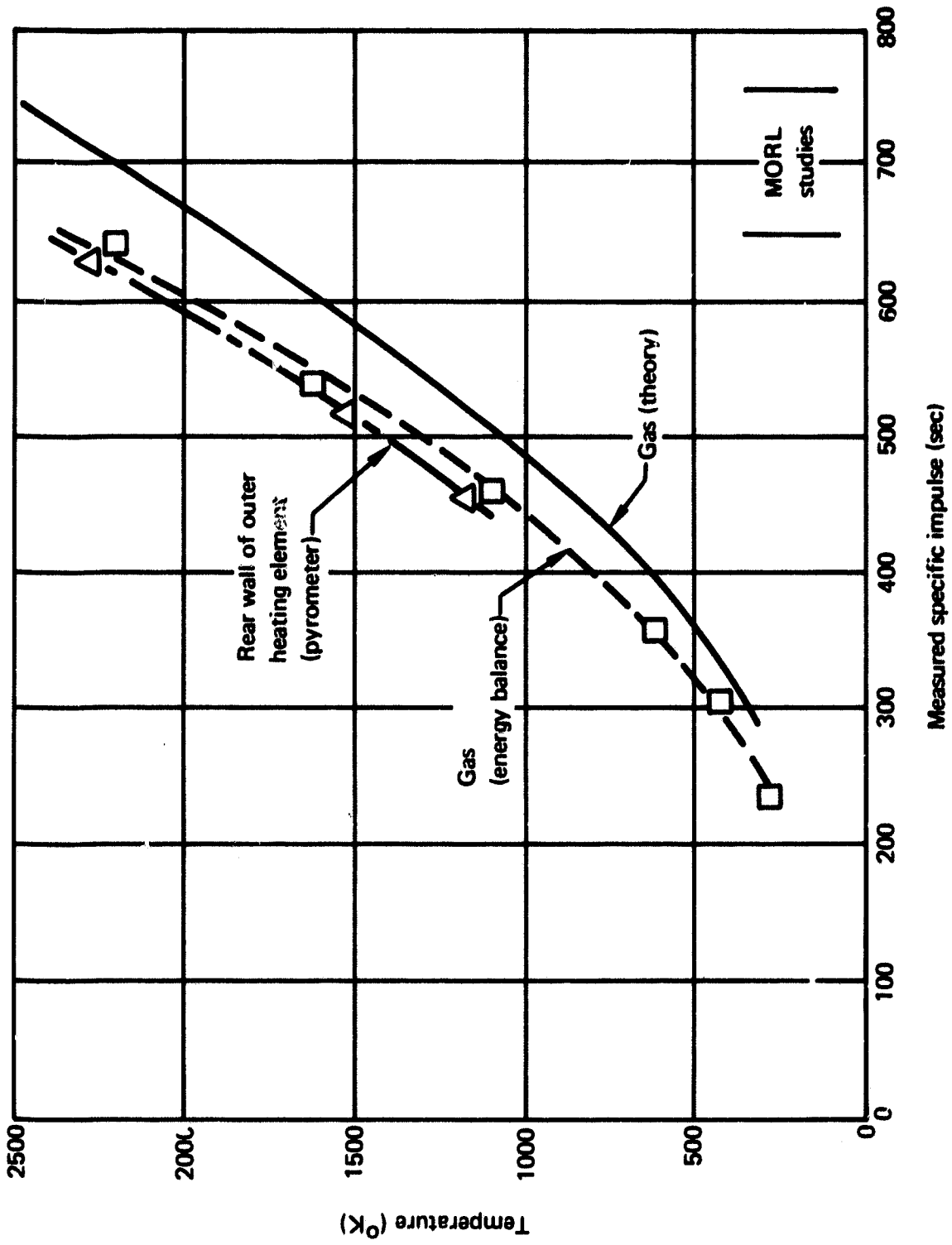


Figure 14. Temperature Comparisons with Theory - 10-milbf Hydrogen Resistojet

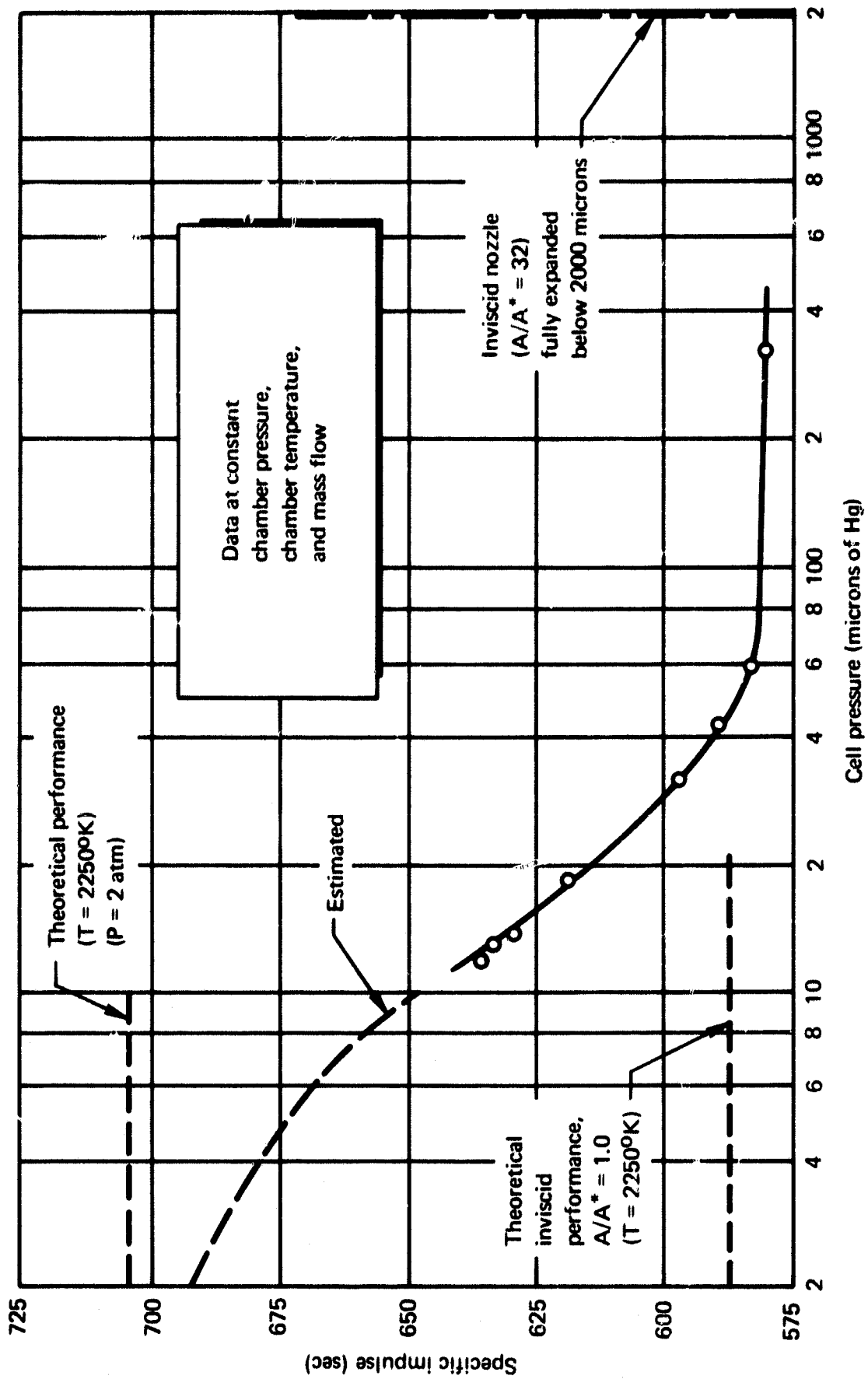


Figure 15. Cell Pressure Effect on Specific Impulse — Hydrogen

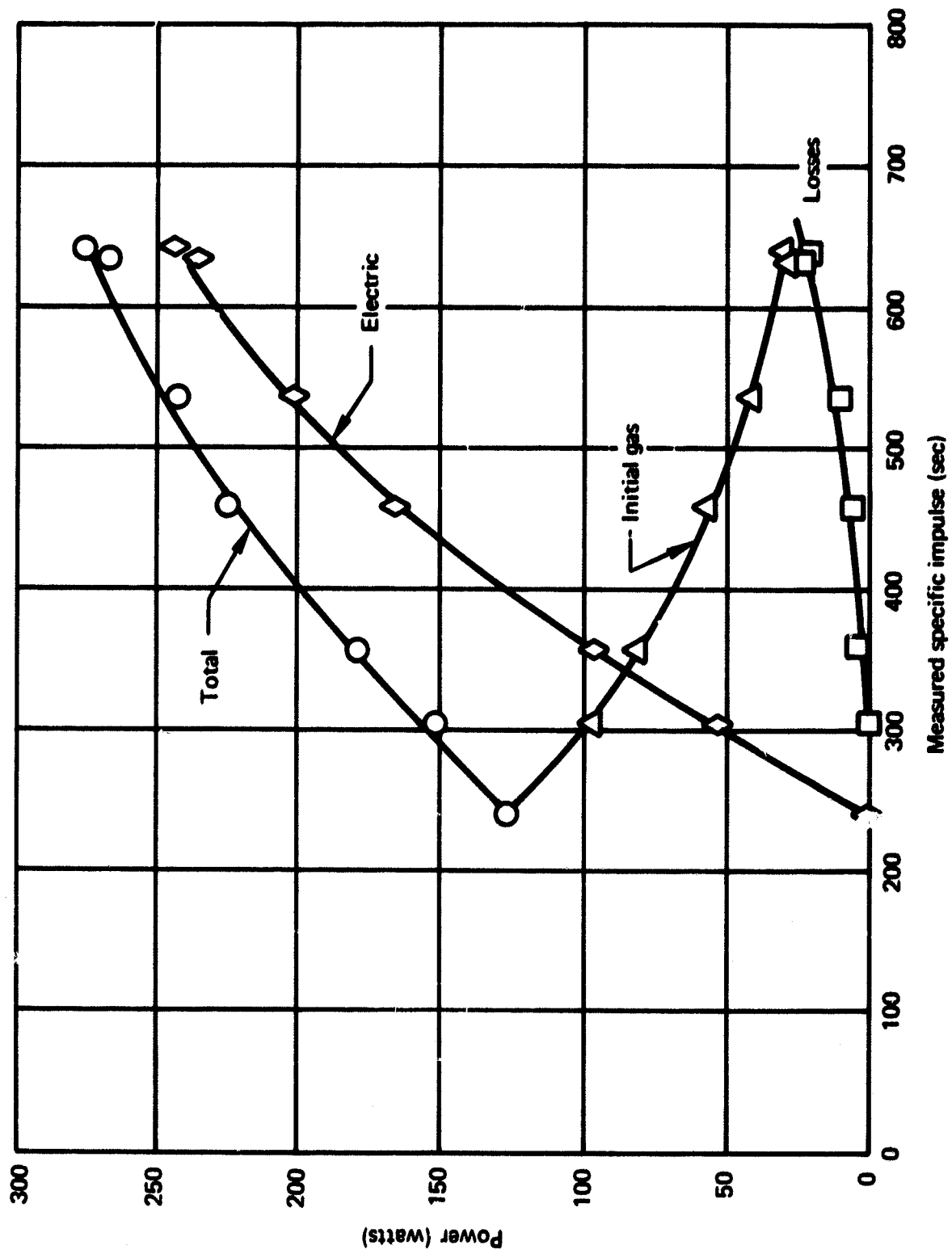


Figure 16. Power Summary -- 10-mlbf Hydrogen Resistojet

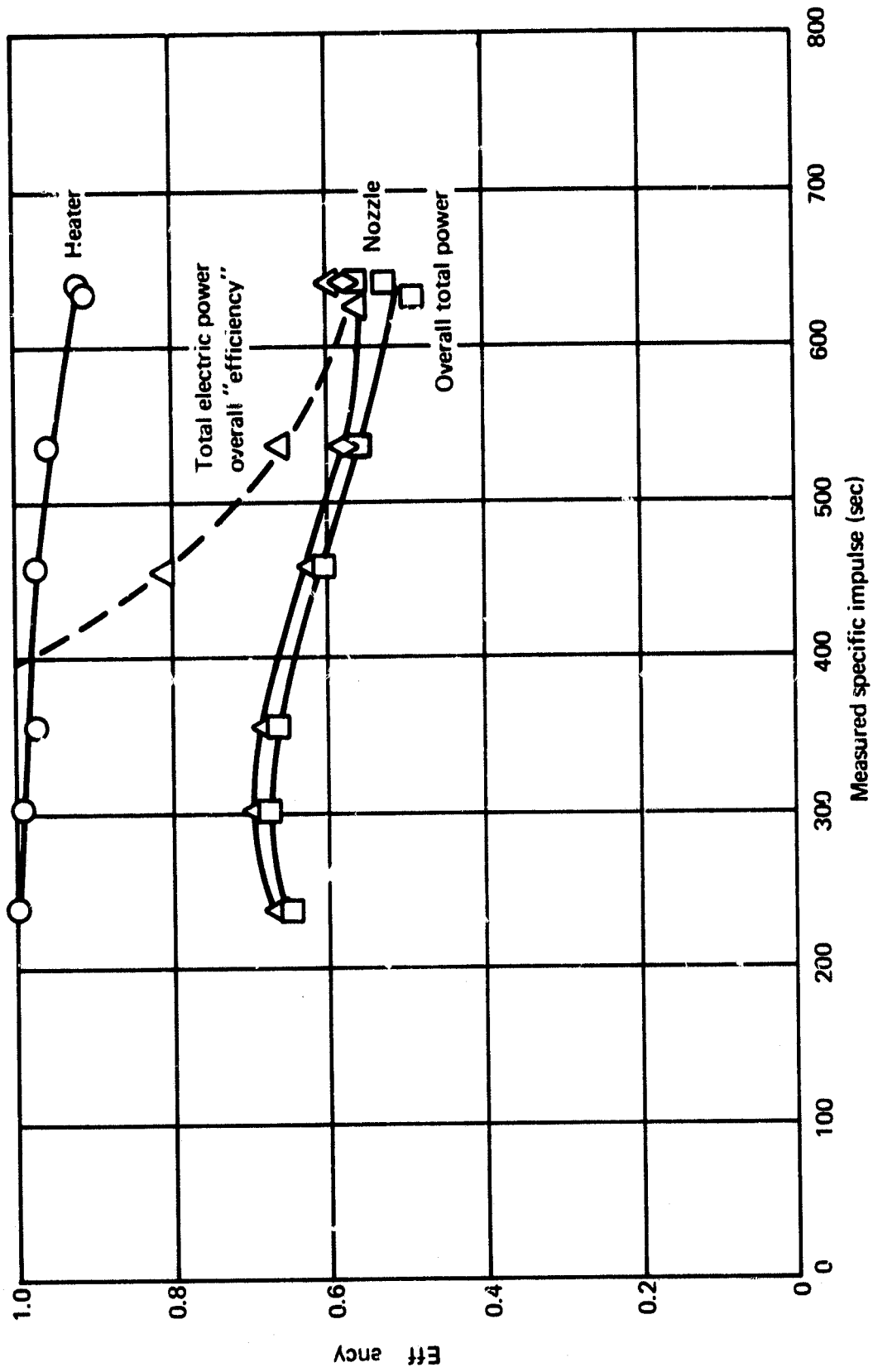


Figure 17. Efficiency Summary - 10-mbf Hydrogen Resistojet

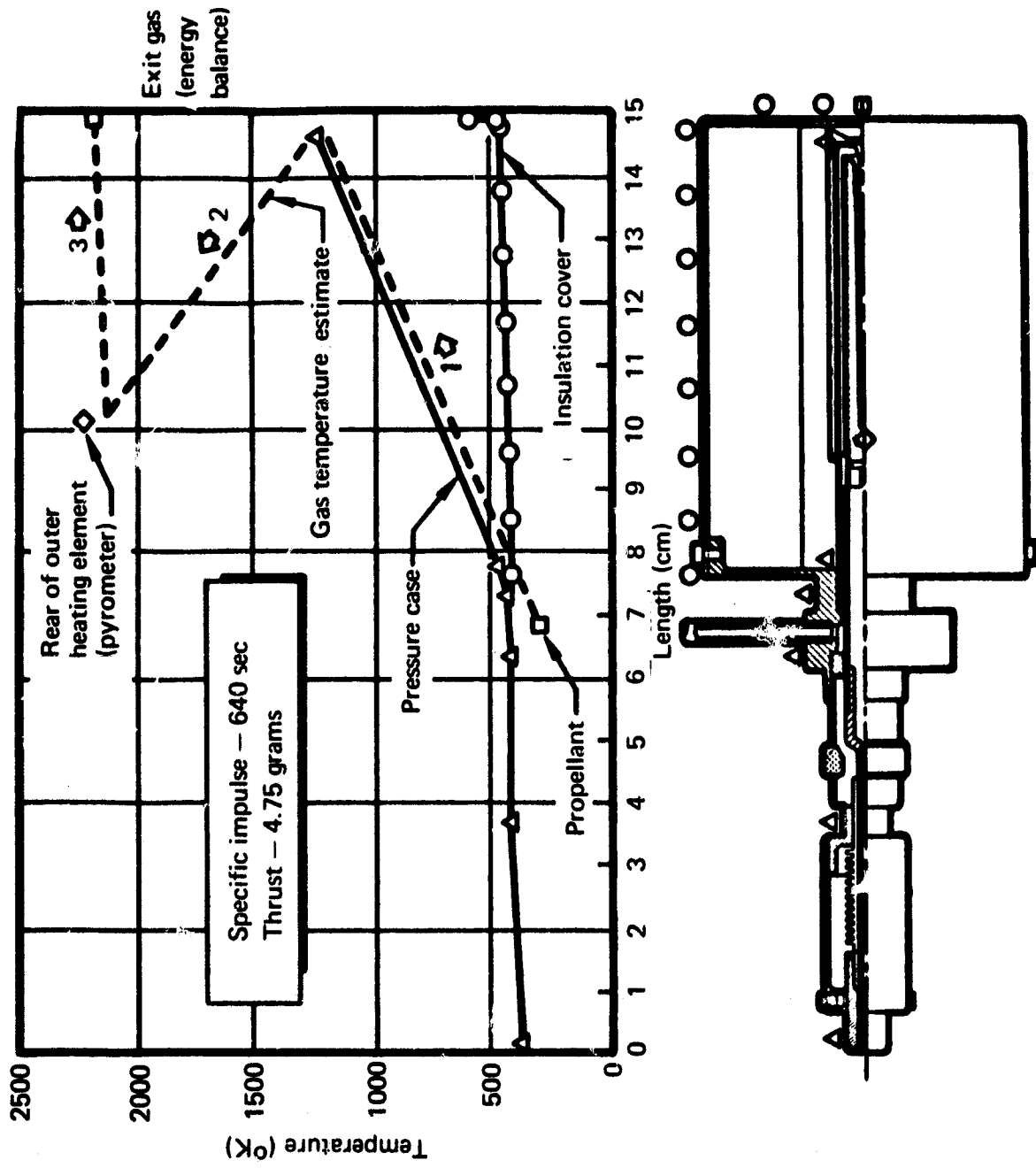


Figure 18. Temperature Distribution - 10-milbf Hydrogen Resistojet

The electrical characteristics of the 10 mlbf resistojet are unique. Fig. 19 shows the terminal voltage-current characteristics. Shown are radial lines from the origin representing the resistance both at design and half that of design. Also shown are lines of constant electric power. Two modes of thruster operation are shown plotted: (1) a constant-thrust mode in which the supply pressure is varied and (2) a constant-supply pressure mode which is the chosen mode for MORL. With an ideal gas, a constant chamber pressure implies constant thrust. The thruster, because of its particular size, operates in the turbulent regime as a cold jet and in the laminar regime, at design. The net effect is to cause the thruster characteristic to be multiple-valued with respect to design current.

For the constant-supply-pressure operating mode, the current limiter can not be set at design current, for the thruster will stop at the first stable operating point, namely, at half resistance of 0.075 ohms. The current limiter must be set above the peak current to avoid this "hang-up." A limiter set at 50A for H₂ has been found safe in life-test operation.

Life-Test Unit Calibration

The life-test thrusters and the B-2 (DVT) thruster were individually calibrated on NH₃ and/or H₂ as shown in table 7. These reference calibrations are shown in figs. 20 and 21 in terms of the parameters needed to evaluate endurance time accrual as given in table 6. Due to the difference in nozzle throat diameters there is a thrust level variation of from 4 to 5 g between the smallest and largest thrusters, based on NH₃ at 320 sec. Figs. 22 and 23 compare resistance and normalized power requirements per unit mass flow versus specific impulse, for ammonia and hydrogen, respectively.

TABLE 7
THRUSTER REFERENCE CALIBRATIONS

Thruster	Assignment	Calibration
S-1	H ₂	H ₂ , NH ₃
S-2	H ₂	H ₂
S-3	NH ₃	NH ₃
S-4	NH ₃	NH ₃
S-5	NH ₃	NH ₃ , H ₂
S-6	NH ₃	NH ₃
B-2 (DVT)	Spare	H ₂ , NH ₃

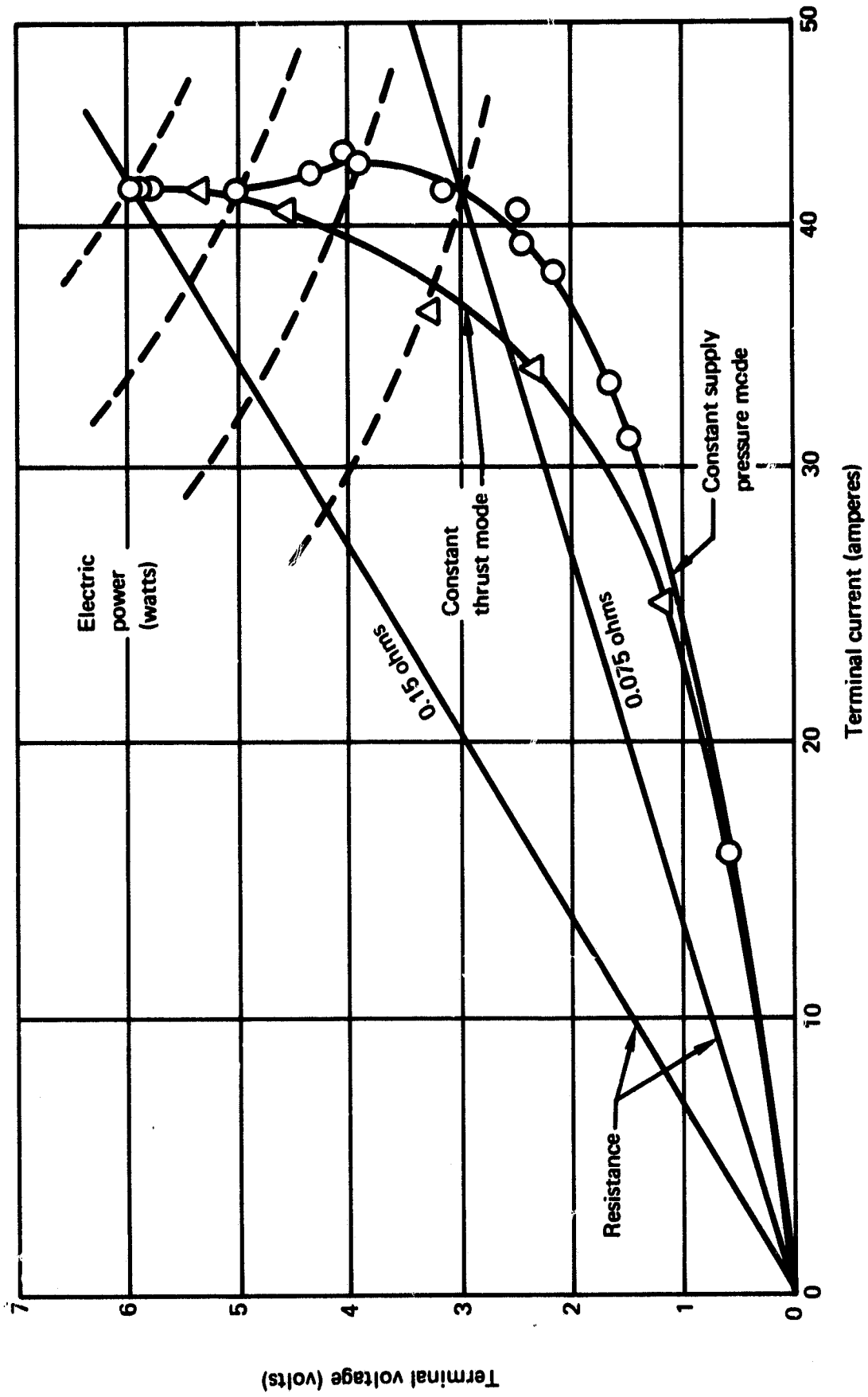


Figure 19. Electrical Characteristics - 10-mbf Hydrogen Resistojet

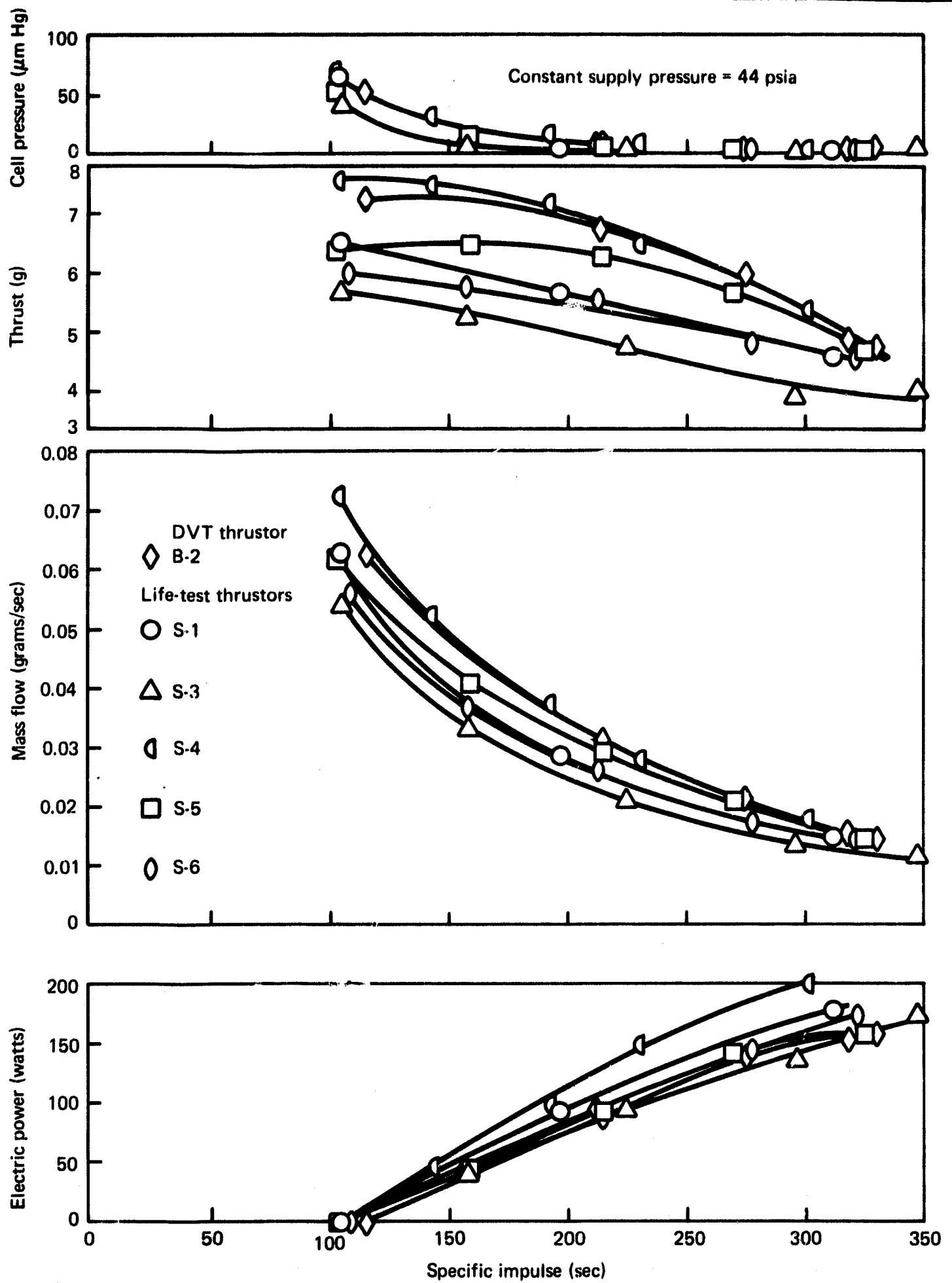


Figure 20. Performance Calibrations for Ammonia – Pretest Reference Conditions

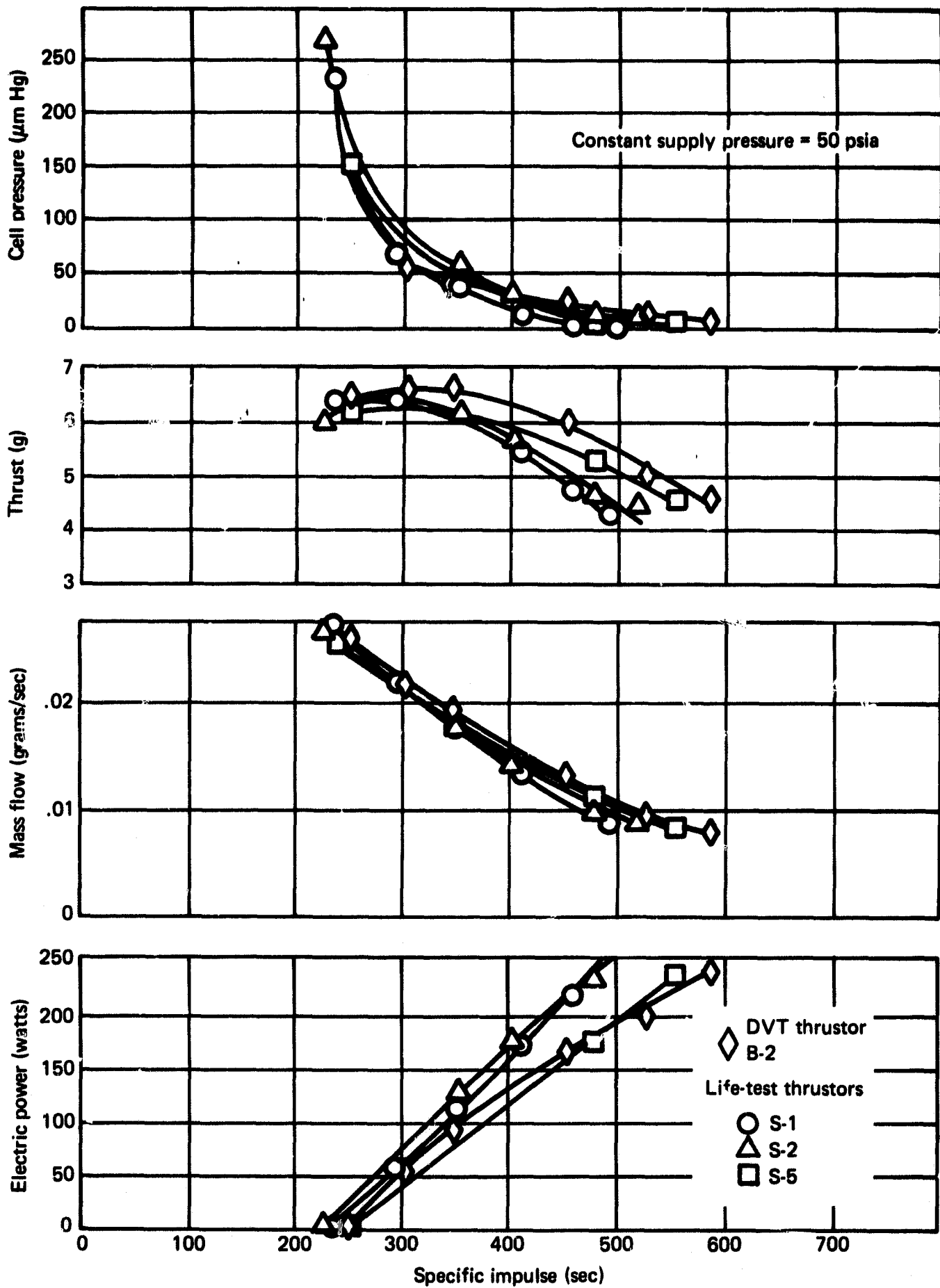
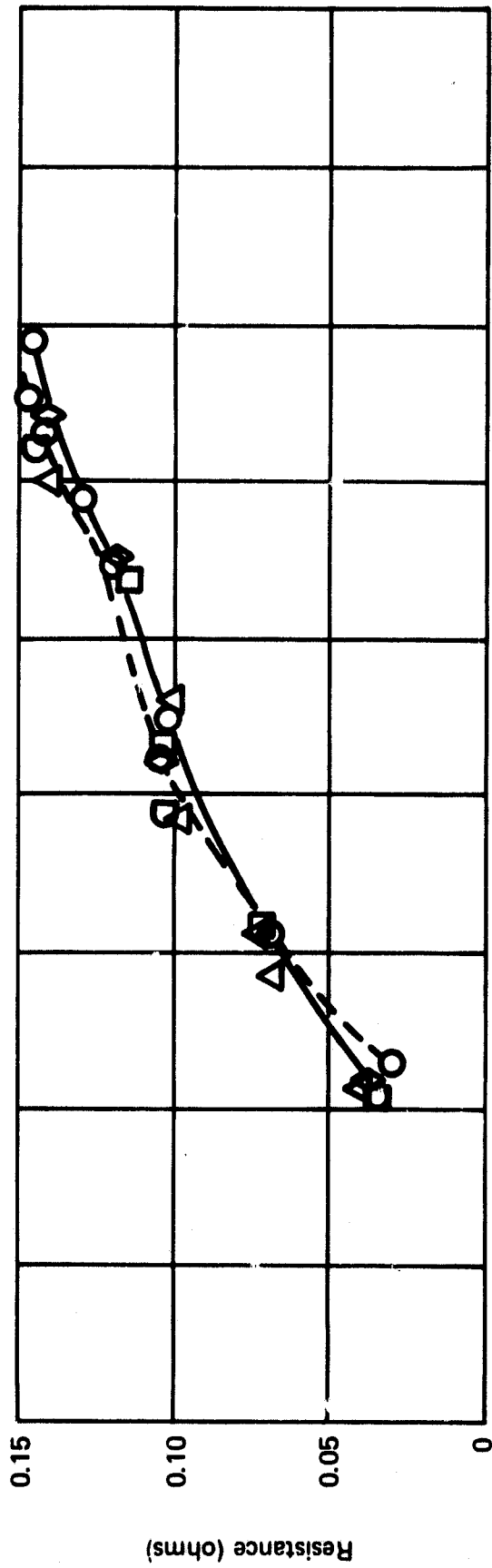
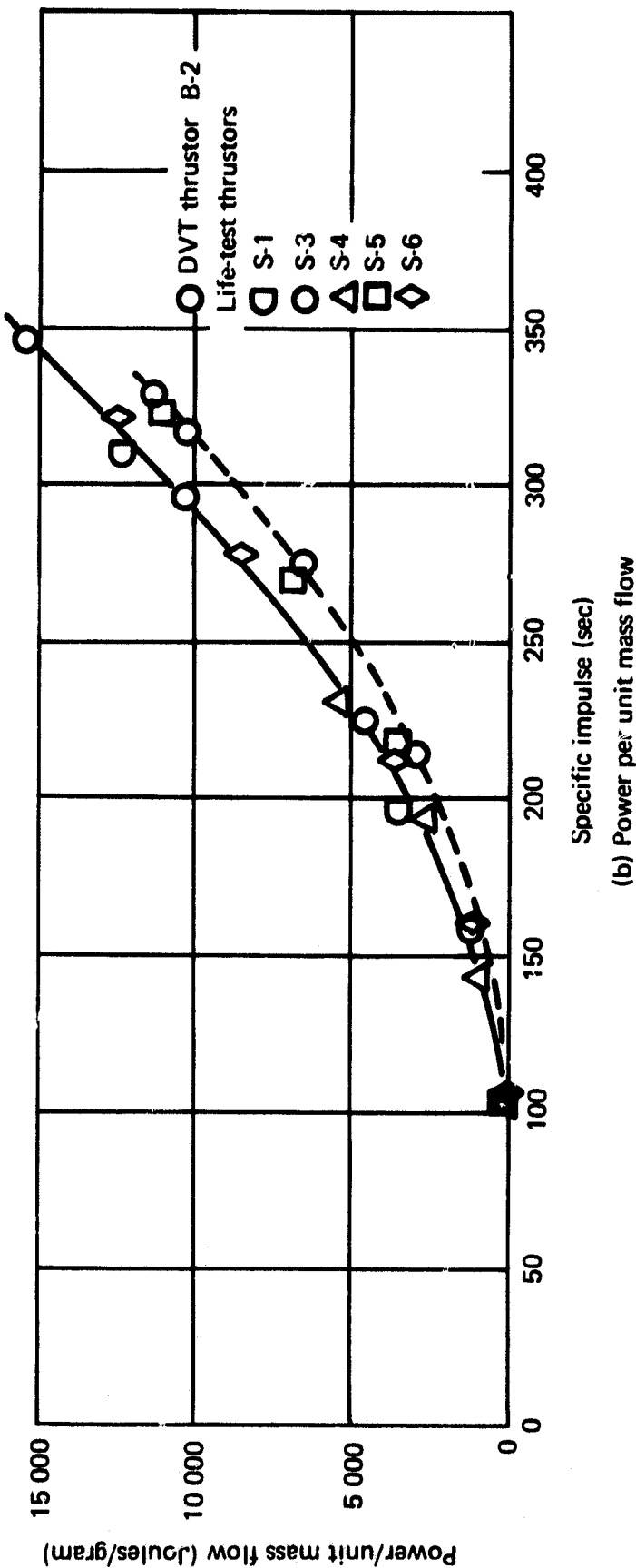


Figure 21. Performance Calibrations for Hydrogen – Pretest Reference Conditions



(a) Terminal resistance



(b) Power per unit mass flow

Figure 22. Calibration Characteristics — Ammonia

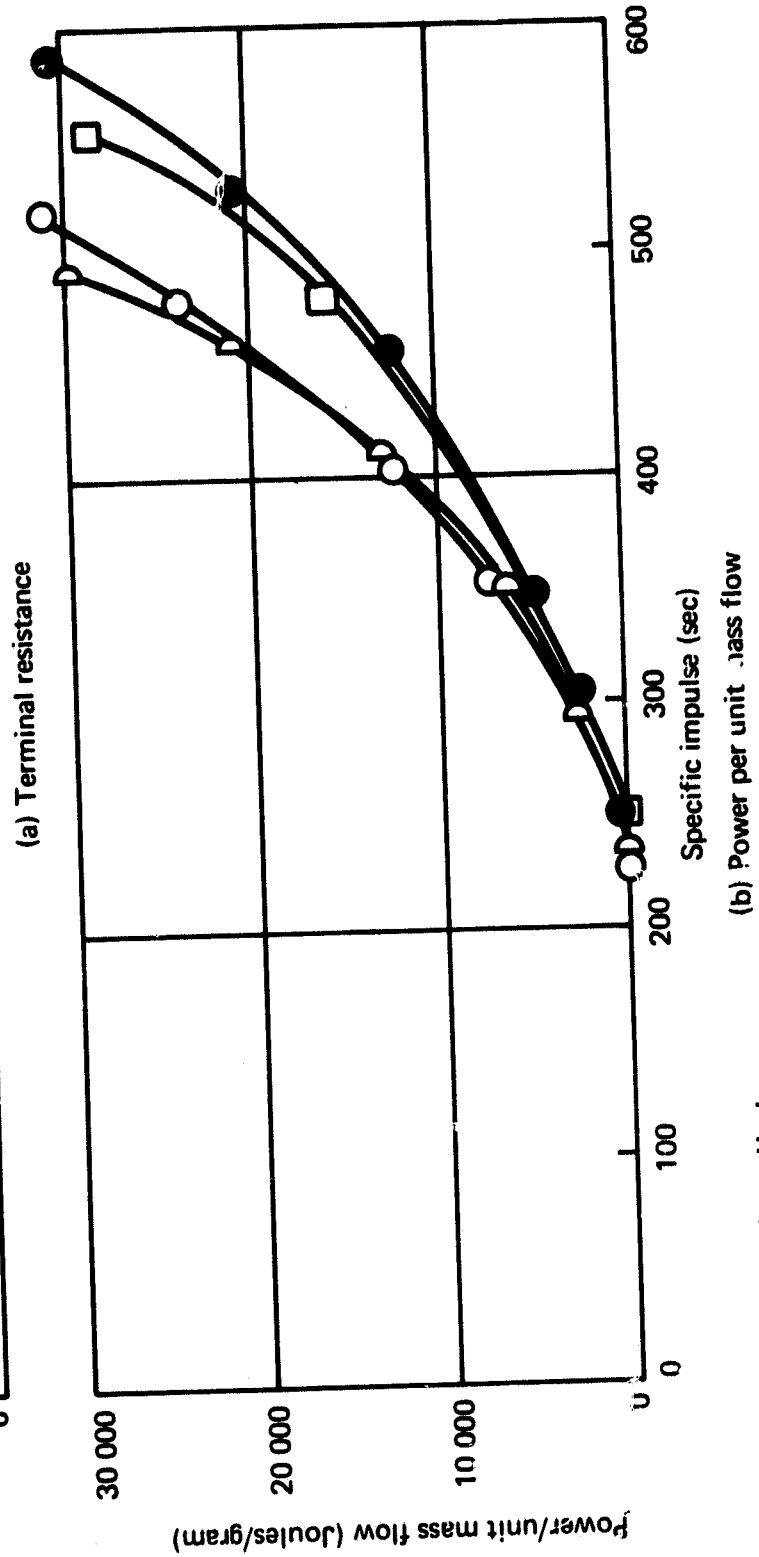
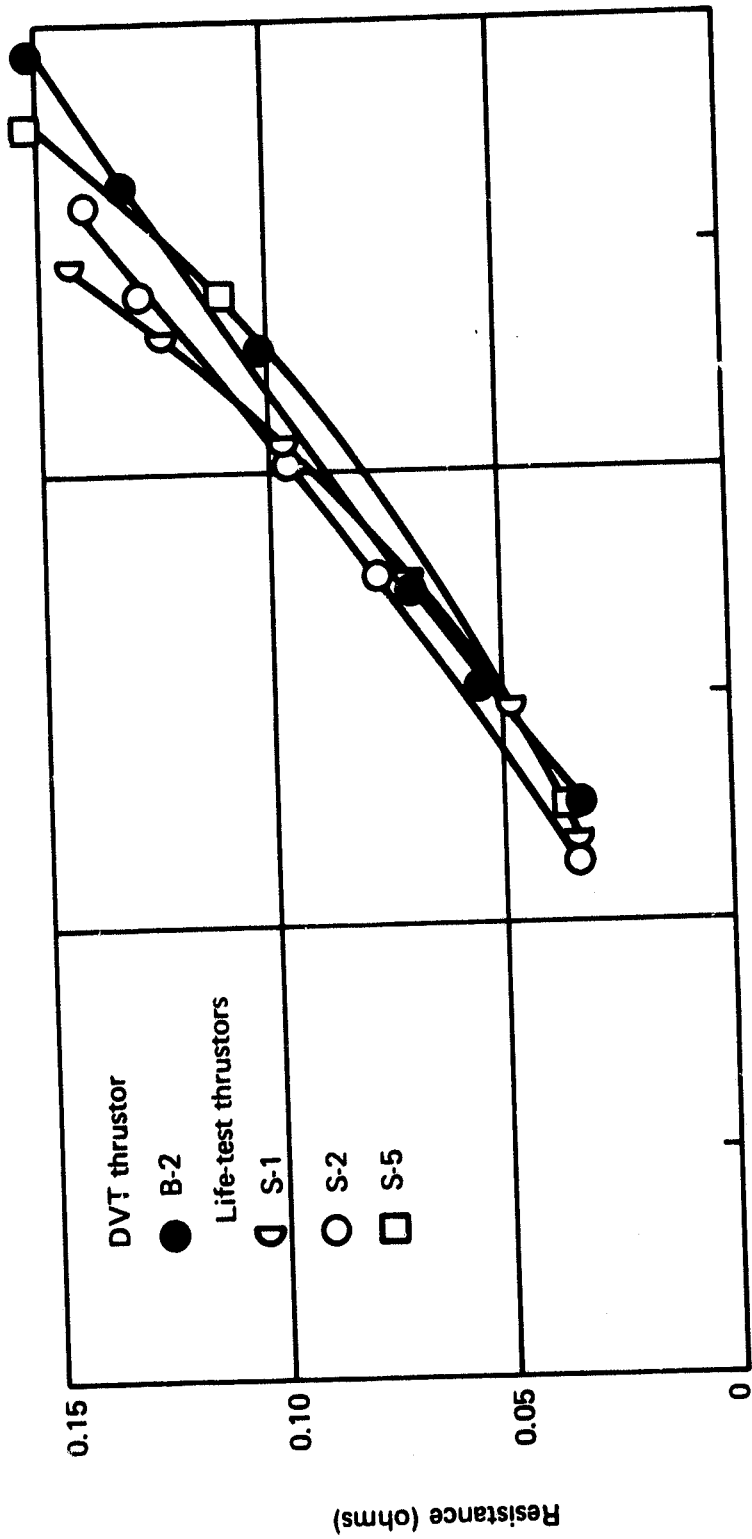


Figure 23. Electrical Calibration Characteristics -- Hydrogen

RESULTS AND DISCUSSION

Since the life of the thrusters is much greater than the 720-hour period of the test reported here, little can be said about life-governing mechanisms, performance changes with time, and the other purposes of the test. These things must await the results of the extended test, covering an additional period of 7200 hours under Contract No. NAS1-8090.

The life-test data are completely presented in the tables in Appendix B.

All thrusters completed the 720-hour period successfully under the conditions of the test plan, with one deviation. The H_2 engines were operated at the same wall temperature as the NH_3 units instead of the specific impulse value as prescribed by fig. 9. Temperature was verified both by pyrometer measurements of the outer heater element wall (Part No. 3) and by the operational terminal resistance values. The defect in specific impulse is attributed to cell pressure effect. This does not explain a further decrement in performance of the S-1 thruster below what would be accounted for by cell pressure. A slight leak from the thruster system could account for the set of symptoms observed. Such a leak might not have appeared until the thruster had experienced high temperature operation.

The NH_3 thrusters met the specific impulse objectives of the test on a measured basis. This means that, in terms of space specific impulse performance, the NH_3 units were subjected to and passed a much more severe test than planned. It is believed that a measured specific impulse value of 320 sec corresponds to at least 360 sec in space. Again, this has yet to be verified.

Thermal Expansion Compensator Performance

A phenomenon was observed on a small number of the starts on the H_2 units, which is believed to be the short circuiting of the inner to the outer element. The effect was evidenced by the thruster operating in the current control mode. For example, the voltage and current would be, say, 3.5 V and 53 A and then change to 5.6 V and 41 A, near design values. With a current limiting power controller, this posed no serious problem. The power input during this condition was approximately 80% of design. This condition could last from seconds to minutes. With the fault clearing, the unit would quickly proceed to design power. The thrusters always produced at least design thrust during the whole propellant on-period. The only disadvantages to this operation were slightly greater mass flow during the fault and possibly a reduction in life ultimately.

The problem is believed caused by the fact that these H_2 units had the lowest bellows' spring rates of the set in combination with the highest propellant supply pressure, that is, 50 psia compared to 44 psia for NH_3 .

(See table 8 for the bellows summary.) The purpose of the bellows is to allow axial differential thermal expansion (ref. 1) but still provide a spring force nulling the pressure-area force. An unbalance in force causes creep of the inner element.

Three recommendations to eliminate this phenomenon are (1) to increase the i.d. of the inner heating assembly from 0.031 in. to 0.041 in., which raises the section modulus substantially, hence, column strength, (2) to increase the minimum annulus clearance between the heater parts (Part Nos. 3 and 4) from 0.012 in. to 0.022 in., and (3) to increase quality control on the bellows (Part No. 20) by checking the extension under design pressure in addition to separately verifying that the spring rate is within tolerance.

Performance Change with Time

No direct measurements of sublimation can be made till test termination. The two indirect measurements of cold resistance and throat size however are useful in making some inferences.

Terminal resistance. - Table 9 summarizes (cold) resistances made after some duration running on May 10, 1968 during a facility shut down for vacuum station repairs.

TABLE 8
BELLOWS CHARACTERISTICS

Thrustor	Spring rate (lbf/in.)
S-1	112
S-2	110
S-3	117
S-4	117
S-5	112
S-6	114
Nominal effective area 0.030 in. ² (0.194 cm ²)	
Nominal spring rate 120 lbf/in. (2.10 x 10 ⁴ N/m)	

TABLE 9
TERMINAL RESISTANCE

Thruster	Start	First measurement	
	Resistance (Ω)	Elapsed time (hours)	Resistance (Ω)
S-1	0.034	688	0.0514*
S-2	0.034	458	0.0235*
S-3	0.0338	758	0.0331
S-4	0.0339	770	0.0332
S-5	0.0361	761	0.0649*
S-6	0.0364	774	0.0332

*See discussion.

The resistances of three of the units S-3, S-4, and S-6 showed no change. The H₂ units S-1, S-2, because of the aforementioned difficulties appeared to have changed. Thruster S-1 increased resistance, and S-2 was in the short mode (cold). These units have been run substantially since. The operating characteristics of S-1 and S-5 do not seem to reflect such a change, so these later resistance data values are of low confidence.†

Throat size. — Cold-flow measurements are taken as a means of checking the effective area of the throat, nozzle performance, and leakage. Table 10 compares the mass flow, thrust, and specific impulse at the test beginning on March 28, 1968 and later on May 10, 1968. Thrusters S-1, S-3, and S-4 compared closely in both mass flow and cold thrust, indicating no change in throat size or cold flow performance. Thrusters S-5 and S-6 compared reasonably well (4%) before and after in specific impulse.

The throat would appear to have closed down on S-5 and open on S-6 even though the temperatures were comparable. These data may be explainable by the fact that difficulty has been experienced in the past with back-streaming ring-jet booster oil depositing in the nozzle after a short unfired period in the cell. This has been verified by running a properly sized drill blank through the throat and immediately repeating the cold flow check. This technique was not done for any of the data of table 10.

The behavior of S-2 is unexplainable till it is ultimately sectioned in post-test analysis.

† Later extended test measurements agree with the start resistances.

TABLE 10
COLD-FLOW MEASUREMENTS

Thruster (gas)	Elapsed time (h)	Mass flow (g/sec)	Thrust (g)	Specific impulse (sec)
S-1 (H ₂)	0	0.0271	6.41	237
	667.8	0.0263	6.34	241
S-2 (H ₂)	0	0.0265	6.33	227
	455	0.0126 [†]	2.79	221
S-3 (NH ₃)	*0	0.0540	5.66	105
	759.4	0.0547	5.82	106.4
S-4 (NH ₃)	*0	0.0722	7.54	104
	770.4	0.0724	7.54	104.1
S-5 (NH ₃)	*0	0.0618	6.39	103
	760.8	0.0515	5.46	106
S-6 (NH ₃)	*0	0.0557	5.99	108
	774.2	0.0635	6.58	103.7

*Not previously fired.

† Later extended test measurements discovered this effort to be caused by a partially clogged propellant line in the dynamometer propellant array.

CONCLUDING REMARKS

The life-test thrusters were the first of this type built in any quantity. In spite of the fact that they were hand built in an experimental model shop, without the advantage of carefully developed tooling or the quality control procedures such as that in force on the production of R4-D thrusters (Marquardt Apollo), the test was successful in establishing feasibility. Quality control and assurance, during production though, can give closer thrust level reproducibility.

The 720-hour life test, which culminates for this contract the resistojet development effort, has demonstrated that high performance ($\sim 2400^{\circ}\text{K}$) resistojets built of rhenium are feasible for hydrogen and ammonia propellants.

All six thrusters completed the test according to the plan with minor deviations. The test duration was insufficient to evaluate the life, life-governing mechanisms, cycling effect, or performance changes with time. These tests, fortunately, have been extended and are in process at the time of this report to answer these test objectives.

Electrical shorts can occasionally occur up to minutes on some thrusters during starting but do not appear to result in permanent damage or interrupt its thrust function. With minor dimensional changes and additional quality assurance during fabrication, this phenomenon can be eliminated.

At least half the thrusters had extremely stable electrical characteristics and throat dimensions over the period of the test.

The specific impulse values associated with these tests are extremely conservative because of inadequate cell pressure to demonstrate space performance. To verify this, it is recommended that these units should be tested in a vacuum of less than $0.1 \mu\text{m Hg}$.

The thrust variation between thrusters shows that improved quality control is required in throat sizing. Optical comparison of nozzle throats and cold flow thrust measurements prior to assembly are recommended.

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APPENDIX A

DEFINITIONS OF PERFORMANCE PARAMETERS

Specific impulse, I_{sp} , sec

$$I_{sp} \triangleq \frac{F}{\dot{m}} \quad (1)$$

where

F = measured thrust by dynamometer, g_f (a)

\dot{m} = propellant mass flow, g/sec (b)

Electric power to terminals, P_e , W

$$P_e = E_t \times I_t \quad (2)$$

E_t = electric voltage difference between thruster terminals, V (c)

I_t = electric current passing between terminals, A (d)

Supply pressure, p_s , atmospheres

p_s = propellant pressure measured at a tee fitting at entrance to thruster. (e)

NOTE: Chamber pressure is not directly measured but is inferred from nozzle throat continuity calculations.

Efficiency - electric power overall, η_o^*

$$\eta_o^* \triangleq \frac{F \times I_{sp}}{20.8 P_e} \quad (3)$$

Efficiency - total power overall, η_o

$$\eta_o \triangleq \frac{F \times I_{sp}}{20.8 (P_e + P_i)} \quad (4)$$

Initial power in gas, P_i , W

$$P_i = \dot{m} h(4,186)$$

h = enthalpy of an ideal gas above absolute zero, °K, cal/g (as documented in JANAF Thermochemical tables, The Dow Chemical Company, Midland, Michigan) (f)

Power in the jet, P_j , W

$$P_j = P_e + P_i - P_l \quad (6)$$

P_l = heat lost from the thruster prior to the exhaust jet, W (g)

NOTE: Δ means "definition"

Heater efficiency, η_H

$$\eta_H \Delta \frac{P_j}{P_e + P_i} \quad (7)$$

Nozzle efficiency, η_N

$$\eta_N = \frac{F \times I_{sp}}{20.8 P_j} \quad (8)$$

or

$$\eta_N = \frac{\eta_o}{\eta_H} \quad (9)$$

APPENDIX B

The tables B-1 through B-6 contain the life-test data summary obtained during the 720-hour test period for thrusters S-1 through S-6, respectively. All values shown are measured from test instrumentation, with the exception of specific impulses (measured) which was obtained from the thrust and propellant flow rate.

TABLE B-1
LIFE-TEST DATA SUMMARY - S-1 HYDROGEN THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
1017*	---	0	0	0	---	6.41
1018*	---	1.650	34.0	56.7	0.0485	6.41
1019*	---	2.770	39.6	109.7	0.0699	6.12
1020*	---	4.069	41.9	170.5	0.0971	5.44
1021*	---	5.149	41.7	214.7	0.1235	4.71
1022*	---	6.089	42.7	260.0	0.1426	4.27
1023†	---	0	0	0	---	6.52
1024†	---	3.094	30.2	93.4	0.1025	5.64
1025†	---	5.074	35.2	178.6	0.1441	4.58
1026	15.0	5.619	41.9	235.4	0.1341	---
1027	34.6	5.649	42.1	237.8	0.1342	4.56
1028	50.4	5.629	41.9	235.9	0.1343	---
1029	58.4	5.299	41.9	222.0	0.1265	---
1030	73.8	5.327	42.3	225.3	0.1259	4.81
1031	117.4	5.239	41.9	219.5	0.1250	---
1032	134.6	5.299	41.9	222.0	0.1265	4.50
1033	159.6	5.519	41.9	231.2	0.1317	---
1034	176.8	5.495	42.0	230.8	0.1308	4.53
1036	209.8	5.459	41.9	228.7	0.1303	5.12
1037	283.8	5.579	41.9	233.8	0.1332	---
1038	298.6	5.569	42.3	235.6	0.1317	---
1039	324.4	5.569	41.9	233.3	0.1329	5.46
1040	342.0	5.599	42.1	235.7	0.1330	---
1041	365.2	5.452	41.9	228.4	0.1301	4.52
1042	434.6	5.559	40.5	225.1	0.1373	4.52
1043	458.4	5.599	40.6	227.3	0.1379	---
1044	479.4	5.620	40.5	227.6	0.1388	4.54
1045	481.6	5.605	40.5	227.0	0.1384	4.54
1046	503.8	5.653	39.5	223.3	0.1431	---

*Calibration, H₂/†Calibration, NH₃

TABLE B-1 (Continued)
LIFE-TEST DATA SUMMARY - S-1 HYDROGEN THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m H _g)	Temperature (°C)		
					Case	Cover	Mount
0.0271	237	50.00	24.65	235	22	23	26
0.0217	295	50.00	25.15	70	70	32	27
0.0174	352	50.00	25.37	42	120	48	30
0.0132	412	50.00	25.60	17	202	69	34
0.0102	460	50.00	26.24	6.1	365	100	39
0.0087	493	50.00	26.69	4.0	926	168	44
0.0628	104	44.00	25.97	64	34	51	46
0.0287	197	44.00	25.53	4.3	327	86	39
0.0147	312	44.00	25.28	1.3	1020	201	46
0.0094	---	50.00	24.98	70	566	151	63
0.0094	485	50.00	25.81	13	593	152	66
0.0094	---	50.00	25.20	88	590	151	64
0.0102	---	50.30	25.70	88	415	140	60
0.0101	477	50.60	26.04	13	426	143	63
0.0102	---	50.30	26.48	88	405	140	61
0.0101	446	50.60	25.68	8.7	426	142	63
0.0096	---	50.20	26.00	74	538	156	67
0.0097	469	50.50	26.48	10	506	147	65
0.0094	542	49.80	24.94	8.2	550	170	73
0.0094	---	50.30	23.91	74	561	152	63
0.0092	---	50.20	23.95	75	559	155	65
0.0094	584	50.40	25.00	8.8	579	110	70
0.0094	---	50.18	23.60	77	602	160	68
0.0092	490	50.00	23.76	11	537	138	53
0.0091	500	50.00	25.41	7.5	624	149	64
0.0093	---	50.00	26.20	74	583	158	68
0.0091	502	50.00	24.96	70	592	154	66
0.0091	499	50.00	25.02	8.2	590	158	67
0.0094	---	50.00	24.90	67	550	158	72

TABLE B-1 (Continued)
LIFE-TEST DATA SUMMARY - S-1 HYDROGEN THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
1047	524.2	5.629	40.5	228.0	0.1390	4.55
1048	593.4	5.579	40.8	231.7	0.1392	4.51
1049	620.8	5.639	40.8	230.1	0.1382	---
1050	644.6	5.602	40.7	228.0	0.1376	4.54
1051	663.2	5.591	40.4	225.9	0.1384	---
1052	665.6	5.689	39.9	227.0	0.1426	4.52
1053	666.0	5.571	40.2	224.0	0.1386	4.74
1054	666.6	5.669	40.3	228.5	0.1407	4.69
1055	667.2	5.744	41.0	235.5	0.1401	4.68
1056	667.8	0	0	0	---	6.34
1057	689.0	5.758	41.0	236.7	0.1401	---
1058	709.6	5.725	40.4	231.3	0.1417	4.45
1059	780.0	5.659	41.3	233.7	0.1370	4.45

TABLE B-1 (Concluded)
LIFE-TEST DATA SUMMARY - S-1 HYDROGEN THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0092	494	49.98	24.95	8.6	569	153	66
0.0090	500	50.00	24.83	8.4	605	162	71
0.0093	---	50.00	24.37	67	600	159	70
0.0089	509	50.00	24.18	9.2	610	155	72
0.0094	---	49.99	24.10	70	534	158	72
0.0092	491	50.00	24.04	10.3	562	124	53
0.0093	508	49.99	24.06	69	532	118	50
0.0091	514	50.00	24.10	65	585	115	48
0.0090	519	50.02	24.25	63	604	113	45
0.0263	241	50.00	24.59	280	24	24	24
0.0092	---	49.90	25.19	68	672	164	67
0.0094	473	49.90	25.25	6.8	619	157	62
0.0094	474	49.80	25.32	7.5	647	161	65

TABLE B-2
LIFE-TEST DATA SUMMARY - S-2 HYDROGEN THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
2001*	---	0	0	0	---	6.33
2002*	---	0	0	0	---	4.25
2003†	---	0	0	0	---	6.00
2004†	---	3.100	40.5	125.6	0.0765	6.17
2005†	---	4.070	42.5	173.0	0.0960	5.64
2006†	---	5.415	42.5	230.0	0.1275	4.62
2007†	---	6.100	43.7	266.6	0.1395	4.41
2008	7.9	5.579	40.7	227.1	0.1371	4.66
2009	16.4	5.449	39.9	217.4	0.1366	---
2010	35.2	5.390	40.8	219.9	0.1321	4.91
2011	54.4	5.422	40.8	221.2	0.1329	---
2012	62.0	5.408	39.6	214.2	0.1366	4.59
2013	67.6	5.399	39.6	213.8	0.1363	---
2014	83.2	5.397	39.6	213.7	0.1363	---
2015	109.0	5.402	39.9	215.5	0.1354	5.18
2016	126.6	5.439	39.9	217.0	0.1363	---
2017	148.8	5.589	40.0	223.6	0.1397	4.48
2018	220.6	5.599	39.9	223.4	0.1403	4.14
2019	244.6	5.619	38.9	218.7	0.1444	---
2020	267.0	5.603	39.0	218.5	0.1437	4.04
2021	289.4	5.585	39.3	219.5	0.1421	---
2022	311.4	5.604	39.1	219.1	0.1433	4.07
2023	382.0	5.537	39.1	216.5	0.1416	4.02
2024	408.8	5.599	38.2	213.9	0.1466	---
2025	432.4	5.619	39.0	219.1	0.1441	3.96
2026	452.6	5.583	39.0	217.7	0.1432	---
2027	453.8	5.695	39.4	224.4	0.1445	3.96
2028	454.2	5.707	39.5	225.4	0.1445	3.86
2029	455.0	0	0	0	---	2.79

*Cold flow measurement / †Calibration, H₂

TABLE B-2 (Continued)
LIFE-TEST DATA SUMMARY - S-2 HYDROGEN THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0275	230	50.00	26.21	240	18	18	18
---	---	35.00	25.14	52	18	18	18
0.0265	227	50.00	25.10	270	30	44	36
0.0174	354	49.90	24.76	59	143	60	36
0.0140	404	50.00	24.63	29	215	76	36
0.0096	479	50.00	24.47	11	482	123	40
0.0085	519	50.00	24.60	6.8	916	183	44
0.0089	524	50.00	25.04	7.8	638	158	72
0.0087	---	50.30	25.91	72	662	152	69
0.0096	511	50.70	24.78	8.6	494	140	70
0.0092	---	50.75	24.67	74	524	145	70
0.0083	556	49.88	24.65	6.8	667	125	78
0.0084	---	50.50	23.67	69	588	144	68
0.0082	---	50.30	23.85	70	657	153	70
0.0078	662	50.25	25.10	7.8	681	155	71
0.0078	---	50.32	23.90	67	754	158	73
0.0078	578	50.10	23.37	6.8	770	156	68
0.0071	583	50.30	25.40	6.1	891	177	72
0.0070	---	50.18	26.20	67	922	181	73
0.0070	575	50.15	25.02	6.4	795	123	70
0.0070	---	50.18	25.15	67	925	179	78
0.0071	570	50.16	24.84	6.1	917	180	75
0.0070	574	50.35	24.64	6.4	899	178	74
0.0069	---	50.19	24.58	67	878	179	75
0.0069	578	50.20	24.15	6.8	810	185	72
0.0068	---	50.18	23.98	67	869	185	75
0.0068	586	50.40	24.34	7.5	28	175	45
0.0068	570	50.40	24.12	93	948	161	45
0.0126	221	50.00	24.56	26	23	23	23

TABLE B-2 (Continued)
LIFE-TEST DATA SUMMARY - S-2 HYDROGEN THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
2030	476.8	5.520	38.8	214.2	0.1423	---
2031	497.6	5.415	37.9	205.2	0.1429	3.97
2032	568.4	5.390	38.4	207.0	0.1404	3.89
2033	591.4	5.465	38.1	208.2	0.1434	---
2034	617.0	5.460	38.1	208.0	0.1433	3.84
2035	637.8	5.533	38.2	211.4	0.1448	---
2036	662.8	5.545	38.1	211.3	0.1455	3.69
2037	734.6	5.523	38.0	209.9	0.1453	3.60

TABLE B-2 (Concluded)
LIFE-TEST DATA SUMMARY - S-2 HYDROGEN THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m H _g)	Temperature (°C)		
					Case	Cover	Mount
0.0074	---	50.08	25.31	60	758	179	75
0.0073	545	50.08	25.31	4.0	700	162	72
0.0073	535	50.15	25.21	5.3	751	174	73
0.0071	---	49.99	25.12	72	789	184	74
0.0072	533	50.00	25.32	8.2	---*	180	74
0.0070	---	50.18	25.88	67	500*	200	77
0.0067	549	50.00	25.53	8.2	563*	209	77
0.0065	550	50.25	25.90	5.7	611*	216	75

*T. C. Probably lost.

TABLE B-3
LIFE-TEST DATA SUMMARY - S-3 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
3001*	---	0	0	0	---	5.52
3002*	---	0	0	0	---	3.60
3003†	---	0	0	0	---	5.66
3004†	---	1.656	24.1	39.9	0.0687	5.33
3005†	---	3.103	30.4	94.3	0.1021	4.74
3006†	---	4.206	32.4	136.3	0.1298	3.94
3007†	---	5.055	34.7	175.3	0.1456	3.99
3008	8.5	4.169	33.1	138.0	0.1266	4.20
3009	15.0	4.173	33.0	137.7	0.1215	---
3010	32.8	4.180	32.9	137.5	0.1271	4.52
3011	50.4	4.210	32.9	138.5	0.1282	---
3012	58.6	4.129	32.9	135.8	0.1260	---
3013	77.2	4.174	32.8	136.9	0.1773	4.24
3014	124.4	4.199	32.9	138.1	0.1276	---
3015	145.4	4.239	32.9	139.5	0.1288	4.05
3016	160.0	4.299	32.9	141.4	0.1307	---
3017	180.8	4.269	32.8	140.0	0.1302	---
3018	207.6	4.241	32.4	137.4	0.1309	---
3019	231.4	4.229	32.2	136.2	0.1313	4.08
3020	248.8	4.189	32.2	134.9	0.1301	---
3021	275.4	4.219	31.9	134.6	0.1323	4.26
3022	282.4	4.149	31.9	132.4	0.1300	---
3023	306.4	4.199	32.1	134.8	0.1308	4.63
3024	378.0	4.290	31.9	136.9	0.1345	---
3025	392.8	4.249	32.6	138.5	0.1303	---
3026	418.8	4.273	32.2	137.6	0.1327	4.43
3027	436.4	4.251	32.5	138.2	0.1308	---
3028	461.0	4.188	31.9	133.6	0.1313	4.08
3029	531.2	4.170	32.4	135.1	0.1287	4.04

*Hydrogen cold flow measurement.

†Calibration.

TABLE B-3 (Continued)
LIFE-TEST DATA SUMMARY - S-3 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0237	233	50.00	26.19	400	18	18	18
---	---	35.00	25.24	42	18	18	18
0.0540	105	44.00	26.99	42	31	38	36
0.0332	158	44.00	27.44	6	159	50	32
0.0211	225	44.00	27.65	45	376	94	34
0.0133	296	44.00	27.82	1.5	801	165	37
0.0115	347	44.00	27.87	4	>1200	294	45
0.0141	298	44.00	25.13	5	724	128	66
0.0140	---	44.00	25.26	70	728	118	63
0.0140	323	44.25	25.81	5	723	122	61
0.0139	---	44.30	25.66	85	753	120	61
0.0141	---	44.20	25.92	85	700	120	60
0.0140	304	44.25	26.19	6	729	118	58
0.0139	---	44.30	26.76	85	755	122	61
0.0137	296	44.35	26.48	6	793	127	61
0.0136	---	44.15	26.23	73	827	139	67
0.0137	---	44.14	27.47	5.5	795	132	63
0.0136	---	44.30	26.59	15	798	142	132
0.0135	302	44.30	24.68	5.5	792	143	57
0.0137	---	44.22	24.79	14.0	780	150	60
0.0134	317	44.25	25.04	4.0	795	150	64
0.0137	---	44.15	24.98	14.5	722	138	64
0.0136	340	44.30	25.20	5	715	132	74
0.0137	---	44.65	24.58	72	726	127	63
0.0138	---	44.85	24.58	75	730	133	65
0.0136	326	44.65	25.84	5	735	128	76
0.0135	---	44.57	24.34	82	747	135	68
0.0138	296	44.48	24.00	5	702	125	62
0.0136	297	44.25	25.93	3.5	706	132	66

TABLE B-3 (Continued)
LIFE-TEST DATA SUMMARY - S-3 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal current (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
3030	553.6	4.186	32.3	135.2	0.1296	---
3031	575.6	4.229	31.9	134.9	0.1326	4.07
3032	599.0	4.200	31.9	134.0	0.1317	---
3033	622.6	4.220	31.9	134.6	0.1323	4.09
3034	689.6	4.218	32.3	136.2	0.1306	4.09
3035	715.8	4.162	32.3	134.4	0.1289	---
3036	757.2	4.199	32.5	136.4	0.1292	4.11

TABLE B-3 (Concluded)
LIFE-TEST DATA SUMMARY - S-3 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0138	---	44.18	26.23	72	705	130	68
0.0138	296	44.30	24.96	4	722	129	65
0.0140	---	44.16	25.10	66	680	130	72
0.0138	296	44.10	24.91	4	690	124	68
0.0135	303	43.95	24.91	4	742	135	68
0.0139	---	43.93	24.63	66	685	128	70
0.0139	297	44.20	24.33	5	712	135	70

TABLE B-4
LIFE-TEST DATA SUMMARY - S-4 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (gf)
4001*	---	0	0	0	---	6.47
4002*	---	0	0	0	---	4.39
4003†	---	0	0	0	---	7.54
4004†	---	1.765	25.7	45.4	0.0687	7.46
4005†	---	3.098	31.6	97.9	0.0980	7.17
4006†	---	4.046	36.9	149.3	0.1096	6.46
4007†	---	5.283	37.8	199.7	0.1398	5.36
4008	9.1	5.009	37.4	187.3	0.1339	5.41
4009	15.0	4.760	38.1	181.4	0.1249	---
4010	37.6	4.980	37.4	186.3	0.1332	5.90
4011	54.4	4.999	36.9	184.5	0.1355	---
4012	65.0	4.939	36.9	182.2	0.1338	---
4013	82.4	4.961	36.9	183.1	0.1344	5.64
4014	129.8	4.959	36.9	183.0	0.1344	---
4015	150.4	4.990	36.9	184.1	0.1352	5.13
4016	166.0	4.999	35.9	179.5	0.1392	---
4017	185.6	5.012	36.6	183.4	0.1369	---
4018	206.2	5.038	36.3	182.9	0.1388	---
4019	239.6	4.893	36.4	178.1	0.1344	5.36
4020	254.8	4.923	35.6	175.6	0.1383	---
4021	282.2	4.903	35.9	176.0	0.1366	5.42
4022	287.0	4.870	35.9	175.2	0.1359	---
4023	309.4	4.929	35.9	177.0	0.1373	5.42
4024	384.6	4.979	35.9	178.7	0.1387	---
4025	401.0	4.987	35.2	175.5	0.1417	---
4026	426.6	4.950	35.9	177.1	0.1379	5.15
4027	444.6	4.939	35.9	177.3	0.1376	---
4028	467.6	4.903	35.9	176.0	0.1366	4.99
4029	539.2	4.946	36.8	182.0	0.1344	5.16

*Hydrogen cold flow measurement.

†Calibration NH₃.

TABLE B-4 (Continued)
LIFE-TEST DATA SUMMARY - S-4 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0287	225	50.00	24.93	240	18	18	18
---	---	35.00	24.87	53	18	18	18
0.0722	104	44.00	26.46	67	28	37	31
0.0521	143	44.00	26.16	32	121	48	30
0.0371	193	44.00	25.99	15	288	94	35
0.0287	231	44.00	25.71	8	418	122	39
0.0178	301	44.00	25.42	2.5	887	206	49
0.0188	288	43.87	25.09	5.7	680	135	70
0.0214	---	43.70	25.22	24	546	124	65
0.0189	312	44.10	25.95	6.1	659	132	61
0.0187	---	44.15	24.44	52	475	115	63
0.0191	---	43.90	25.78	44	665	137	62
0.0197	286	44.08	26.12	9.3	601	128	58
0.0192	---	44.30	26.56	28	652	132	60
0.0185	278	44.10	26.26	7.2	708	144	63
0.0189	---	43.95	26.17	72	653	131	69
0.0179	---	43.90	27.06	6.1	753	146	64
0.0176	---	44.01	25.49	15	793	160	172
0.0180	298	44.20	24.80	6.5	682	127	78
0.0180	---	44.10	24.88	73	675	130	70
0.0182	298	44.10	25.30	5.1	711	143	63
0.0177	---	44.00	24.87	14	704	150	67
0.0176	309	44.10	25.58	5.1	750	155	75
0.0182	---	44.50	24.40	67	658	124	68
0.0186	---	44.72	24.52	71	643	131	70
0.0181	285	44.50	25.90	6.1	717	138	72
0.0177	---	44.48	24.58	67	743	143	73
0.0179	279	44.33	21.14	6.8	698	128	65
0.0182	284	44.00	25.87	4.4	709	136	69

TABLE B-4 (Continued)
LIFE-TEST DATA SUMMARY - S-4 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
4030	562.2	4.989	37.2	185.6	0.1341	---
4031	583.6	4.969	35.9	178.9	0.1384	5.22
4032	586.0	4.929	36.9	181.9	0.1336	---
4033	597.2	4.834	37.4	180.8	0.1293	---
4034	630.2	4.995	35.0	174.8	0.1427	5.22
4035	700.6	4.900	36.6	179.3	0.1339	5.13
4036	726.4	4.905	36.4	178.5	0.1348	---

TABLE B-4 (Concluded)
LIFE-TEST DATA SUMMARY - S-4 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0187	---	44.05	26.19	67	675	142	73
0.0185	282	44.00	25.10	5.4	666	132	64
0.0185	---	44.00	25.18	64	675	132	73
0.0193	---	44.00	25.31	67	625	124	78
0.0184	284	43.90	25.33	5.4	598	127	72
0.0180	286	43.80	24.70	5.1	693	139	74
0.0183	---	43.80	24.73	67	658	140	75

TABLE B-5
LIFE-TEST DATA SUMMARY -- S-5 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (μ_f)
5001*	---	0	0	0	---	6.02
5002*	---	0	0	0	---	3.98
5003†	---	0	0	0	---	6.39
5004†	---	1.795	25.4	45.6	0.0707	6.47
5005†	---	3.112	30.0	93.4	0.1037	6.27
5006†	---	4.038	35.2	142.1	0.1147	5.67
5007†	---	4.831	32.9	158.9	0.1468	4.08
5008‡	---	0	0	0	---	6.19
5009‡	---	4.394	39.4	173.1	0.1115	5.28
5010A†	---	5.984	39.2	234.6	0.1527	4.54
5010	15.0	4.471	33.0	147.5	0.1355	---
5011	31.0	4.419	33.9	149.8	0.1304	5.65
5012	55.6	4.219	33.0	139.2	0.1278	---
5013	63.6	4.269	31.0	132.3	0.1377	---
5014	82.8	4.234	32.3	136.8	0.1311	5.45
5015	128.8	4.301	30.7	132.0	0.1401	---
5016	150.2	4.249	32.9	139.8	0.1291	5.23
5017	163.4	4.319	33.9	146.4	0.1274	---
5018	184.6	4.299	32.9	141.1	0.1307	---
5019	211.4	4.243	33.7	143.0	0.1259	---
5020	237.0	4.278	33.9	145.0	0.1262	5.26
5021	251.8	4.301	33.5	144.1	0.1284	---
5022	278.6	4.299	32.9	141.4	0.1307	5.32
5023	283.2	4.209	32.9	138.5	0.1279	---
5024	306.8	4.288	33.3	142.8	0.1288	5.26
5025	378.8	4.329	33.9	146.8	0.1278	---
5026	395.0	4.332	33.3	144.3	0.1301	---
5027	422.6	4.378	31.9	139.7	0.1372	4.85
5028	438.0	4.376	31.2	136.5	0.1403	---

*Hydrogen cold flow measurement.

†Calibration NH₃.

‡Calibration H₂.

TABLE B-5 - (Continued)
LIFE-TEST DATA SUMMARY - S-5 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0262	230	50.00	26.07	180	18	18	18
---	---	35.00	26.06	---	18	18	18
0.0618	103	44.00	25.68	52	22	25	23
0.0408	159	44.00	25.95	15	136	40	22
0.0291	215	44.00	26.25	5.1	300	79	26
0.0210	270	44.00	26.70	3.1	433	111	22
0.0144	325	44.00	27.10	1.3	820	205	39
0.0246	252	50.00	22.53	155	26	35	42
0.0110	480	50.00	23.67	9.3	229	63	34
0.0082	554	50.00	24.77	4.0	784	130	34
0.0175	---	44.10	25.32	69	537	105	63
0.0180	315	44.35	25.06	6.4	505	86	50
0.0193	---	44.15	25.70	88	468	100	61
0.0206	---	44.20	25.89	88	441	100	60
0.0199	274	44.25	26.33	8.1	450	100	59
0.0201	---	44.50	26.64	88	450	95	61
0.0196	268	44.40	27.20	7.1	457	100	61
0.0184	---	44.12	26.34	74	528	108	67
0.0185	---	44.08	28.14	6.8	462	101	63
0.0184	---	44.10	26.70	15	481	105	132
0.0184	286	44.40	24.88	6.8	490	114	62
0.0178	---	44.34	24.95	14	510	117	60
0.0183	292	44.25	25.30	5.3	485	107	64
0.0189	---	44.20	25.60	14.5	470	107	64
0.0181	291	44.29	25.40	5.3	493	110	73
0.0181	---	44.75	24.65	74	483	101	63
0.0180	---	44.68	24.61	76	488	105	65
0.0185	262	44.30	25.78	6.8	450	102	69
0.0193	---	44.22	24.39	77	433	105	68

TABLE B-5 -- (Continued)
LIFE-TEST DATA SUMMARY -- S-5 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
5029	464.0	4.270	31.9	136.2	0.1339	5.16
5030	533.2	4.401	31.9	140.4	0.1380	4.96
5031	554.6	4.354	32.7	142.4	0.1331	---
5032	574.8	4.329	32.9	142.4	0.1316	4.82
5033	600.0	4.345	28.9	125.6	0.1503	---
5034	622.2	4.336	29.3	127.0	0.1480	3.95
5035	692.6	4.358	30.1	131.2	0.1448	3.90
5036	717.0	4.290	30.0	128.7	0.1430	---
5037	760.2	4.319	29.9	129.1	0.1444	3.95

TABLE B-5 - (Concluded)
LIFE-TEST DATA SUMMARY - S-5 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m H _g)	Temperature (°C)		
					Case	Cover	Mount
0.0188	274	44.10	24.19	5.3	453	102	63
0.0173	287	43.97	26.32	4.0	537	112	64
0.0175	---	44.02	26.20	74	506	110	68
0.0173	279	43.60	24.08	4.0	510	110	66
0.0120	---	44.21	25.17	67	878	147	72
0.0128	308	44.10	25.05	4.0	778	134	70
0.0125	313	43.90	25.10	3.7	711	135	69
0.0129	---	43.92	24.65	67	708	137	70
0.0128	309	43.83	24.00	4.7	735	141	75

TABLE B-6
LIFE-TEST DATA SUMMARY - S-6 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g_f)
6001*	---	0	0	0	---	5.42
6002*	---	0	0	0	---	3.60
6003†	---	0	0	0	---	5.99
6004†	---	1.779	24.5	43.6	0.0726	5.76
6005†	---	3.098	30.4	94.2	0.1019	5.55
6006†	---	4.123	35.1	144.7	0.1175	4.80
6007†	---	4.961	35.0	173.6	0.1417	4.56
6008	15.0	4.401	34.5	151.8	0.1276	---
6009	36.8	4.390	34.5	151.5	0.1272	5.02
6010	54.8	4.307	33.9	146.0	0.1271	---
6011	65.2	4.119	34.9	143.8	0.1180	---
6012	83.8	4.188	33.3	139.5	0.0152	4.42
6013	130.0	4.259	32.9	140.1	0.1295	---
6014	151.6	4.279	32.9	140.8	0.1301	4.24
6015	166.2	4.299	33.0	141.9	0.1303	---
6016	186.8	4.321	32.5	140.4	0.1330	---
6017	206.4	4.329	32.2	139.4	0.1344	---
6018	240.4	4.369	31.9	139.4	0.1370	4.26
6019	254.8	4.329	31.9	138.1	0.1357	---
6020	282.0	4.329	31.9	138.1	0.1357	4.20
6021	288.0	4.294	31.9	137.0	0.1346	---
6022	313.8	4.347	32.4	140.8	0.1340	4.34
6023	385.0	4.292	32.9	141.2	0.1305	---
6024	401.2	4.299	31.9	137.1	0.1348	---
6025	428.4	4.326	32.9	142.3	0.1315	4.17
6026	445.8	4.296	32.9	141.3	0.1306	---
6027	469.8	4.314	32.9	141.9	0.1311	4.21
6028	540.2	4.349	33.3	144.8	0.1306	4.42

*Hydrogen cold flow measurement. †Calibration.

TABLE B-6 - (Continued)
LIFE-TEST DATA SUMMARY - S-6 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0242	224	50.00	25.00	103	18	18	18
---	---	35.00	25.00	38	18	18	18
0.0557	108	44.00	27.14	38	31	49	36
0.0366	157	44.00	27.12	8.1	166	56	34
0.0262	212	44.00	27.08	6.8	349	89	35
0.0173	277	44.00	26.93	4.3	520	117	40
0.0142	321	44.00	26.25	3.7	1136	234	51
0.0160	---	44.20	25.32	24	679	128	65
0.0159	317	44.40	26.14	5.3	678	132	56
0.0160	---	44.30	24.52	52	643	118	63
0.0174	---	44.40	25.86	43	540	114	62
0.0152	291	44.50	26.32	6.1	630	119	60
0.0147	---	44.60	26.56	28	700	122	60
0.0143	297	44.65	26.91	6.1	747	135	63
0.0145	---	44.23	26.35	72	733	130	69
0.0141	---	44.25	27.82	6.1	782	142	65
0.0137	---	44.20	25.52	14.5	796	154	172
0.0136	314	44.60	24.98	5.7	800	136	69
0.0136	---	44.52	24.99	74	800	135	70
0.0137	307	44.45	25.00	4.0	775	143	63
0.0134	---	44.40	24.90	13.7	785	145	67
0.0138	316	44.45	25.40	4.0	795	145	74
0.0148	---	44.90	24.58	69	703	122	68
0.0145	---	44.83	24.78	70	758	134	70
0.0142	294	44.60	25.82	4.7	795	138	70
0.0142	---	44.59	24.61	67	788	140	73
0.0144	293	44.28	24.11	4.3	794	132	65
0.0151	294	44.00	26.10	3.7	743	132	69

TABLE B-6 - (Continued)
LIFE-TEST DATA SUMMARY - S-6 AMMONIA THRUSTOR

Point	Accrued time (hours)	Terminal voltage (V)	Terminal voltage (A)	Electric power (W)	Terminal resistance (Ω)	Thrust (g)
6029	562.2	4.329	33.2	143.7	0.1311	---
6030	582.6	4.329	32.9	142.4	0.1316	4.33
6031	598.0	4.723	33.9	160.1	0.1393	---
6032	632.2	4.714	33.9	159.8	0.1391	4.45
6033	701.6	4.679	33.8	158.2	0.1384	4.36
6034	726.2	4.659	34.0	158.4	0.1370	---

TABLE B-6 - (Concluded)
LIFE-TEST DATA SUMMARY - S-6 AMMONIA THRUSTOR

Mass flow (g/sec)	I _{sp} (sec)	Supply pressure (psia)	Propellant temperature (°C)	Test cell pressure (μ m Hg)	Temperature (°C)		
					Case	Cover	Mount
0.0154	---	44.12	26.20	67	780	138	73
0.0150	289	43.75	24.92	4.0	734	136	66
0.0143	---	44.12	25.20	67	963	173	78
0.0144	309	43.95	25.05	4.0	955	167	73
0.0142	307	43.70	24.71	4.0	953	171	75
0.0144	---	43.85	24.67	67	950	171	75