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Radiative Resistojet Performance Characterization Tests

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Redmond, Washington

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ABA: Author
ABS: The test article, test approach, data analysis and results of a study undertaken to characterize performance of the augmentation section of the Rocket Research Company Augmented Catalytic Thruster as a gas resistojet using hydrogen, nitrogen and ammonia as propellants are described. This renewed interest in resistojets is a result of propulsion systems definition studies which indicate potential application to space station auxiliary propulsion.

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1.0 INTRODUCTION AND SUMMARY

This report describes the test article, test approach, data analysis and results of a study undertaken to characterize performance of the augmentation section of the Rocket Research Company Augmented Catalytic Thruster as a gas resistojet using hydrogen, nitrogen and ammonia as propellants. This renewed interest in resistojets is a result of propulsion systems definition studies which indicate potential application to space station auxiliary propulsion. This report is submitted in fulfillment of the data package requirements of NASA Contract No. NAS3-23868, Statement of Work, Exhibit A. Technical direction and monitoring was provided by Mr. James Sovey of the NASA-Lewis Research Center.

The augmented catalytic thruster is a flight qualified hydrazine resistojet based on use of a catalytic reactor for hydrazine decomposition and thermally isolated radiative heater/ heat exchanger subassembly for post decomposition heat addition. This device is illustrated in Figures 1-1 and 1-2 and is described in more detail in Reference 1.

When used to augment the performance of propellant which is already in a gaseous state, the decomposition reactor can be eliminated. This propellant gas is then ducted directly to the augmentation heat exchanger through a simple gas inlet tube. This is the configuration that was tested and reported herein. A production augmentation subassembly and mounting structure was used. No attempt was made to modify (other than replace the decomposition reactor with the gas inlet tube) or optimize the design for the selected propellants or for a projected mission application.

Testing, conducted in an altitude chamber with thrust and propellant flow rate measurement, consisted of a matrix of propellant flow rates and augmentation heater power levels for the three propellants. Resultant thrust levels ranged from 57.5 to 496.2 mN (12.9 to 111.5 mlbf) with augmentation power levels up to one kilowatt. Firings were 20-minute steady-state runs with performance data measured at end of run equilibrium conditions.

AUGMENTED CATALYTIC THRUSTER

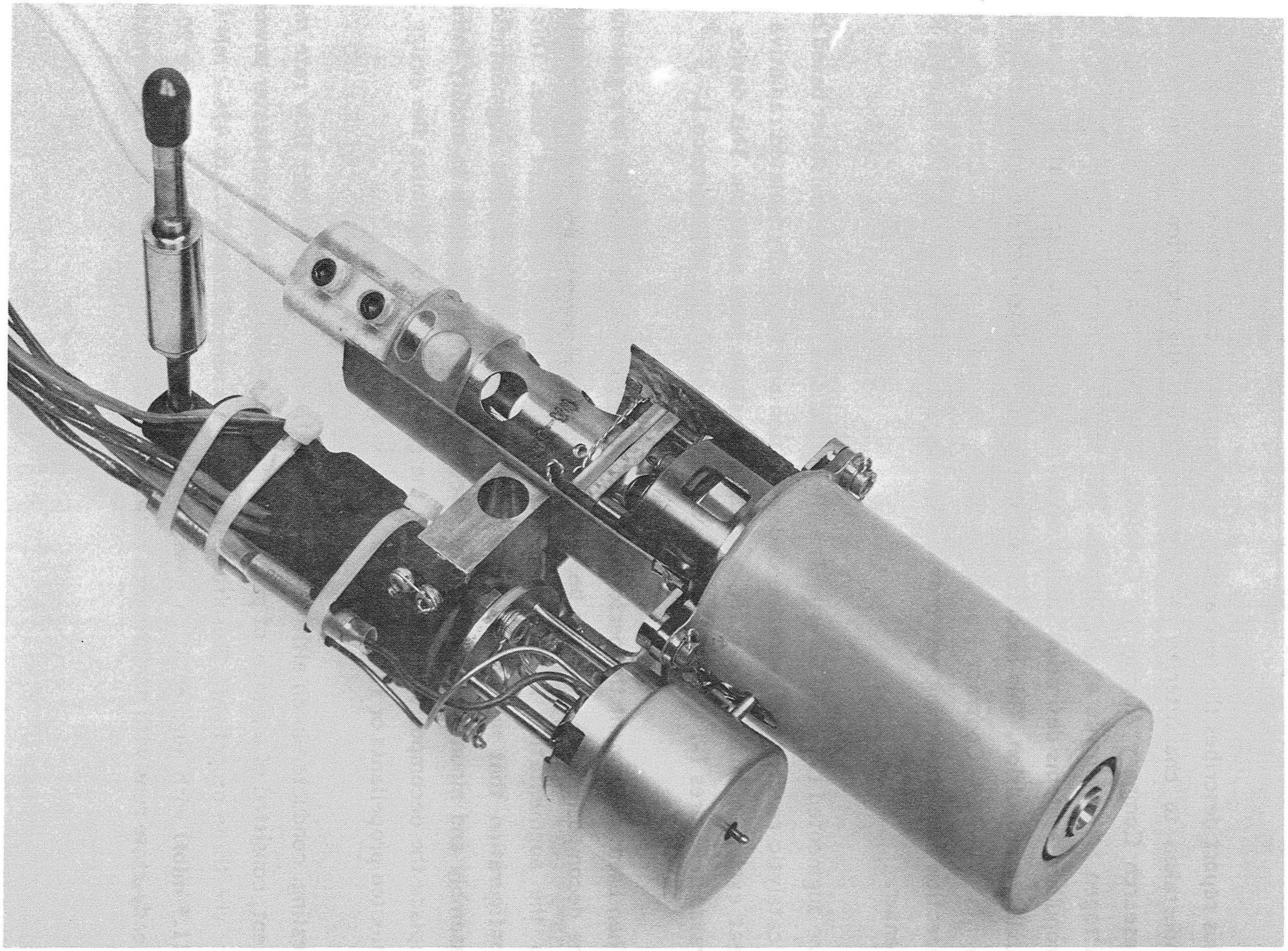

Figure 1-1

Augmented Catalytic Thruster

(SECTIONAL VIEW)

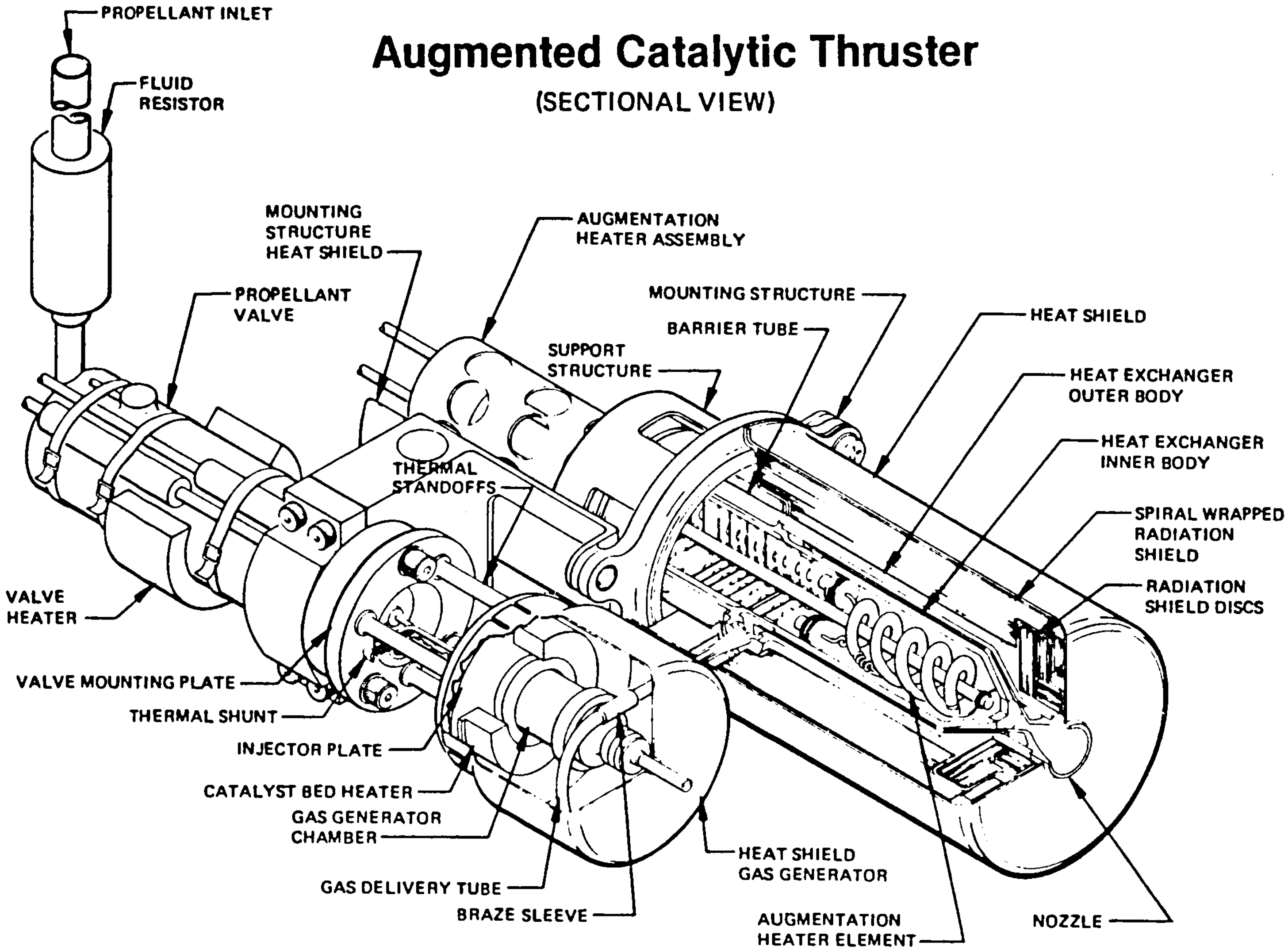

Figure 1-2

2.0 TEST ARTICLE

2.1 RADIATIVE RESISTOJET DESCRIPTION

The resistojet thruster, shown conceptually in Figure 2-1, used in the testing was identical to the production ACT augmentation assembly (heat exchanger with nozzle, augmentation heater and heat shielding) presently qualified and in flight service (Reference 2). As the conceptual schematic shows, the augmentation heater is isolated from the propellant stream which eliminates the need for high temperature electrical pass-throughs as well as precluding direct contact of the heating element with the propellant.

As shown in Figure 1-2, the heat exchanger is an annular section surrounding the augmentation heater element. The gas inlet tube discharges into a manifold which provides circumferential distribution of the flow. The gas then flows through the heated axial flutes raising its temperature. Internal heat shielding isolates the external heat exchanger walls to reduce heat losses. The flutes discharge into a plenum and the gas then exits through an insert type nozzle.

The heat exchanger is surrounded by an extensive set of radiation shields contained in a rhodium plated external shell. The Technion, Incorporated augmentation heater also includes multiple radiation shield diskettes to minimize axial heat loss. A production ACT mounting structure and support structure was used to mount the heat exchanger. Figure 2-2 shows the resistojet test article with the augmentation heater removed.

The test augmentation heater was identical in design to the production ACT heater except the heater element length and diameter were slightly adjusted to provide a nominal power of 700 watts at 28 vdc.

RADIATIVE RESISTOJET CONCEPTUAL SCHEMATIC

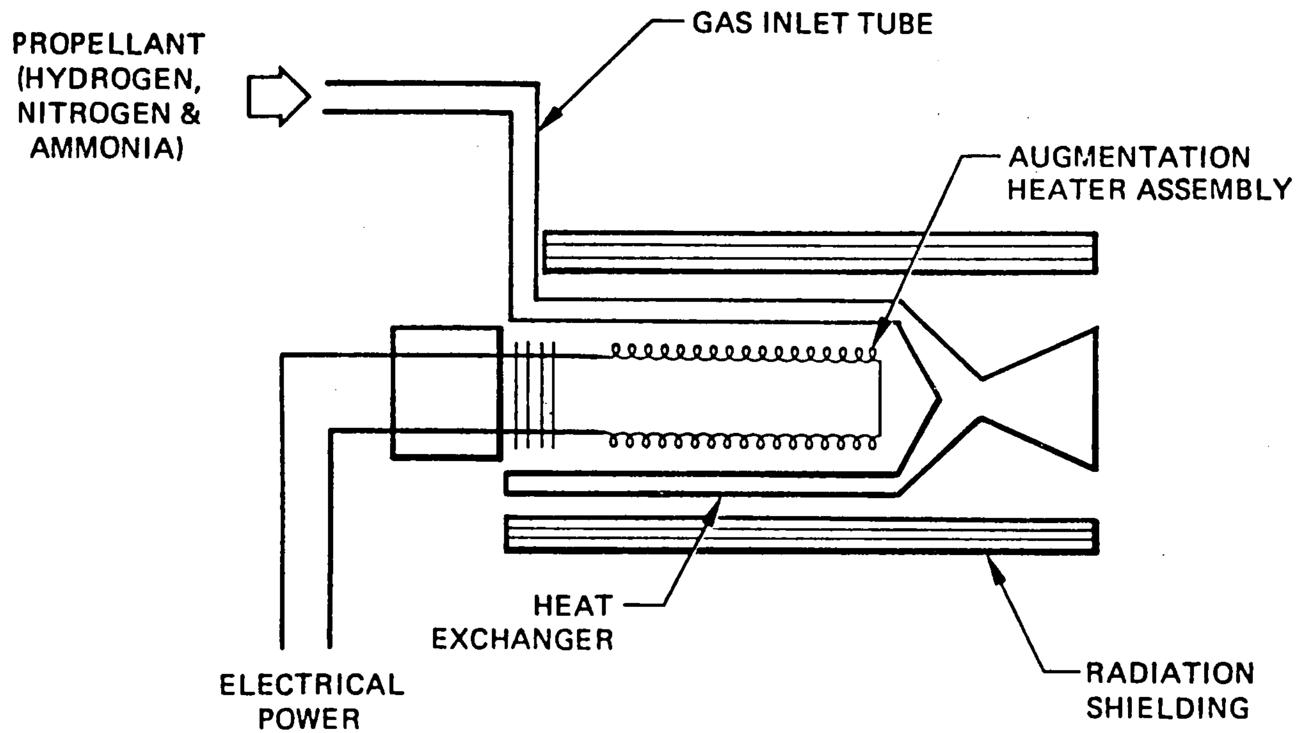

Figure 2-1

RESISTOJET AND AUGMENTATION HEATER

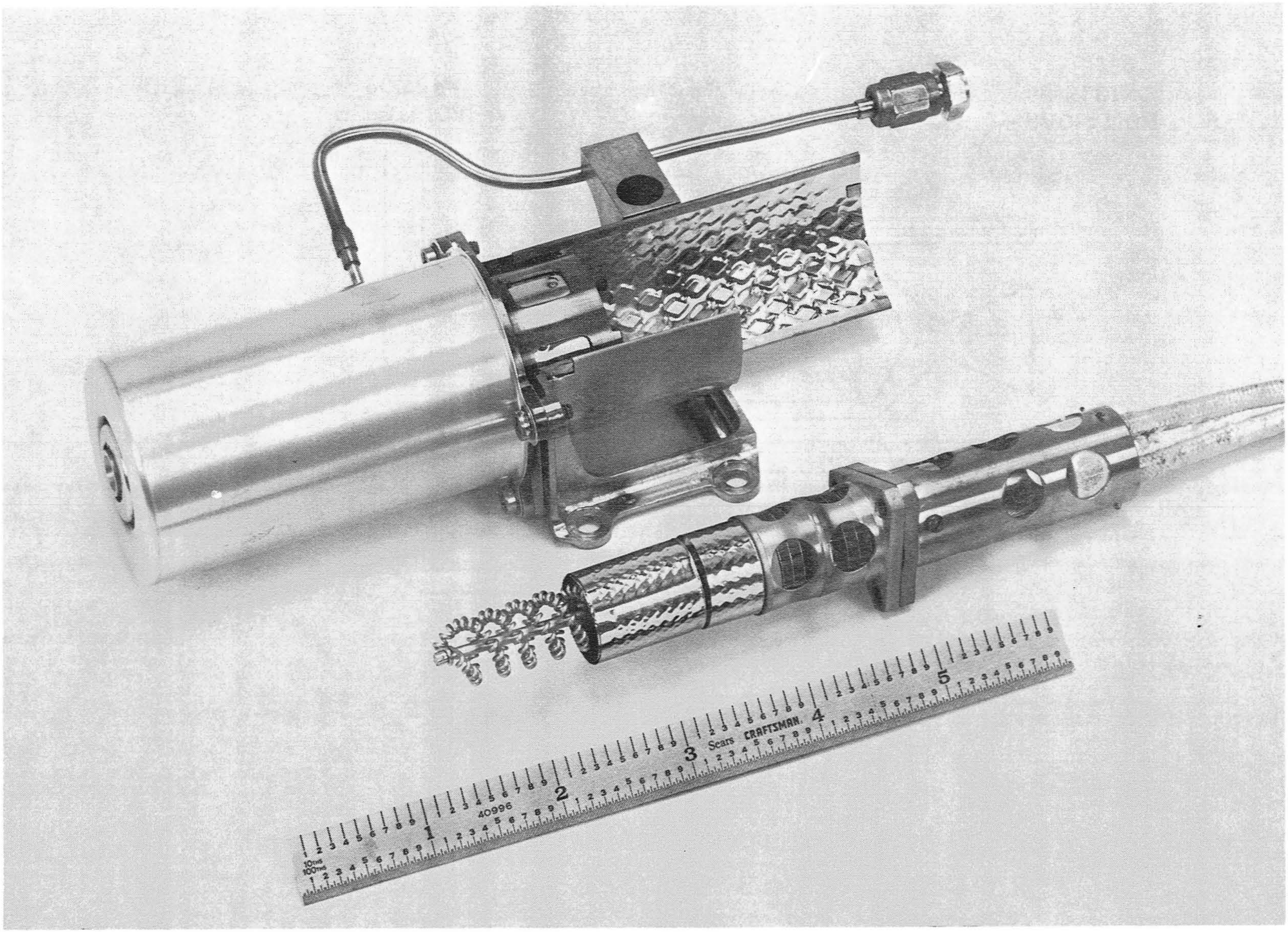

Figure 2-2

3.0 TEST FACILITY AND INSTRUMENTATION

3.1 TEST FACILITY DESCRIPTION

Testing was conducted in a 2.8 cubic meter (98 cubic foot) altitude chamber at the RRC Redmond, Washington facility. A mechanical vacuum pump rated at 1,280 cfm used in this chamber provides the capability of maintaining vacuum levels on the order of one torr during firing.

Figure 3-1 shows the propellant system schematic. Inlet pressure is controlled by a pressure regulator located near the gas source bottle. Flow rate is determined by measuring pressure drop across a calibrated fluid resistor for hydrogen and nitrogen tests. Ammonia flow rate was determined by direct measurement from a mass flowmeter. For ammonia firings only, a heat exchanger was added to the system immediately downstream of the pressure regulator to ensure no condensation occurs due to expansion through the pressure regulator.

Two facility gas solenoid valves were used in the system for propellant flow control and to provide for proper calibration. At run completion, Valve 2 (refer to Figure 3-1) is closed to stop propellant flow. This maintains pressure between the regulator and Valve 2 allowing a mass flowmeter zero to be recorded while pressurized with no propellant flowing. Additionally, this allows the thrust stand to be calibrated while the propellant flex lines are pressurized. Valve 1 is then closed and Valve 2 is opened allowing the system to vent to the test chamber. This allows the pressure transducer zero's to be recorded. The sequencing and calibrations are controlled by the system described below.

3.2 TEST CONTROL SYSTEM

Test control was performed by a Hewlett Packard 9836A desktop computer/controller. The test system schematic is shown in Figure 3-2. The HP9836A interactively controls the augmentation heater by monitoring the voltage-current characteristics of the heater and adjusting the voltage as needed to maintain a constant power. The computer also controls sequencing of the facility valves controlling gas flow.

PROPELLANT SYSTEM SCHEMATIC

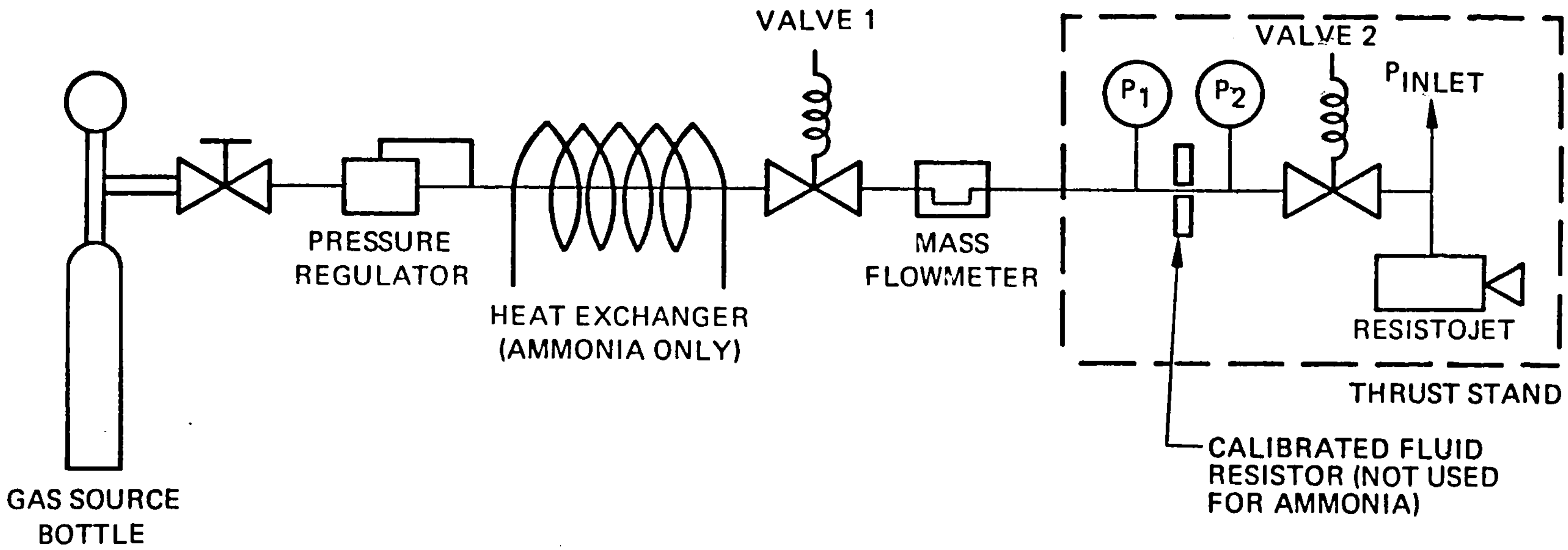

Figure 3-1

RESISTOJET TEST CONTROL SYSTEM

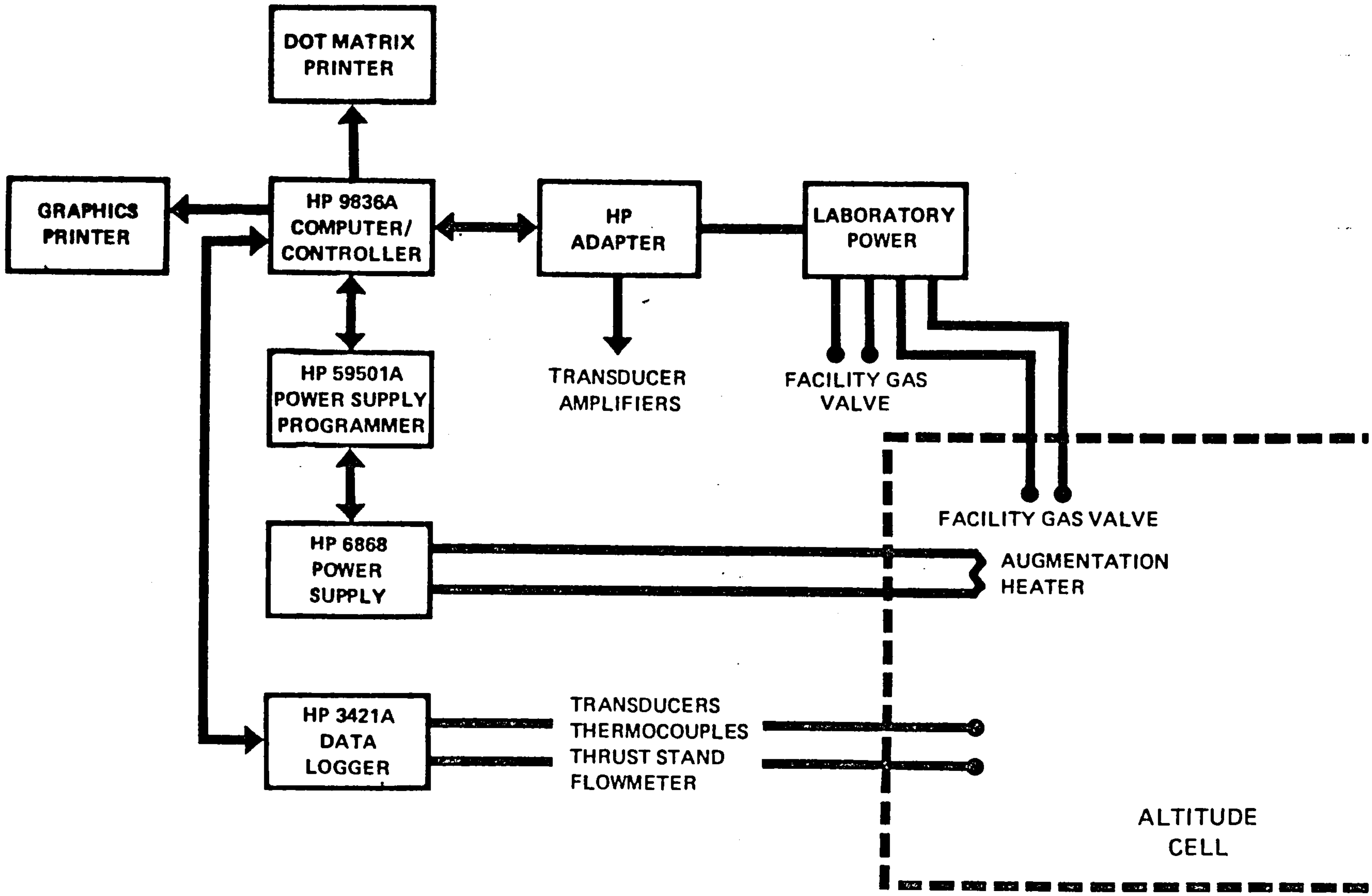

Figure 3-2

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At the completion of each run, a system calibration was performed under control of the HP9836A. Trasducer zero and spans and thrust stand calibrations were automated. These calibrations, which were performed immediately after each run, were used in the data reduction for the run just completed.

Data was recorded on floppy disc along with run information such as test sequence number and calibration information. Analog pressure transducer, heater characteristic, thermocouple, mass flowmeter, and thrust stand linear displacement transformer output are digitized by the HP3421 Data Logger. Analog data was also displayed on strip chart recorders for visual observation and as a redundant recording system.

3.3 THRUST BALANCE

Steady-state thrust was measured using the RRC compound pendulum thrust balance. The principle of operation is that of a freely suspended pendulum. The pendulum is displaced by the thrust force applied. Thus, steady-state thrust is measured by allowing the balance to reach an equilibrium position with the applied thrust and measuring the displacement with the linear variable differential transformer (LVDT). The balance is calibrated immediately after each run to obtain a "hot" calibration. A schematic of the thrust balance is shown in Figure 3-3.

The resistojet is thermally isolated from the thrust stand by a titanium-kapton sandwich. The sandwich simulates a high resistance conductive path typical of a spacecraft installation.

3.4 INSTRUMENTATION

Table 3-1 shows the instrumentation used for resistojet test firings.

Pressure was measured using Statham PL-288 strain gauge pressure transducers calibrated for the test operating range. Each transducer was dead weight calibrated prior to testing. Transducer span and zero was verified following each firing.

Temperature was measured with Type K (Chromel-Alumel) thermocouples. The HP3421A data logger provides an internal temperature reference.

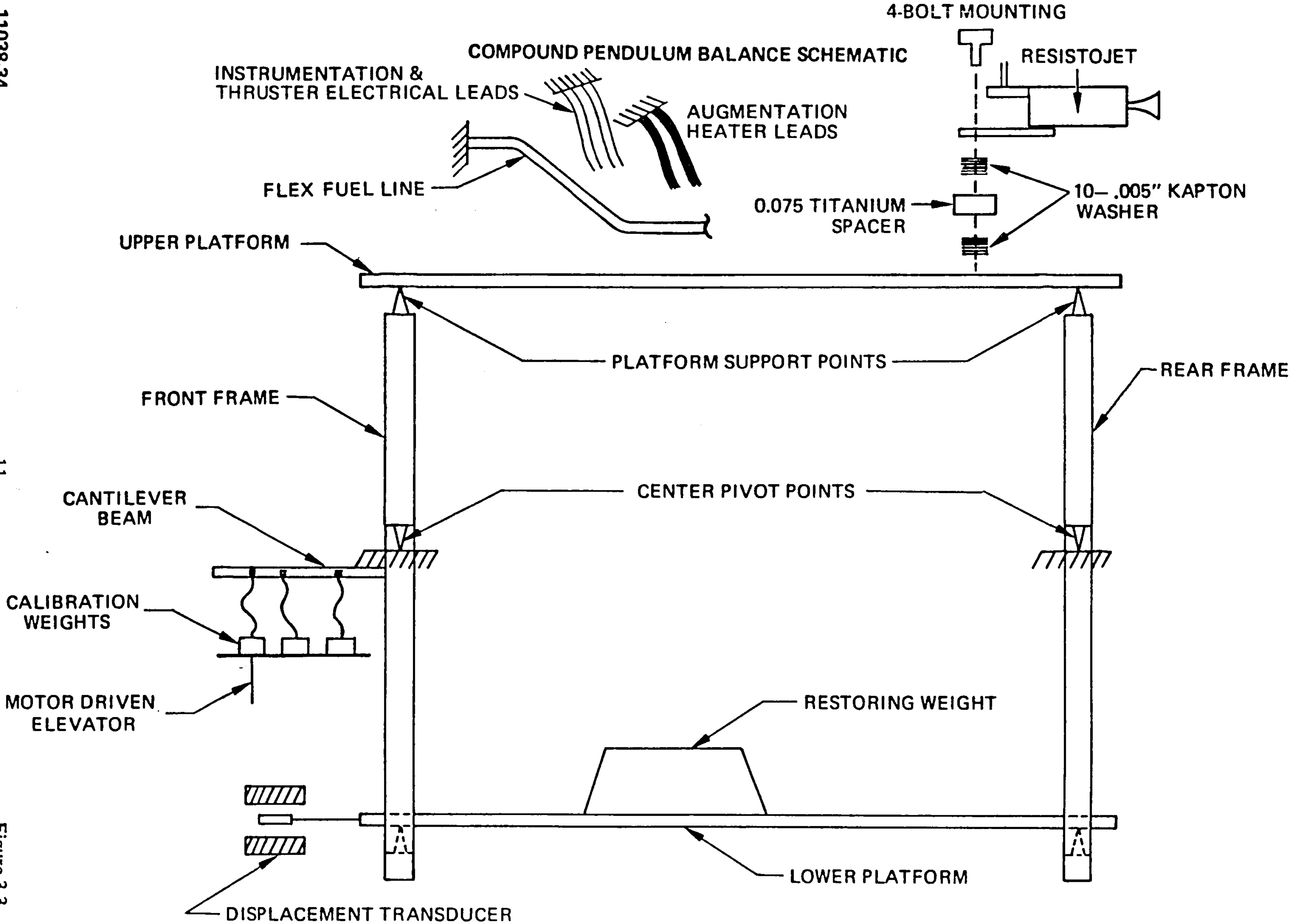

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Figure 3-3

Table 3-1

RESISTOJET INSTRUMENTATION LIST

Parameter	Type	Range
Thrust	Linear Variable Differential Transformer	0 - 0.12 lbf
Flow Rate(1)	Mass Flowmeter	0 - 3 lbm/hr
Upstream Visco-Jet(2) Pressure	Strain Gauge Transducer	0 - 500 psia
Downstream Visco-Jet(2) Pressure	Strain Gauge Transducer	0 - 500 psia
Inlet Pressure	Strain Gauge Transducer	0 - 150 psia
Cell Pressure	Strain Gauge Transducer	0 - 0.5 psia
Heater Voltage	Voltmeter	0 - 50 vdc
Heater Current	Current Shunt	0 - 1 vdc
Inlet Temperature (immersion in gas inlet)	Chromel/Alumel Thermocouple	0 - 10 mv
Tube Temperature (on gas delivery tube)	Chromel/Alumel Thermocouple	0 - 10 mv
Structure Temperature (on support structure)	Chromel/Alumel Thermocouple	0 - 50 mv
Mount Temperature (on mounting foot closest to support structure)	Chromel/Alumel Thermocouple	0 - 50 mv
Visco-Jet Inlet Temperature (immersion in gas at fluid resistor inlet)	Chromel/Alumel Thermocouple	0 - 5 mv

(1) Ammonia tests.

(2) Nitrogen and hydrogen tests.

Heater current is determined by measuring voltage drop across a low resistance calibrated shunt. Voltage is measured directly using the data logger.

Flow rate measurement for hydrogen and nitrogen was made with a calibrated fluid resistor (Lee Corporation, Visco-Jet, P/N VDCA 6815880D). The fluid resistor was flow calibrated at the Colorado Engineering Experiment Station in Nunn, Colorado with both hydrogen and nitrogen. Calibration data sheets are provided in Appendix B.

Flow rate measurement for ammonia was made with a Micromotion Incorporated Model No. C-6 vibrating U-tube mass flowmeter.

3.5 PROPELLANTS

Ultra high purity nitrogen, hydrogen and ammonia were used as the resistojet propellants. Manufacturers purity specifications are listed in Table 3-2.

Table 3-2

GAS PURITY SPECIFICATION

Gas	Purity	Max.	O_2	H_2O	Dew Point °F
Hydrogen	99.9995%	5	0.5	1	-105
Nitrogen	99.999 %	10	1.0	1	-105
Ammonia	—	—	1.0	1	--

4.0 TEST RESULTS AND EVALUATION

4.1 SPECIFIC IMPULSE AND THRUST

The primary objective of the performance mapping tests for the three propellants was to characterize the resistojet specific impulse as related to thrust and applied power. Specific impulse was calculated from direct thrust and flow rate measurement as explained in Appendix A. Appendix A also provides tabulated raw test data and reduced data. Appendix B presents the data reduction algorithms and assumptions.

Figure 4-1 shows the relation between thrust and inlet pressure for hydrogen propellant. Inlet pressure is measured at the inlet to the gas delivery tube and provides an approximate measurement of nozzle total pressure. Some pressure drop occurs in the delivery tube and heat exchanger. The magnitude of this pressure drop is dependent on the specific operating parameters and is on the order of a few percent of the maximum pressure. Thrust is seen to be a near linear function of inlet pressure with the unaugmented runs displaying a slightly different trend. This is possibly due to an increase in pressure drop between the inlet pressure and nozzle plenum pressure as the gas temperature increases and/or test cell back pressure effects on the nozzle. Inlet pressure, and therefore nominal chamber pressure, ranges from 0.12 to 0.67 MPa (17 to 97 psia). A maximum of 0.69 MPa (100 psia) was used to limit heat exchanger operating pressure to the nominal ACT design level. Thrust shows no significant dependence on heater power level.

As Figure 4-2 shows the resistojet demonstrated for the test matrix selected, hydrogen specific impulse ranging from 461.1 to 686.9 lbf-sec/lbm. The unaugmented tests showed an almost constant specific impulse of approximately 273 lbf-sec/lbm. For the augmented tests heater powers ranged from 600 to 1,000 watts with correspnding specific power ranging from 1.79 to 7.52 kW/N (7.96 to 33.51 watts/mlbf) for the data obtained. Specific power was limited so as to keep the heater element temperature from exceeding 2,700°K (4,400°F). For the test matrix performed, thrust ranged from 57.5 to 364.9 mN (12.9 to 82 mlbf).

THRUST VS INLET PRESSURE FOR HYDROGEN

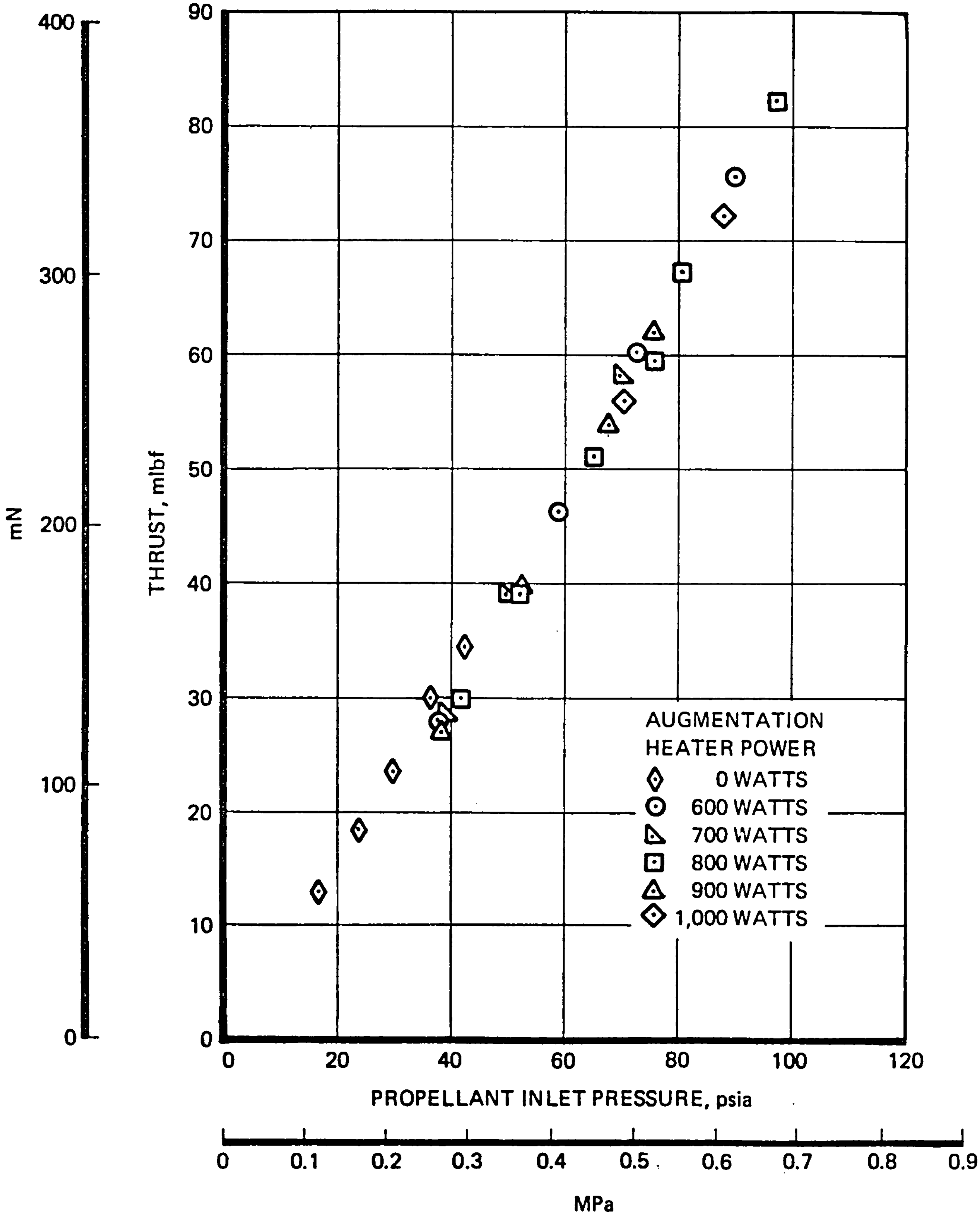

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Figure 4-1

RESISTOJET PERFORMANCE WITH HYDROGEN

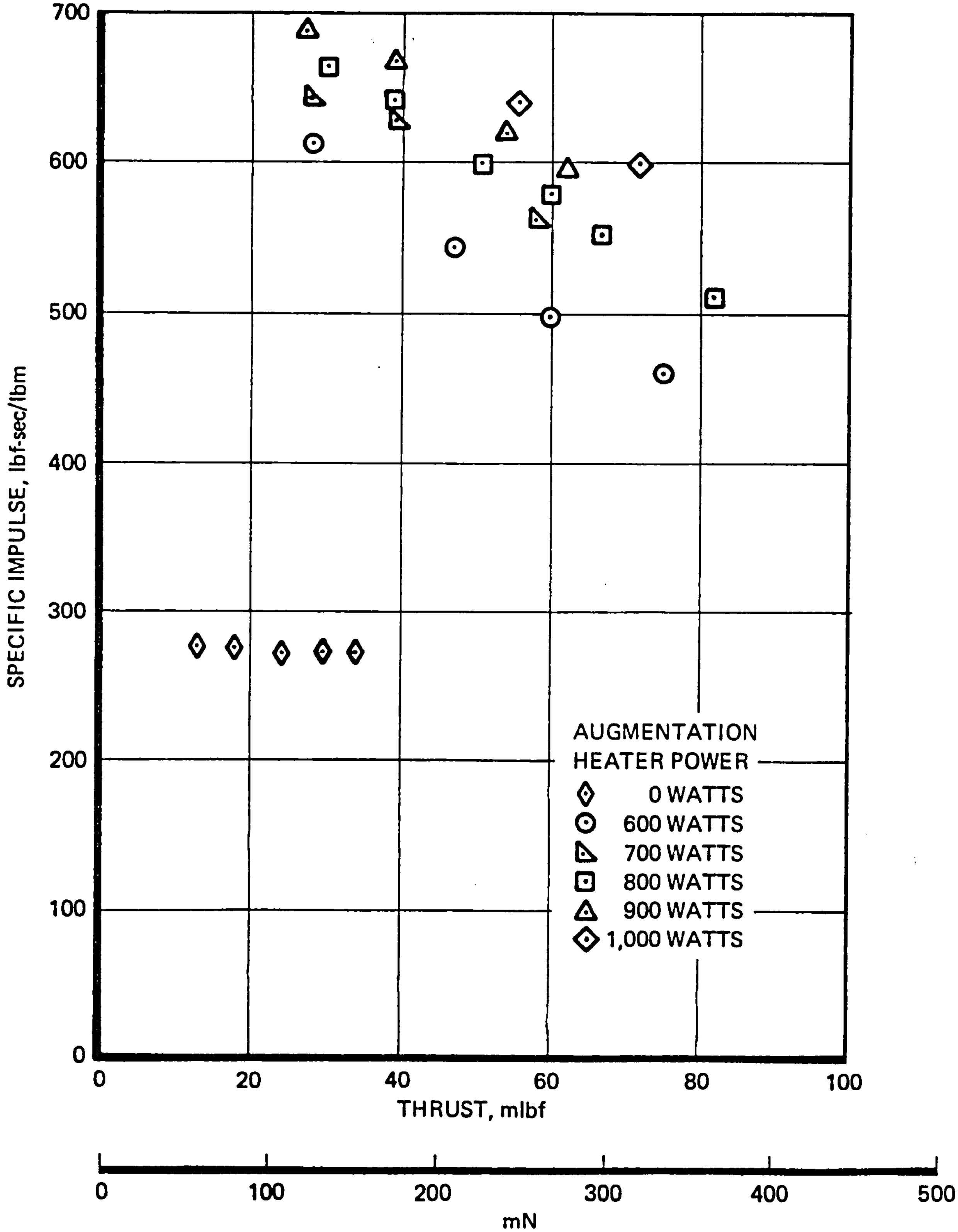

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Figure 4-2

Nitrogen performance trends are similar to those obtained with hydrogen. Figure 4-3 shows the inlet pressure versus thrust relationship. As with hydrogen, the unaugmented runs show a slightly different trend, but to a much lesser degree. Inlet pressure ranges from 0.11 to 0.89 MPa (16.3 to 128.7 psia) while thrust ranges from 58.7 to 496.2 mN (13.2 to 111.5 mlbf). Figure 4-4 shows specific impulse versus thrust. For the matrix performed, heater power was varied from 200 to 600 watts with resultant specific impulse ranging from 143.8 to 191.6 lbf-sec/lbm. Unaugmented runs were also conducted showing specific impulse to be fairly constant at approximately 75 lbf-sec/lbm. For the augmented runs specific power varies between 0.8 to 3.02 kW/N (3.54 to 13.46 watts/mlbf).

Ammonia performance trends are generally the same as with the other propellants. Figure 4-5 shows inlet pressure versus thrust. For the matrix tested, inlet pressure ranges from 0.31 to 0.64 MPa (45.3 to 93.4 psia) while thrust ranges from 161.1 to 363.1 mN (36.2 to 81.6 mlbf). As with the other propellants, no distinct power dependency is seen in the relationship between inlet pressure and thrust. Figure 4-6 shows specific impulse versus thrust. Specific impulse for ammonia ranged from 205.7 to 342 lbf-sec/lbm for heater powers between 400 and 900 watts. Unaugmented mapping was not conducted due to potential condensation in the resistojet. For the augmented portion of the test matrix specific power varied between 1.2 and 4.9 kW/N (5.34 and 21.81 watts/mlbf).

4.2 EFFICIENCY

Conceptually, overall efficiency is the ratio of the exit jet power to total input power where total input power consists of the electrical augmentation power and the chemical energy of the propellant. Overall efficiency, as used in this report, is defined in Appendix B.

Overall resistojet efficiency was calculated for the three propellants and is shown as a function of thrust in Figures 4-7, 4-8, and 4-9.

Figure 4-7 shows overall efficiency versus thrust at various heater powers for hydrogen. Efficiency ranges from 41.2 to 82.9 percent for the powered runs. Efficiency increases as thrust increases for a given heater power level. Conversely, as heater power is increased for a given thrust level, efficiency decreases. Gas temperature is higher at higher power levels increasing heat losses. Drag losses in the nozzle are also higher at the lower Reynolds Numbers typical of low thrust and high augmentation power.

THRUST VS INLET PRESSURE FOR NITROGEN

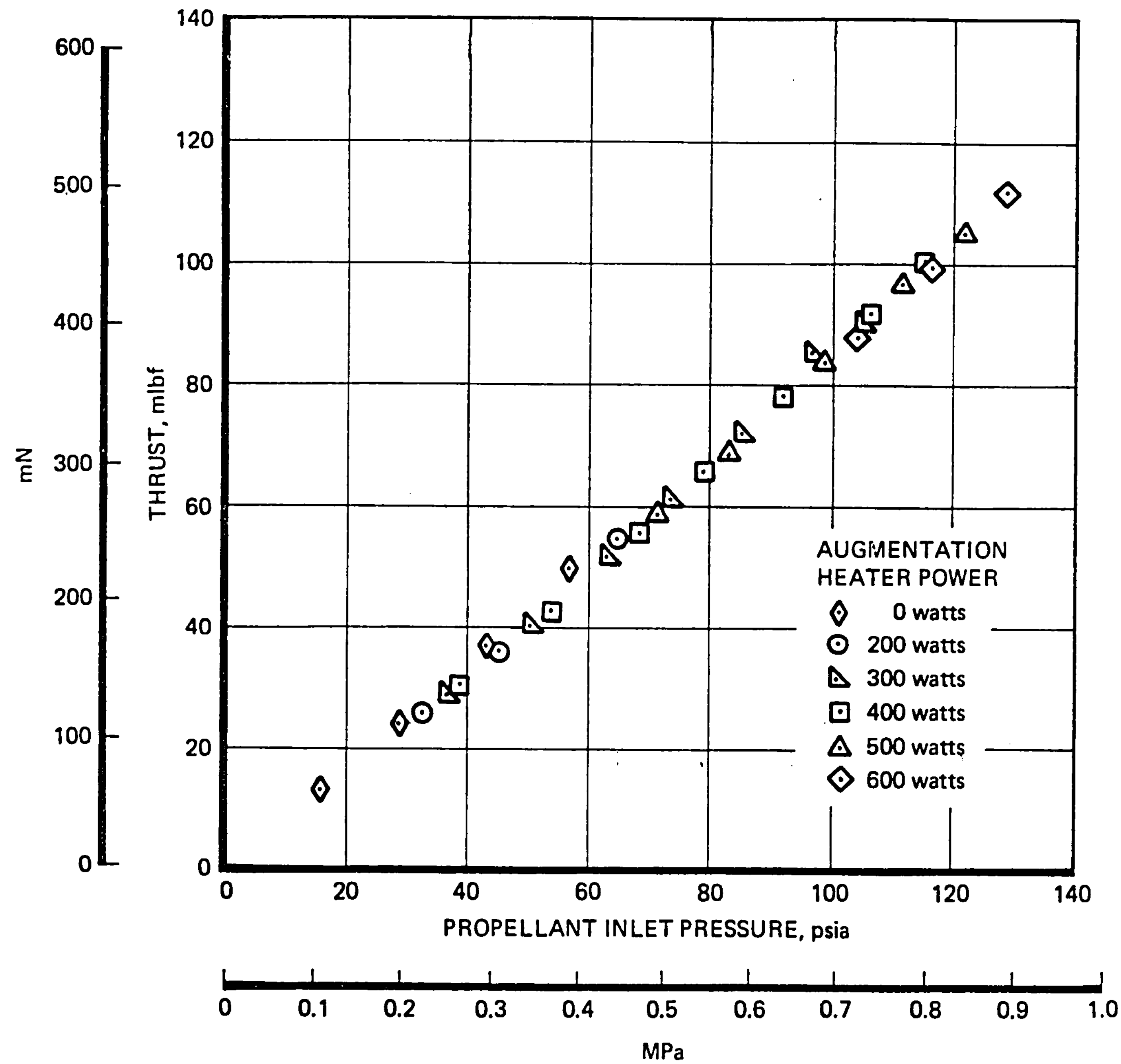

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Figure 4-3

RESISTOJET PERFORMANCE WITH NITROGEN

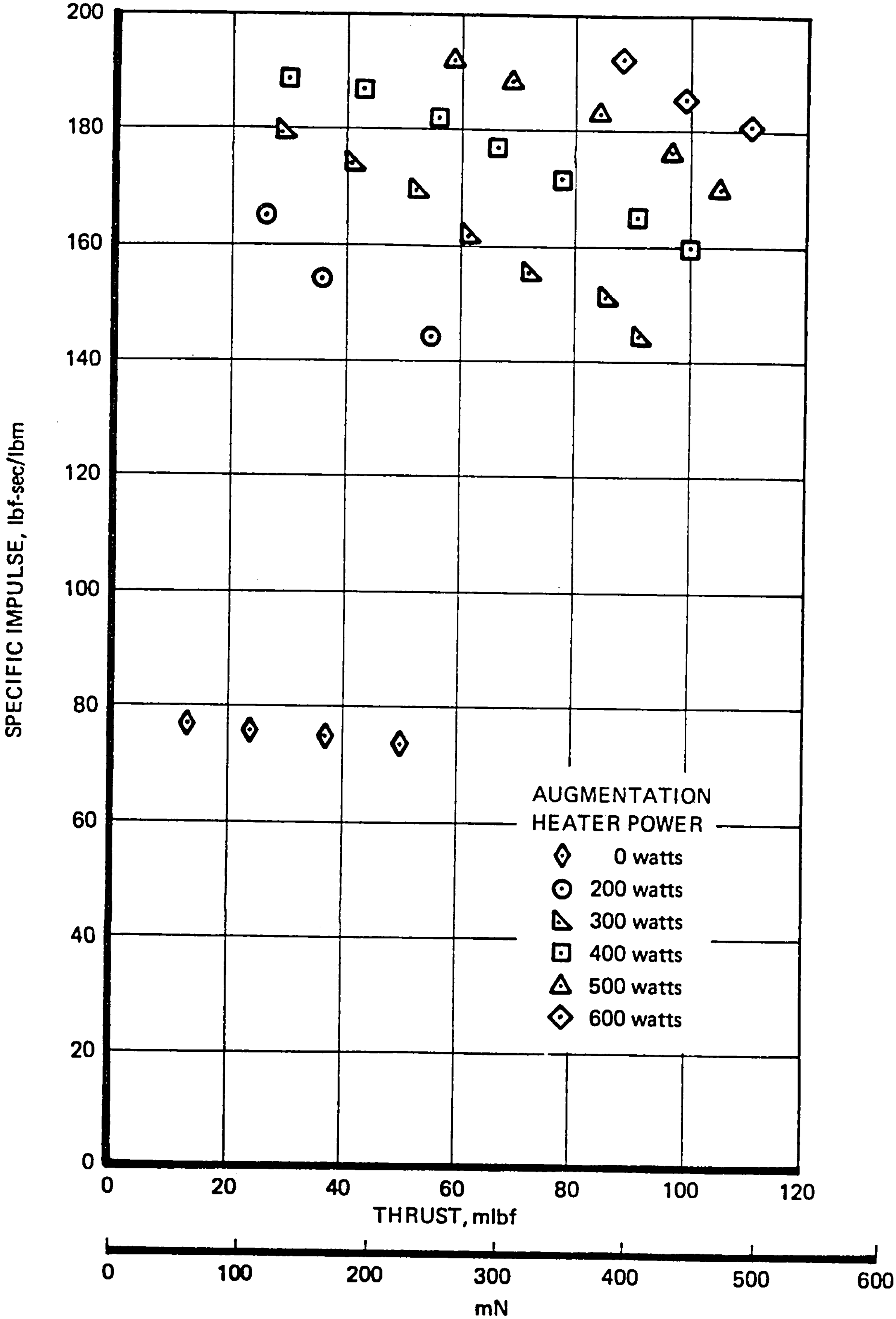

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Figure 4-4

THRUST VS INLET PRESSURE FOR AMMONIA

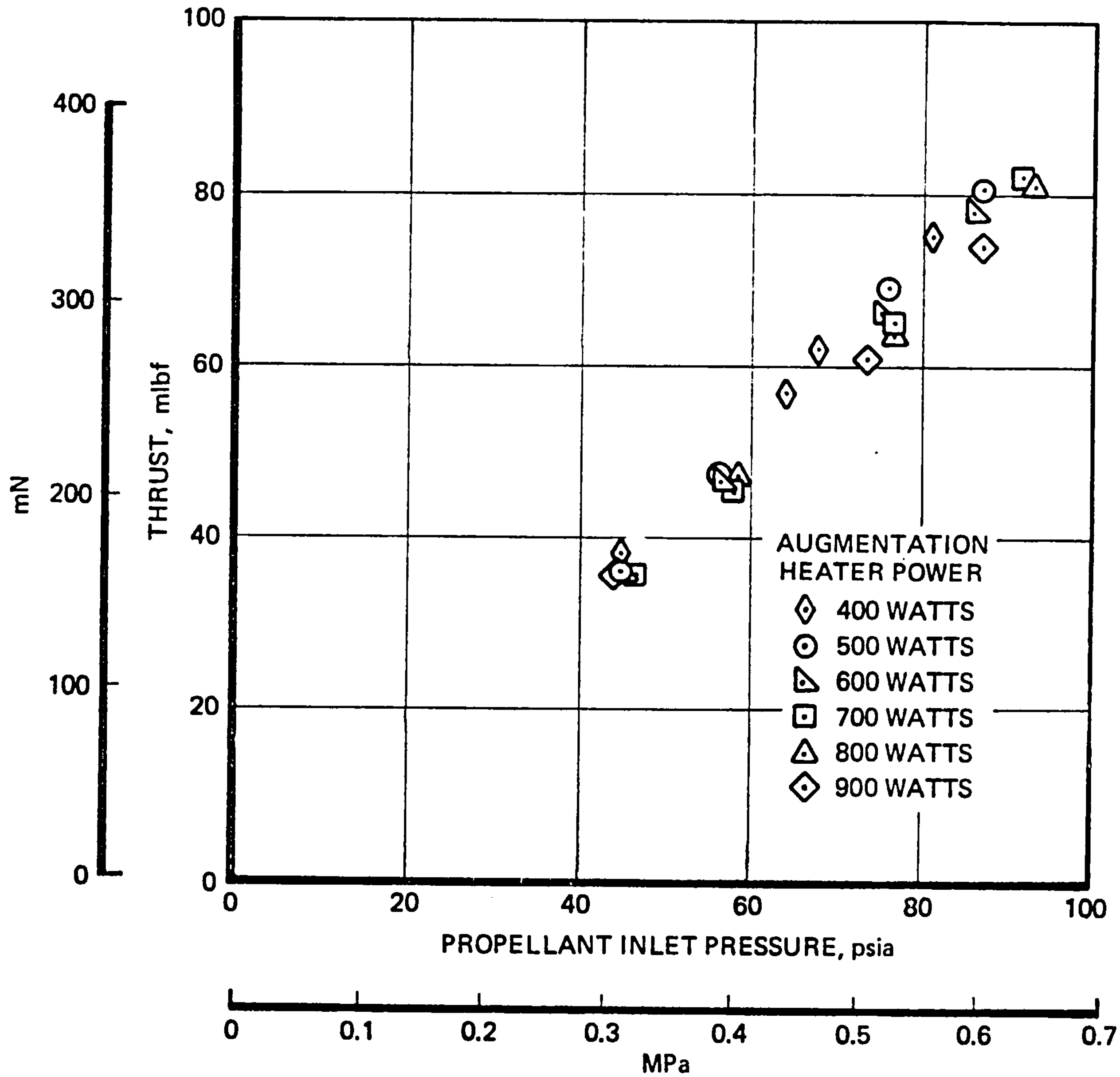

Figure 4-5

RESISTOJET PERFORMANCE WITH AMMONIA

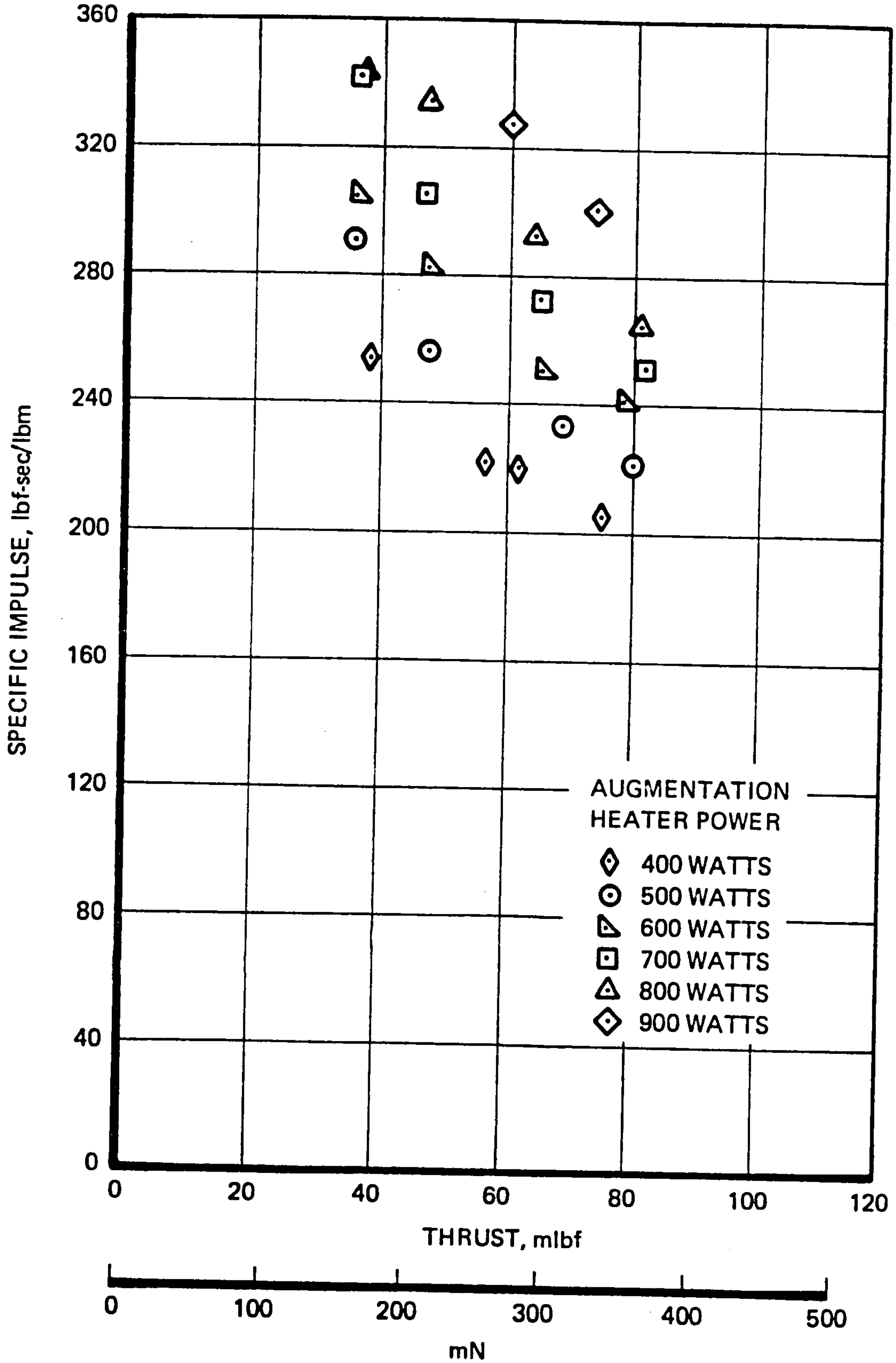

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Figure 4-6

RESISTOJET EFFICIENCY WITH HYDROGEN

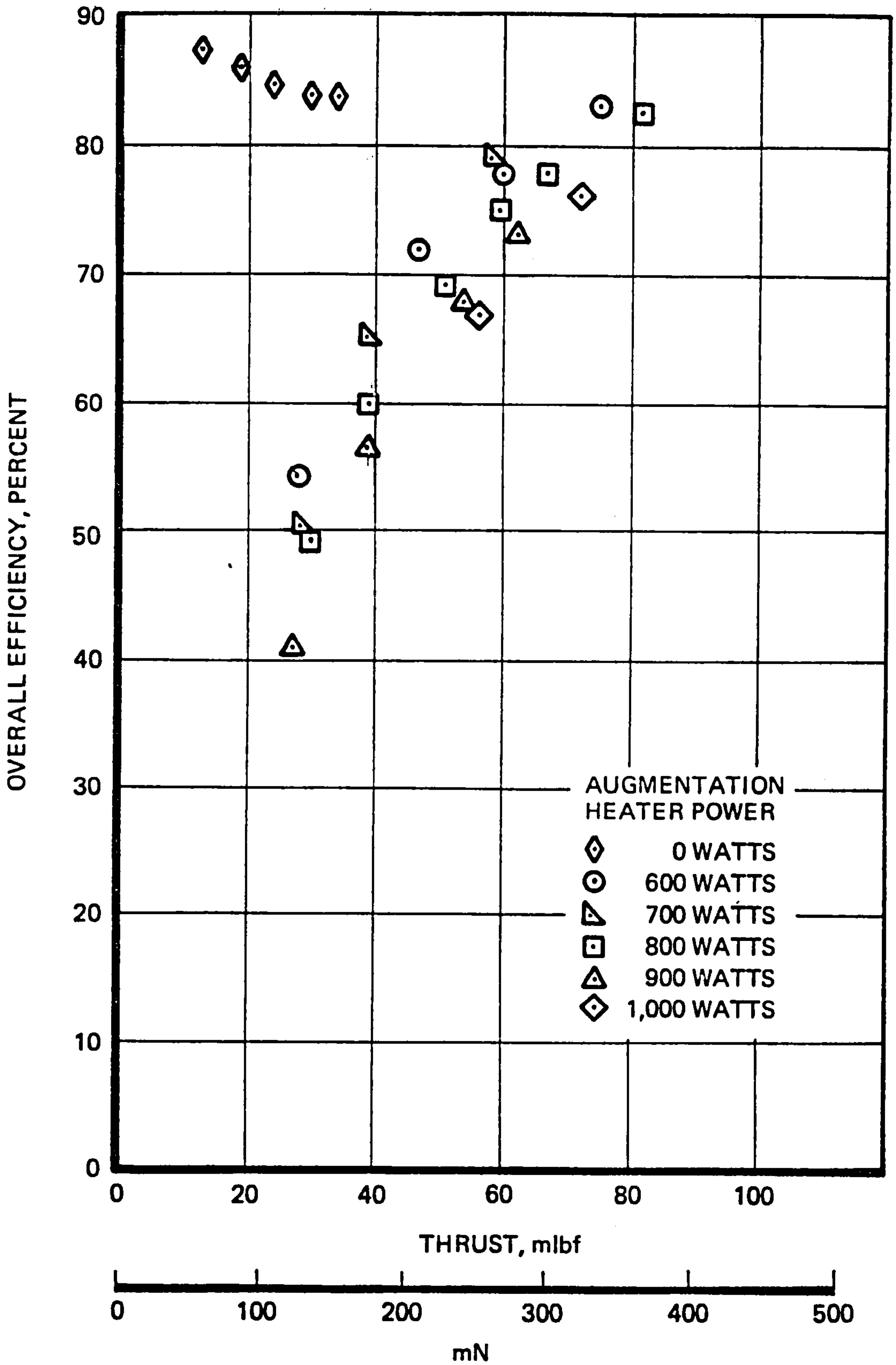

Figure 4-7

RESISTOJET EFFICIENCY WITH NITROGEN

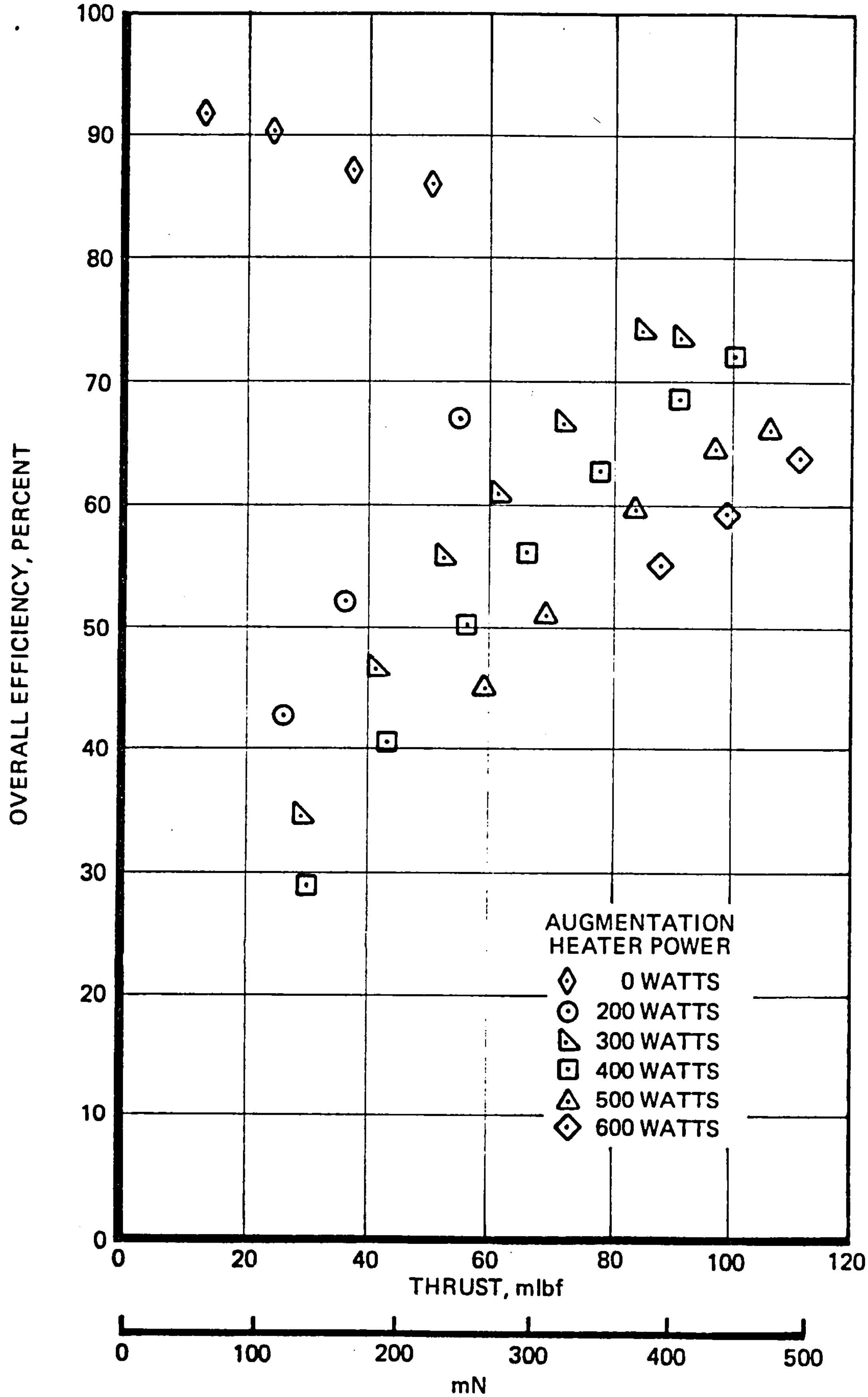

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Figure 4-8

RESISTOJET EFFICIENCY WITH AMMONIA

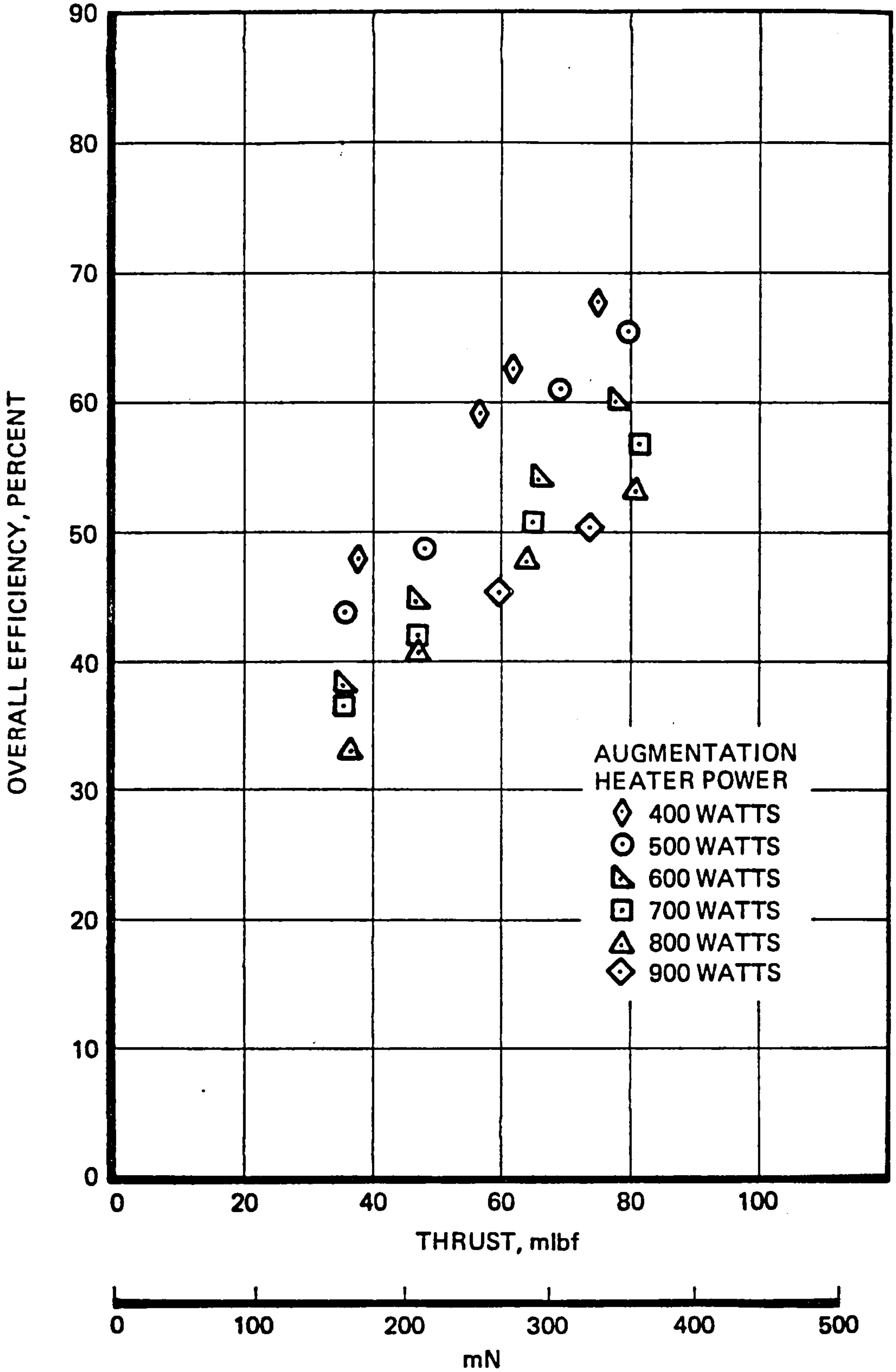

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Figure 4-9

Overall efficiency for nitrogen is shown in Figure 4-8 ranging from 28.9 to 73.5 percent. Efficiency trends are the same as hydrogen. Figure 4-9 shows overall efficiency for ammonia ranging from 33 to 67 percent. Efficiency trends are also the same as the other propellants.

For unaugmented runs with both hydrogen and nitrogen efficiency is relatively high and shows a decreasing trend as thrust increases. Since no energy is added to the gas stream, the overall efficiency should primarily be a measure of nozzle efficiency. This trend could be a result of test cell backpressure effects on the nozzle or flow rate measurement errors due to the relatively large calibration density correction that needs to be applied to the unpowered runs.

4.3 POST-TEST HARDWARE EXAMINATION

Post test visual examination verified that no degradation had occurred in the heater or heat exchanger. Thermal control shielding also showed no degradation. The support structure and mounting bracket were slightly discolored due to heating, as expected. The heater element was not affected. Heater circuit resistance remained nominal and visual examination under magnification revealed no material degradation. Visual examination of the nozzle throat reveals no deposition in the throat or material degradation.

5.0 SUMMARY AND CONCLUSION

The flight qualified augmentation assembly from the ACT demonstrated the capability to perform effectively as a resistojet with hydrogen, nitrogen or ammonia. A specific impulse of 687 lbf-sec/lbm was demonstrated with hydrogen. Overall efficiencies as high as 82.9 percent were also verified within the test matrix conducted. Nitrogen specific impulse ranged up to 191.6 lbf-sec/lbm and overall efficiency of up to 73.5 percent was measured. Ammonia specific impulse to 342 lbf-sec/lbm and efficiency up to 67 percent was also demonstrated. All testing was conducted with inlet propellant at ambient conditions to an ummodified ACT augmentation assembly. Testing verified the capability to produce high performance and efficiency in a thrust range of 133.5 mN - 890 mN (30 - 200 mlbf) for potential space station applications.

This test demonstrated the gas resistojet performance capability of the ACT augmentation assembly. Future investigations should address the capability of conceptually similar optimized resistojet designs to survive space station mission life requirements. Life testing combined with the results of the performance mapping, conducted herein, would provide a data base upon which to build required resistojet technology for space station propulsion system planning and application.

REFERENCES

1. McKevitt, F. X., "Design and Development Approach for the Augmented Catalytic Thruster (ACT), AIAA 83-1255.

2. Feconda, R. T., and Weizman, J.I., "Satellite Reaction Control Subsystem with Augmented Catalytic Thrusters", AIAA 84-1235.

APPENDIX A — RAW TEST DATA, REDUCED TEST DATA

RAW TEST DATA

ENGLISH/METRIC UNITS

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR HYDROGEN

SEQ	Pinlet (psia)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mlbf)	Tinlet (F)	P1 (psia)	P2 (psia)	Ttube (F)	Tstruc (F)	Tmount (F)	Pa (psia)
7	87.00	33.60	29.79	71.23	99.4	292.80	86.90	132.3	554.4	252.2	0.0157
8	81.10	29.39	27.24	66.09	107.5	293.90	82.80	134.1	485.8	259.7	0.0152
9	64.70	29.59	27.04	52.46	121.2	205.20	64.30	165.9	511.7	322.5	0.0112
10	68.10	31.69	28.31	53.14	125.3	211.00	67.90	177.1	672.2	352.0	0.0111
11	70.60	33.74	29.64	55.26	130.0	212.60	70.50	189.1	735.2	382.6	0.0112
12	39.40	28.18	24.92	23.13	150.3	103.90	39.20	279.4	935.7	474.2	0.0255
13	41.70	30.49	25.32	29.92	140.6	107.50	41.50	229.5	1017.5	524.8	0.0255
14	37.90	32.09	27.29	26.70	137.7	91.50	37.20	352.4	1181.7	615.9	0.0247
15	51.90	29.68	25.98	38.85	122.5	145.00	51.00	211.5	782.6	394.2	0.0275
16	49.90	27.33	25.60	38.52	110.6	146.20	45.20	179.8	688.3	337.8	0.0274
17	52.40	31.99	28.09	39.02	134.5	141.60	51.70	251.5	911.9	454.1	0.0274
18	69.50	26.88	25.98	56.97	122.3	247.40	69.00	155.8	503.4	287.3	0.0134
19	73.20	26.93	27.64	58.92	121.9	251.20	72.50	152.9	546.2	321.1	0.0130
20	76.30	30.99	28.99	61.20	102.0	250.80	76.20	145.8	575.2	293.6	0.0135
21	77.90	32.43	29.69	61.78	110.8	250.00	78.00	159.9	615.3	315.2	0.0130
22	97.00	28.53	26.04	80.88	104.9	390.90	97.30	129.8	449.7	255.8	0.0222
23	89.50	24.37	24.61	74.20	100.0	395.10	89.40	119.1	374.0	218.2	0.0222
24	73.20	24.47	24.55	59.25	103.4	290.90	73.00	127.7	410.7	230.8	0.0122
25	58.90	24.67	24.32	45.95	115.8	205.10	58.60	152.2	491.2	269.4	0.0111
26	38.40	25.27	23.79	27.38	137.7	105.20	38.40	242.5	732.0	395.7	0.0057
27	42.60	0.00	0.00	33.48	85.8	235.90	42.90	125.7	75.3	71.7	0.0157
28	36.80	0.00	0.00	28.72	89.4	252.10	35.90	15.5	75.3	73.0	0.0141
29	29.90	0.00	0.00	23.06	93.8	199.70	30.00	-72.3	79.9	73.9	0.0111
30	23.90	0.00	0.00	18.20	96.7	154.00	24.10	97.8	81.4	74.8	0.0255
31	17.00	0.00	0.00	12.62	104.8	103.20	17.30	95.9	84.1	75.7	0.0257

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR NITROGEN

SEQ	Pinlet (psia)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mlbf)	Tinlet (F)	P1 (psia)	P2 (psia)	Ttube (F)	Tstruc (F)	Tmount (F)	Pa (psia)
55	91.70	20.82	19.21	77.80	124.1	295.40	91.30	391.6	789.9	364.3	0.0240
56	96.50	24.09	20.79	84.05	114.7	299.00	95.30	455.4	897.2	427.5	0.0238
57	103.50	27.03	23.21	67.82	141.1	323.50	103.50	558.6	1016.5	522.3	0.0232
58	114.70	20.77	19.26	100.24	138.3	397.70	114.60	273.0	679.1	354.4	0.0252
59	122.40	23.68	21.19	105.33	140.6	357.90	122.20	325.2	734.1	427.9	0.0232
60	126.70	25.98	22.95	111.27	144.7	358.50	128.60	377.2	883.0	481.3	0.0231
61	105.30	17.36	17.27	92.97	141.6	298.30	105.20	223.1	577.0	334.3	0.0233
62	85.40	17.41	17.23	72.03	147.8	322.50	85.00	332.6	650.0	345.8	0.0229
63	63.60	17.61	17.03	51.55	162.8	203.90	62.70	546.5	817.2	415.9	0.0236
64	67.80	21.27	18.80	55.93	145.8	203.80	67.60	550.1	955.7	475.1	0.0233
65	71.30	24.67	22.33	58.68	168.3	204.80	71.20	781.5	1086.8	573.9	0.0232
66	35.50	18.05	16.64	26.48	184.9	104.50	35.30	916.3	1030.4	533.7	0.0214
67	38.20	21.87	18.27	29.61	158.0	103.90	38.10	1070.3	1163.2	638.5	0.0214
68	33.30	13.86	14.35	26.10	201.9	103.60	33.30	753.5	855.3	466.1	0.0214
69	57.10	0.00	0.00	49.45	86.7	399.00	57.30	84.9	74.5	73.6	0.0255
70	43.20	0.00	0.00	36.47	101.7	299.00	43.00	97.9	73.6	74.8	0.0241
71	28.90	0.00	0.00	24.03	115.5	196.80	28.70	105.0	84.4	77.0	0.0227
72	16.30	0.00	0.00	13.16	127.9	105.10	16.20	113.7	87.7	79.3	0.0216
73	96.50	17.35	17.25	84.37	114.7	352.20	96.50	235.4	565.3	272.2	0.0247
74	105.40	20.76	19.17	92.92	129.5	353.20	105.40	329.6	717.5	366.0	0.0247
75	112.50	23.72	21.06	96.45	138.5	353.70	112.70	376.2	835.7	432.0	0.0243
76	116.70	26.08	23.09	99.00	128.4	352.00	116.50	435.6	945.5	475.1	0.0245
77	65.30	13.55	14.80	54.51	148.7	245.20	65.40	325.6	585.5	333.6	0.0233
78	73.20	17.45	17.05	60.90	155.2	245.40	73.50	430.4	735.0	350.0	0.0231
79	78.80	21.07	18.95	65.52	158.6	244.60	78.80	539.7	853.3	455.7	0.0233
80	82.60	24.42	20.47	68.72	167.6	243.40	83.70	651.6	1017.8	534.4	0.0231
81	44.90	13.65	14.57	35.86	121.7	149.40	45.00	494.1	672.3	327.2	0.0230
82	50.60	17.76	16.89	40.65	151.3	152.30	50.80	637.9	905.7	457.5	0.0230
83	53.60	21.56	16.61	43.02	169.8	152.20	53.90	844.4	1055.7	554.5	0.0230

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR AMMONIA

SEQ	Pinlet (psia)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mlbf)	Tinlet (F)	FLOWRATE (lbm/hr)	Ttube (F)	Tstruc (F)	Tmount (F)	Pe (psia)
33	81.30	19.86	20.13	74.58	101.80	1.3097	165.8	525.5	275.0	0.0252
34	86.70	22.67	22.13	80.21	106.60	1.3044	186.3	594.1	318.9	0.0253
35	86.20	25.17	23.83	77.68	122.20	1.1654	232.6	650.3	361.9	0.0254
36	92.00	27.43	25.50	81.27	124.20	1.1701	239.5	664.5	358.7	0.0253
37	93.40	29.58	27.13	80.98	132.50	1.1042	269.4	694.6	373.3	0.0259
38	87.00	31.89	28.28	73.93	112.10	0.8871	321.3	770.2	385.8	0.0255
39	63.60	20.07	19.94	57.16	129.00	0.9294	260.9	626.7	352.0	0.0237
40	56.50	22.76	21.97	47.37	147.10	0.6669	371.0	683.1	366.6	0.0241
41	57.30	25.28	23.76	46.58	157.70	0.5946	431.6	737.8	390.8	0.0243
42	57.90	27.94	25.04	46.34	160.90	0.5480	520.5	851.1	445.1	0.0243
43	58.10	30.79	25.93	46.61	176.30	0.5035	596.2	1019.4	532.1	0.0235
44	68.20	20.22	19.77	61.85	145.90	1.0181	255.0	618.0	359.2	0.0241
47	76.80	27.68	25.31	64.87	145.90	0.8599	330.1	704.0	377.9	0.0256
46	76.20	25.37	23.69	66.14	137.40	0.9547	288.7	672.6	364.9	0.0251
45	76.40	22.98	21.76	69.12	124.10	1.0635	236.2	633.5	341.4	0.0245
48	77.40	29.78	26.87	64.03	153.80	0.7912	374.0	750.0	398.9	0.0259
49	73.50	32.29	27.85	60.13	166.20	0.6529	460.8	919.0	490.4	0.0252
50	45.30	20.07	19.92	37.85	118.00	0.5354	400.9	674.9	311.2	0.0232
51	45.30	22.87	21.82	36.08	145.00	0.4492	491.4	753.9	373.1	0.0233
52	45.40	25.78	23.26	36.05	163.70	0.4274	609.1	916.2	454.2	0.0230
53	45.70	28.68	24.34	35.57	178.70	0.3761	717.0	1056.3	545.2	0.0229
54	46.60	31.49	25.37	36.47	189.10	0.3852	793.1	1169.9	620.0	0.0225

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR HYDROGEN
(metric units)

SEQ	Pinlet (MPa)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mN)	Tinlet (C)	P1 (MPa)	P2 (MPa)	Ttube (C)	Tstruc (C)	Tmount (C)	Pa (kPa)
7	0.599	33.60	29.79	316.83	37.4	2.017	0.599	55.7	290.2	137.9	0.108
8	0.559	29.39	27.24	294.00	41.9	2.025	0.557	56.7	254.3	132.1	0.110
9	0.446	29.59	27.04	224.47	49.6	1.421	0.443	74.4	322.1	161.4	0.076
10	0.469	31.69	28.31	236.36	52.4	1.454	0.468	80.6	354.6	177.8	0.076
11	0.486	33.74	29.64	245.82	54.4	1.465	0.486	87.3	391.1	194.9	0.077
12	0.271	28.18	24.92	125.14	65.7	0.716	0.270	137.4	503.7	245.7	0.038
13	0.287	30.48	26.32	133.11	60.3	0.741	0.287	143.1	547.5	262.7	0.039
14	0.261	33.09	27.29	118.78	58.7	0.630	0.256	182.4	638.7	324.4	0.032
15	0.358	29.68	26.98	173.01	50.3	1.006	0.351	99.7	417.6	195.7	0.052
16	0.344	27.33	25.60	171.33	43.8	1.007	0.339	81.6	364.6	169.9	0.051
17	0.361	31.99	28.09	173.57	56.9	0.976	0.356	121.9	488.8	234.5	0.051
18	0.479	26.88	25.98	253.43	50.2	1.705	0.475	69.3	261.9	141.8	0.092
19	0.504	28.93	27.64	262.07	49.9	1.731	0.500	71.6	285.7	149.5	0.094
20	0.526	30.99	28.99	272.21	38.9	1.728	0.525	63.8	301.8	145.3	0.094
21	0.537	32.43	29.89	274.79	43.8	1.723	0.537	71.1	324.1	159.0	0.094
22	0.668	28.53	28.04	359.78	40.5	2.693	0.670	54.3	232.1	126.0	0.154
23	0.617	24.37	24.61	330.05	37.8	2.722	0.616	48.4	190.0	103.4	0.157
24	0.504	24.47	24.55	263.54	39.7	2.004	0.503	53.2	210.4	110.4	0.112
25	0.406	24.67	24.32	204.58	46.6	1.413	0.404	66.8	255.1	131.9	0.076
26	0.265	25.27	23.79	121.81	58.7	0.725	0.265	117.2	422.2	202.1	0.039
27	0.294	0.00	0.00	148.94	29.9	2.039	0.296	52.1	24.6	22.1	0.115
28	0.254	0.00	0.02	127.77	31.9	1.737	0.254	-9.2	25.7	22.8	0.097
29	0.206	0.00	0.00	102.57	34.3	1.376	0.207	-57.9	26.6	23.3	0.076
30	0.165	0.00	0.00	80.95	37.1	1.061	0.166	36.6	27.4	23.8	0.059
31	0.117	0.00	0.00	56.15	40.4	0.711	0.119	37.2	28.9	24.3	0.039

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR NITROGEN
(metric units)

SEQ	Pinlet (MPa)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mN)	Tinlet (C)	P1 (MPa)	P2 (MPa)	Ttube (C)	Tstruc (C)	Tmount (C)	Pa (kPa)
55	0.632	20.82	19.21	346.06	51.2	2.035	0.629	199.8	409.9	184.6	0.028
56	0.679	24.09	20.79	374.00	45.9	2.060	0.677	235.8	480.7	219.7	0.026
57	0.713	27.09	22.21	390.65	60.6	2.084	0.713	292.6	546.9	272.4	0.027
58	0.790	20.77	19.26	445.88	59.1	2.740	0.790	136.7	359.5	184.7	0.036
59	0.843	23.68	21.19	468.53	60.3	2.742	0.842	162.9	417.8	208.8	0.036
60	0.887	25.98	22.95	494.97	62.6	2.746	0.886	191.8	475.6	238.5	0.035
61	0.726	17.36	17.27	404.65	60.9	2.744	0.725	115.1	302.8	162.4	0.037
62	0.588	17.41	17.23	320.42	64.3	2.070	0.586	167.0	348.9	174.3	0.027
63	0.431	17.61	17.02	229.49	72.7	1.384	0.432	286.9	436.2	213.8	0.018
64	0.467	21.27	18.80	248.74	63.2	1.404	0.466	343.4	513.7	246.7	0.018
65	0.491	24.67	20.32	261.00	75.7	1.411	0.491	416.4	586.0	300.5	0.018
66	0.251	18.06	16.64	126.67	84.9	0.721	0.250	491.3	549.1	278.7	0.010
67	0.263	21.87	18.27	131.73	92.2	0.716	0.263	576.8	627.9	331.4	0.010
68	0.229	13.86	14.35	116.12	94.4	0.714	0.229	400.8	457.4	241.2	0.010
69	0.393	0.00	0.00	219.94	30.4	2.749	0.395	29.4	23.6	22.6	0.038
70	0.298	0.00	0.00	162.21	38.7	2.060	0.296	36.6	26.4	23.8	0.028
71	0.199	0.00	0.00	106.84	46.4	1.356	0.198	42.2	29.1	25.0	0.019
72	0.112	0.00	0.00	58.55	53.3	0.731	0.112	45.4	30.9	26.3	0.011
73	0.665	17.35	17.25	375.28	45.9	2.427	0.665	113.0	296.8	133.4	0.032
74	0.726	20.76	19.17	404.42	54.2	2.434	0.726	154.2	380.8	185.6	0.032
75	0.775	23.72	21.08	429.02	59.2	2.437	0.777	192.3	447.1	221.1	0.032
76	0.804	26.08	23.09	440.38	53.6	2.412	0.803	224.8	507.5	246.2	0.032
77	0.450	13.55	14.80	242.49	64.8	1.689	0.451	163.1	308.1	162.1	0.023
78	0.504	17.46	17.09	270.88	68.4	1.691	0.506	221.3	392.2	193.3	0.021
79	0.543	21.07	18.95	291.45	70.3	1.685	0.543	282.1	476.3	235.4	0.022
80	0.569	24.42	20.47	305.68	75.3	1.677	0.570	344.2	547.2	279.1	0.021
81	0.309	13.65	14.57	159.52	49.8	1.029	0.310	256.7	355.7	152.9	0.014
82	0.349	17.76	16.89	180.83	66.3	1.049	0.350	364.4	485.4	236.4	0.014
83	0.369	21.56	18.61	191.36	76.6	1.049	0.371	451.3	568.7	290.3	0.014

TEST RESULTS FROM NASA RESISTOJET PERFORMANCE MAPPING TEST FOR AMMONIA
(metric units)

SEQ	Pinlet (MPa)	VOLTAGE (vdc)	CURRENT (amp)	THRUST (mN)	Tinlet (C)	FLOWRATE (kg/hr)	Ttube (C)	Tstruc (C)	Tmount (C)	Pa (kPa)
33	0.560	19.86	20.13	326.97	38.78	0.5946	74.3	274.2	137.2	0.036
34	0.597	22.67	22.13	351.93	41.44	0.5922	85.7	312.3	159.4	0.037
35	0.594	25.17	23.83	341.46	50.11	0.5291	111.4	349.1	183.3	0.037
36	0.634	27.43	25.50	355.72	51.22	0.5312	115.3	351.4	181.5	0.043
37	0.644	29.58	27.13	353.85	55.83	0.5013	131.9	368.1	189.6	0.048
38	0.599	31.89	28.28	322.86	44.50	0.4027	166.3	410.1	196.6	0.045
39	0.438	20.07	19.94	250.87	53.89	0.4220	127.2	331.5	177.8	0.025
40	0.389	22.78	21.97	206.95	63.94	0.3028	188.3	361.2	185.9	0.028
41	0.395	25.28	23.76	203.22	69.83	0.2699	222.0	392.1	199.3	0.030
42	0.399	27.94	25.04	202.42	71.61	0.2488	271.4	460.6	229.5	0.028
43	0.400	30.79	25.99	203.81	80.17	0.2281	313.4	548.6	277.8	0.026
44	0.470	20.22	19.77	271.37	63.28	0.4622	123.9	325.6	181.8	0.028
47	0.529	27.68	25.31	283.40	63.28	0.3904	165.6	373.3	192.2	0.039
46	0.525	25.37	23.69	289.52	58.56	0.4334	142.6	355.9	184.9	0.035
45	0.526	22.98	21.76	303.23	51.17	0.4856	114.6	333.6	171.9	0.032
48	0.533	29.78	26.87	279.38	67.67	0.3592	190.0	398.9	203.8	0.041
49	0.506	32.29	27.86	262.88	74.56	0.3010	238.2	492.8	249.1	0.034
50	0.312	20.07	19.92	165.60	47.78	0.2435	206.1	357.2	155.1	0.021
51	0.312	22.87	21.82	157.42	62.78	0.2035	255.2	401.1	189.5	0.023
52	0.313	25.78	23.26	157.59	73.17	0.1940	320.6	491.2	234.6	0.021
53	0.315	28.68	24.34	155.57	81.50	0.1707	380.6	575.7	285.7	0.020
54	0.321	31.49	25.37	159.56	87.28	0.1749	422.8	632.2	326.7	0.020

REDUCED TEST DATA

ENGLISH/METRIC UNITS

TEST RESULTS FROM NASA RESISTOJET
datafile = h2test

RUN	P1 psia	P2 psia	PINLET psia	POWER watts	FLOW lb/hr	THRUST mlbf	ISP *	PSP w/mlb	Tin F	EFF %	Tw F	Eh vdc	Ih amp
7	292.8	86.9	87.0	1000.9	0.434	72.0	597.7	13.89	99	76.167	4068	33.60	29.79
8	293.9	80.8	81.1	800.6	0.436	66.9	552.5	11.96	108	78.015	3882	29.39	27.24
9	206.2	64.3	64.7	800.1	0.308	51.0	597.5	15.68	121	68.949	3941	29.59	27.04
10	211.0	67.9	68.1	897.1	0.313	53.7	618.2	16.70	126	68.039	4036	31.69	28.31
11	212.6	70.5	70.6	1000.1	0.314	55.8	641.0	17.91	130	66.854	4107	33.74	29.64
12	103.9	39.2	39.4	702.2	0.159	28.4	643.8	24.71	150	50.679	4079	28.18	24.92
13	107.5	41.6	41.7	802.2	0.164	30.2	664.0	26.55	141	49.164	4182	30.48	26.32
14	91.5	37.2	37.9	903.0	0.141	26.9	686.9	33.51	138	41.244	4389	33.09	27.29
15	146.0	51.0	51.9	800.8	0.221	39.3	641.2	20.38	123	59.793	3963	29.68	26.98
16	146.2	49.2	49.9	699.6	0.223	38.9	628.8	17.98	111	65.155	3839	27.33	25.60
17	141.6	51.7	52.4	898.6	0.213	39.4	667.2	22.80	135	56.634	4109	31.99	28.09
18	247.4	69.0	69.5	698.3	0.368	57.7	564.1	12.11	122	79.262	3715	26.88	25.98
19	251.2	72.5	73.2	799.6	0.372	59.6	576.8	13.41	122	75.115	3760	28.93	27.64
20	250.8	76.2	76.3	898.4	0.374	61.9	596.4	14.51	102	73.318	3845	30.99	28.99
21	250.0	78.0	77.9	969.3	0.370	62.5	607.6	15.51	111	70.935	3905	32.43	29.89
22	390.8	97.3	97.0	800.0	0.578	82.0	511.3	9.75	105	82.533	3650	28.53	28.04
23	395.1	89.4	89.5	599.7	0.589	75.4	461.1	7.96	100	82.934	3547	24.37	24.61
24	290.9	73.0	73.2	600.7	0.435	60.1	497.1	10.00	103	78.190	3571	24.47	24.55
25	205.1	58.6	58.9	600.0	0.309	46.6	542.4	12.88	116	72.000	3638	24.67	24.32
26	105.2	38.4	38.4	601.2	0.162	27.7	613.7	21.72	138	53.843	3819	25.27	23.79
27	295.9	42.9	42.6	0.0	0.454	34.4	272.3	0.00	86	84.129	70	0.00	0.00
28	252.1	36.9	36.8	0.0	0.389	29.5	272.4	0.00	89	84.228	70	0.00	0.00
29	199.7	30.0	29.9	0.0	0.312	23.6	273.1	0.00	94	84.634	70	0.00	0.00
30	154.0	24.1	23.9	0.0	0.244	18.6	275.5	0.00	99	86.140	70	0.00	0.00
31	103.2	17.3	17.0	0.0	0.168	12.9	277.4	0.00	105	87.329	70	0.00	0.00

* specific impulse units : lbf-sec/lbm

TEST RESULTS FROM NASA RESISTOJET

datafile = n2test

RUN	P1 psia	P2 psia	PINLET psia	POWER watts	FLOW lb/hr	THRUST mlbf	ISP *	PSP w/mlb	Tin F	EFF %	Tw F	Eh vdc	Ih amp
55	295.4	91.3	91.7	400.0	1.642	78.0	171.1	5.13	124	62.699	3901	20.82	19.21
56	299.0	98.3	98.6	500.8	1.656	84.3	183.2	5.94	115	59.532	4185	24.09	20.79
57	302.5	103.5	103.5	601.7	1.654	88.0	191.6	6.84	141	55.177	4416	27.09	22.21
58	397.7	114.6	114.7	400.0	2.259	100.5	160.2	3.98	138	71.898	3880	20.77	19.26
59	397.9	122.2	122.4	501.8	2.241	105.6	169.7	4.75	141	66.285	4029	23.68	21.19
60	398.5	128.6	128.7	596.2	2.225	111.5	180.5	5.35	145	64.245	4084	25.98	22.95
61	398.3	105.2	105.3	299.8	2.284	91.2	143.8	3.29	142	73.557	3603	17.36	17.27
62	300.5	85.0	85.4	300.0	1.682	72.2	154.6	4.15	148	66.578	3623	17.41	17.23
63	202.9	62.7	62.6	299.7	1.103	51.7	168.8	5.79	163	55.550	3715	17.61	17.02
64	203.8	67.6	67.8	399.9	1.110	56.1	181.8	7.13	146	50.123	4081	21.27	18.80
65	204.8	71.2	71.3	501.3	1.105	58.8	191.6	8.52	168	45.113	4394	24.67	20.32
66	104.6	36.3	36.5	300.5	0.576	28.6	178.4	10.53	185	34.382	3907	18.06	16.64
67	103.9	38.1	38.2	399.6	0.566	29.7	188.7	13.46	198	28.962	4330	21.87	18.27
68	103.6	33.3	33.3	198.9	0.572	26.2	164.8	7.60	202	42.508	3454	13.86	14.35
69	399.0	57.3	57.1	0.0	2.405	49.7	74.4	0.00	87	86.019	70	0.00	0.00
70	299.0	43.0	43.2	0.0	1.760	36.7	75.0	0.00	102	87.331	70	0.00	0.00
71	196.8	28.7	28.9	0.0	1.141	24.2	76.2	0.00	116	90.227	70	0.00	0.00
72	106.1	16.2	16.3	0.0	0.620	13.2	76.9	0.00	128	91.772	70	0.00	0.00
73	352.2	96.5	96.5	299.3	2.013	84.6	151.3	3.54	115	73.859	3605	17.35	17.25
74	353.2	105.4	105.4	398.0	1.995	91.2	164.5	4.37	130	68.697	3898	20.76	19.17
75	353.7	112.7	112.5	500.0	1.973	96.7	176.4	5.17	139	64.458	4058	23.72	21.08
76	350.0	116.5	116.7	602.2	1.936	99.2	184.6	6.07	128	58.919	4074	26.08	23.09
77	245.2	65.4	65.3	200.5	1.372	54.7	143.5	3.67	149	67.337	3264	13.55	14.80
78	245.4	73.5	73.2	298.4	1.357	61.1	162.0	4.89	155	61.367	3665	17.46	17.09
79	244.6	78.8	78.8	399.3	1.338	65.7	176.7	6.08	159	56.048	4007	21.07	18.95
80	243.4	82.7	82.6	499.9	1.318	68.9	188.2	7.26	168	51.252	4314	24.42	20.47
81	149.4	45.0	44.9	198.9	0.839	36.0	154.3	5.53	122	52.245	3344	13.65	14.57
82	152.3	50.8	50.6	300.0	0.842	40.8	174.3	7.36	151	46.537	3779	17.76	16.89
83	152.2	53.9	53.6	401.2	0.830	43.1	187.0	9.30	170	40.541	4184	21.56	18.61

* specific impulse units : lbf-sec/lbm

TEST RESULTS FROM NASA RESISTOJET
datafile = nh3test

RUN	P1 psia	P2 psia	PINLET psia	POWER watts	FLOW lb/hr	THRUST mlbf	ISP *	PSP w/mlb	Tin F	EFF %	Tw F	Eh vdc	Ih amp
33	0.0	0.0	81.3	399.8	1.310	74.9	205.7	5.34	102	67.671	3533	19.86	20.13
34	0.0	0.0	86.7	501.7	1.304	80.5	222.1	6.23	107	65.216	3676	22.67	22.13
35	0.0	0.0	86.2	599.8	1.165	78.2	241.4	7.67	122	60.011	3796	25.17	23.83
36	0.0	0.0	92.0	699.5	1.170	81.6	251.1	8.57	124	56.856	3870	27.43	25.50
37	0.0	0.0	93.4	802.5	1.104	81.3	265.2	9.87	133	53.212	3926	29.58	27.13
38	0.0	0.0	87.0	901.8	0.887	74.3	301.4	12.14	112	50.459	4067	31.89	28.28
39	0.0	0.0	63.6	400.2	0.929	57.4	222.1	6.98	129	59.278	3600	20.07	19.94
40	0.0	0.0	56.5	500.5	0.667	47.6	256.9	10.52	147	48.494	3723	22.78	21.97
41	0.0	0.0	57.3	600.7	0.595	46.8	283.4	12.83	158	44.873	3826	25.28	23.76
42	0.0	0.0	57.9	699.6	0.548	46.5	305.8	15.03	161	41.930	4022	27.94	25.04
43	0.0	0.0	58.1	800.2	0.503	46.8	335.3	17.10	176	40.866	4283	30.79	25.99
44	0.0	0.0	68.2	399.7	1.018	62.1	219.5	6.44	146	62.563	3670	20.22	19.77
47	0.0	0.0	76.8	700.6	0.860	65.2	272.8	10.75	146	50.743	3938	27.68	25.31
46	0.0	0.0	76.2	601.0	0.955	66.4	250.4	9.05	137	54.011	3852	25.37	23.69
45	0.0	0.0	76.4	500.0	1.070	69.4	233.5	7.21	124	60.997	3796	22.98	21.76
48	0.0	0.0	77.4	800.2	0.791	64.3	292.7	12.44	154	47.836	3994	29.78	26.87
49	0.0	0.0	73.5	899.6	0.663	60.4	328.0	14.90	166	45.532	4186	32.29	27.86
50	0.0	0.0	45.3	399.8	0.536	38.0	255.1	10.52	118	48.110	3612	20.07	19.92
51	0.0	0.0	45.3	499.0	0.448	36.2	291.1	13.77	145	43.245	3766	22.87	21.82
52	0.0	0.0	45.4	599.6	0.427	36.2	305.0	16.56	164	38.144	3994	25.78	23.26
53	0.0	0.0	45.7	698.1	0.376	35.7	342.0	19.54	179	36.699	4259	28.68	24.34
54	0.0	0.0	46.6	798.9	0.385	36.6	342.2	21.81	189	33.030	4497	31.49	25.37

* specific impulse units : lbf-sec/lbm

TEST RESULTS FROM NASA RESISTOJET
datafile = h2test
(metric units)

RUN	P1 MPa	P2 MPa	PINLET MPa	POWER watts	FLOW kg/hr	THRUST mN	ISP *	PSP kw/N	Tin C	EFF %	Tw C	Eh vdc	Ih amp
7	2.017	0.599	0.599	1000.9	0.1970	320.5	5856	3.12	37	76.167	2242	33.60	29.79
8	2.025	0.557	0.559	800.6	0.1980	297.7	5413	2.69	42	78.015	2139	29.39	27.24
9	1.421	0.443	0.446	800.1	0.1396	227.0	5854	3.52	50	68.949	2171	29.59	27.04
10	1.454	0.468	0.469	897.1	0.1420	238.9	6057	3.75	52	68.039	2224	31.69	28.31
11	1.465	0.486	0.486	1000.1	0.1424	248.4	6281	4.03	54	66.854	2264	33.74	29.64
12	0.716	0.270	0.271	702.2	0.0722	126.4	6308	5.55	66	50.679	2248	28.18	24.92
13	0.741	0.287	0.287	802.2	0.0744	134.4	6506	5.97	60	49.164	2306	30.48	26.32
14	0.630	0.256	0.261	903.0	0.0641	119.9	6730	7.53	59	41.244	2420	33.09	27.29
15	1.006	0.351	0.358	800.8	0.1002	174.8	6282	4.58	50	59.793	2184	29.68	26.98
16	1.027	0.339	0.344	699.6	0.1011	173.1	6161	4.04	44	65.155	2115	27.33	25.60
17	0.976	0.356	0.361	898.6	0.0965	175.3	6537	5.13	57	56.634	2265	31.99	28.09
18	1.705	0.475	0.479	698.3	0.1671	256.5	5527	2.72	50	79.262	2046	26.88	25.98
19	1.731	0.500	0.504	799.6	0.1690	265.2	5652	3.01	50	75.115	2071	28.93	27.64
20	1.728	0.525	0.526	898.4	0.1697	275.4	5843	3.26	39	73.318	2118	30.99	28.99
21	1.723	0.537	0.537	969.3	0.1681	278.0	5953	3.49	44	70.935	2152	32.43	29.89
22	2.693	0.670	0.668	800.0	0.2622	365.0	5010	2.19	41	82.533	2010	28.53	28.04
23	2.722	0.516	0.617	599.7	0.2672	335.4	4518	1.79	38	82.934	1953	24.37	24.61
24	2.004	0.503	0.504	600.7	0.1976	267.3	4871	2.25	40	78.190	1966	24.47	24.55
25	1.413	0.404	0.406	600.0	0.1403	207.2	5315	2.98	47	72.000	2003	24.67	24.32
26	0.725	0.265	0.265	601.2	0.0737	123.1	6013	4.88	59	53.843	2104	25.27	23.79
27	2.039	0.296	0.294	0.0	0.2062	152.8	2668	0.00	30	84.129	21	0.00	0.00
28	1.737	0.254	0.254	0.0	0.1768	131.1	2669	0.00	32	84.228	21	0.00	0.00
29	1.376	0.207	0.206	0.0	0.1415	105.2	2676	0.00	34	84.634	21	0.00	0.00
30	1.061	0.166	0.165	0.0	0.1106	82.9	2699	0.00	37	86.140	21	0.00	0.00
31	0.711	0.119	0.117	0.0	0.0761	57.5	2718	0.00	40	87.329	21	0.00	0.00

* specific impulse units : N-sec/kg

TEST RESULTS FROM NASA RESISTOJET

datafile = n2test

(metric units)

RUN	P1 MPa	P2 MPa	PINLET MPa	POWER watts	FLOW kg/hr	THRUST mN	ISP *	PSP kw/N	Tin C	EFF %	Tw C	Eh vdc	Ih amp
55	2.035	0.629	0.632	400.0	0.7453	347.0	1676	1.15	51	62.699	2149	20.82	19.21
56	2.060	0.677	0.679	500.8	0.7518	374.9	1795	1.34	46	59.532	2307	24.09	20.79
57	2.004	0.713	0.713	601.7	0.7511	391.6	1877	1.54	61	55.177	2435	27.09	22.21
58	2.740	0.790	0.790	400.0	1.0255	447.1	1569	0.89	59	71.898	2138	20.77	19.26
59	2.742	0.842	0.843	501.8	1.0174	469.7	1662	1.07	60	66.285	2220	23.68	21.19
60	2.746	0.886	0.887	596.2	1.0102	496.2	1768	1.20	63	64.245	2251	25.98	22.95
61	2.744	0.725	0.726	299.8	1.0369	405.9	1409	0.74	61	73.557	1904	17.36	17.27
62	2.070	0.586	0.588	300.0	0.7638	321.3	1514	0.93	64	66.578	1995	17.41	17.23
63	1.384	0.432	0.431	299.7	0.5007	230.1	1654	1.30	73	55.550	2046	17.61	17.02
64	1.404	0.466	0.467	399.9	0.5040	249.3	1781	1.60	63	50.123	2250	21.27	18.80
65	1.411	0.491	0.491	501.3	0.5018	261.6	1877	1.92	76	45.113	2424	24.67	20.32
66	0.721	0.250	0.251	300.5	0.2615	127.0	1748	2.37	85	34.382	2153	18.06	16.64
67	0.716	0.263	0.263	399.6	0.2571	132.1	1849	3.03	92	28.962	2388	21.87	18.27
68	0.714	0.229	0.229	198.9	0.2596	116.4	1614	1.71	94	42.508	1901	13.86	14.35
69	2.749	0.395	0.393	0.0	1.0919	221.2	729	0.00	30	86.019	21	0.00	0.00
70	2.060	0.296	0.298	0.0	0.7992	163.2	735	0.00	39	87.331	21	0.00	0.00
71	1.356	0.198	0.199	0.0	0.5179	107.5	747	0.00	46	90.227	21	0.00	0.00
72	0.731	0.112	0.112	0.0	0.2815	58.9	753	0.00	53	91.772	21	0.00	0.00
73	2.427	0.665	0.665	299.3	0.9141	376.4	1482	0.80	46	73.859	1985	17.35	17.25
74	2.434	0.726	0.726	398.0	0.9059	405.5	1612	0.98	54	68.697	2148	20.76	19.17
75	2.437	0.777	0.775	500.0	0.8956	430.1	1729	1.16	59	64.458	2237	23.72	21.08
76	2.412	0.803	0.804	602.2	0.8788	441.5	1808	1.36	54	58.919	2246	26.08	23.09
77	1.689	0.451	0.450	200.5	0.6229	243.3	1406	0.82	65	67.337	1795	13.55	14.80
78	1.691	0.506	0.504	298.4	0.6161	271.6	1587	1.10	68	61.367	2019	17.46	17.09
79	1.685	0.543	0.543	399.3	0.6076	292.2	1731	1.37	70	56.048	2208	21.07	18.95
80	1.677	0.570	0.569	499.9	0.5983	306.4	1844	1.63	75	51.252	2379	24.42	20.47
81	1.029	0.310	0.309	198.9	0.3809	160.0	1512	1.24	50	52.245	1840	13.65	14.57
82	1.049	0.350	0.349	300.0	0.3821	181.3	1708	1.65	66	46.537	2081	17.76	16.89
83	1.049	0.371	0.369	401.2	0.3769	191.8	1832	2.09	77	40.541	2307	21.56	18.61

* specific impulse units : N-sec/kg

TEST RESULTS FROM NASA RESISTOJET
datafile = nh3test
(metric units)

RUN	P1 MPa	P2 MPa	PINLET MPa	POWER watts	FLOW kg/hr	THRUST mN	ISP *	PSP kw/N	Tin C	EFF %	Tw C	Eh vdc	Ih amp
33	0.000	0.000	0.560	399.8	0.5946	333.0	2016	1.20	39	67.671	1945	19.86	20.13
34	0.000	0.000	0.597	501.7	0.5922	358.0	2176	1.40	41	65.216	2024	22.67	22.13
35	0.000	0.000	0.594	599.8	0.5291	347.7	2366	1.73	50	60.011	2091	25.17	23.83
36	0.000	0.000	0.634	699.5	0.5312	363.0	2460	1.93	51	56.856	2132	27.43	25.50
37	0.000	0.000	0.644	802.5	0.5013	361.8	2598	2.22	56	53.212	2163	29.58	27.13
38	0.000	0.000	0.599	901.8	0.4027	330.4	2953	2.73	44	50.459	2242	31.89	28.28
39	0.000	0.000	0.438	400.2	0.4220	255.1	2177	1.57	54	59.278	1987	20.07	19.94
40	0.000	0.000	0.389	500.5	0.3028	211.7	2517	2.36	64	48.494	2051	22.78	21.97
41	0.000	0.000	0.395	600.7	0.2699	208.2	2777	2.89	70	44.873	2108	25.28	23.76
42	0.000	0.000	0.399	699.6	0.2488	207.0	2996	3.38	72	41.930	2217	27.94	25.04
43	0.000	0.000	0.400	800.2	0.2281	208.2	3285	3.84	80	40.866	2362	30.79	25.99
44	0.000	0.000	0.470	399.7	0.4622	276.1	2150	1.45	63	62.563	2021	20.22	19.77
47	0.000	0.000	0.529	700.6	0.3904	289.9	2673	2.42	63	50.743	2170	27.68	25.31
46	0.000	0.000	0.525	601.0	0.4334	295.4	2454	2.03	59	54.011	2122	25.37	23.69
45	0.000	0.000	0.526	500.0	0.4856	308.5	2287	1.62	51	60.997	2091	22.98	21.76
48	0.000	0.000	0.533	800.2	0.3592	286.2	2868	2.80	68	47.836	2201	29.78	26.87
49	0.000	0.000	0.506	899.6	0.3010	268.7	3213	3.35	75	45.532	2308	32.29	27.86
50	0.000	0.000	0.312	399.8	0.2435	169.1	2499	2.36	48	48.110	1989	20.07	19.92
51	0.000	0.000	0.312	499.0	0.2035	161.2	2853	3.09	63	43.245	2074	22.87	21.82
52	0.000	0.000	0.313	599.6	0.1940	161.1	2988	3.72	73	38.144	2201	25.78	23.26
53	0.000	0.000	0.315	698.1	0.1707	158.9	3351	4.39	81	36.699	2348	28.68	24.34
54	0.000	0.000	0.321	798.9	0.1749	162.9	3353	4.90	87	33.030	2481	31.49	25.37

* specific impulse units : N-sec/kg

APPENDIX B

DATA REDUCTION ASSUMPTIONS AND TECHNIQUES

Analog data is digitized and converted to engineering units directly by the HP9836 desktop computer/controller using calibrations taken after each run. All data presented are end of run equilibrium steady-state parameters.

B.1 THRUST

Thrust is measured directly and is corrected for cell backpressure by:

$$F_{vac} = F_{meas} + Pa * Ae$$

where,

F_{vac} = Vacuum thrust

F_{meas} = Measured thrust determined from thrust stand

Pa = Altitude chamber pressure

Ae = Nozzle exit plane area (cold)

No correction is made for the thermal expansion of the nozzle exit area since the total exit pressure correction is a small fraction of the measured thrust.

B.2 SPECIFIC IMPULSE

Specific impulse is calculated from,

$$I_{sp} = Fvac/\dot{m}$$

where,

I_{sp} = Specific impulse

F_{vac} = Vacuum thrust (determined above)

$\dot{m}$ = Propellant flow rate

Propellant flow rate is measured by the calibrated fluid resistor or the mass flowmeter. The fluid resistor calibration is adjusted for density differences between calibration and test as outlined in Section B.3.

B.3 GAS FLOW RATE

For nitrogen and hydrogen tests the calibrated *fluid* resistor (Lee Corporation, Visco-Jet) was used for gas flow measurement. The fluid resistor was sized to provide a high pressure drop to increase resolution on flow rate measurement. The fluid resistor was calibrated with both nitrogen and hydrogen at the Colorado Engineering Experiment Station in Nunn, Colorado. Calibration accuracy is ± 0.5 percent traceable to the National Bureau of Standards. Upstream and downstream pressures and mass flow rates used in the calibration were determined from the predicted resistojet pressure schedule to minimize density corrections. When directly applied, the calibration is only valid if the same upstream pressure and pressure drop is experienced in test. Since the test results vary from the ideal calibration schedule, a correction must be made to account for gas density differences between test and calibration. Since flow through the fluid resistor is determined by,

$$\dot{m} = \rho K_f A \sqrt{\frac{2g \, \Delta P}{\rho}}$$

taking the ratio of two flow rates at the same pressure drop gives,

$$\frac{\dot{m}_1}{\dot{m}_2} = \sqrt{\frac{\rho_2}{\rho_1}}$$

$$\dot{m}_1 = \dot{m}_2 \sqrt{\frac{P_1 T_2}{P_2 T_1}}$$

where,

$\dot{m}$ = Mass flow rate

ρ = Gas density

P = Gas pressure

T = Temperature

Since the average gas density through the pressure drop is a function of the average pressure, the following correction was used.

$$\dot{m}_{cor} = \dot{m}_{cal} \sqrt{\frac{P_{avg\ test}\, T_{cal}}{P_{avg\ cal}\, T_{test}}}$$

where,

$\dot{m}_{cor}$	=	Flow rate corrected for average pressure differences between actual and calibration conditions.
$\dot{m}_{cal}$	=	Calibration flow rate determined by the measured pressure drop.
$P_{avg\ test}$	=	Average of upstream and downstream pressure measures.
$P_{avg\ cal}$	=	Average pressure at $\dot{m}_{cal}$ from the calibration.
T_{test}	=	Temperature of gas inlet to Visco-Jet in test.
T_{cal}	=	Temperature of gas inlet to Visco-Jet in calibration.

The calibration, for each gas, determines a pressure drop versus flow rate characteristic as shown in Figure B-1. Additionally, the average pressure of the calibration versus flow rate is plotted in Figure B-2. Calibration inlet temperature was constant at 530 R. Actual calibration data sheets are shown as Figures B-3 and B-4. Figures B-1 and B-2 allow the correction for density differences between test and calibration conditions to be determined.

Since the ammonia source bottle pressure was the vapor pressure, using the calibrated fluid resistor would drop the resistojet inlet pressure below desired operating range. The vibrating U-tube mass flowmeter was therefore used for ammonia since very little pressure drop occurs in this type of flowmeter.

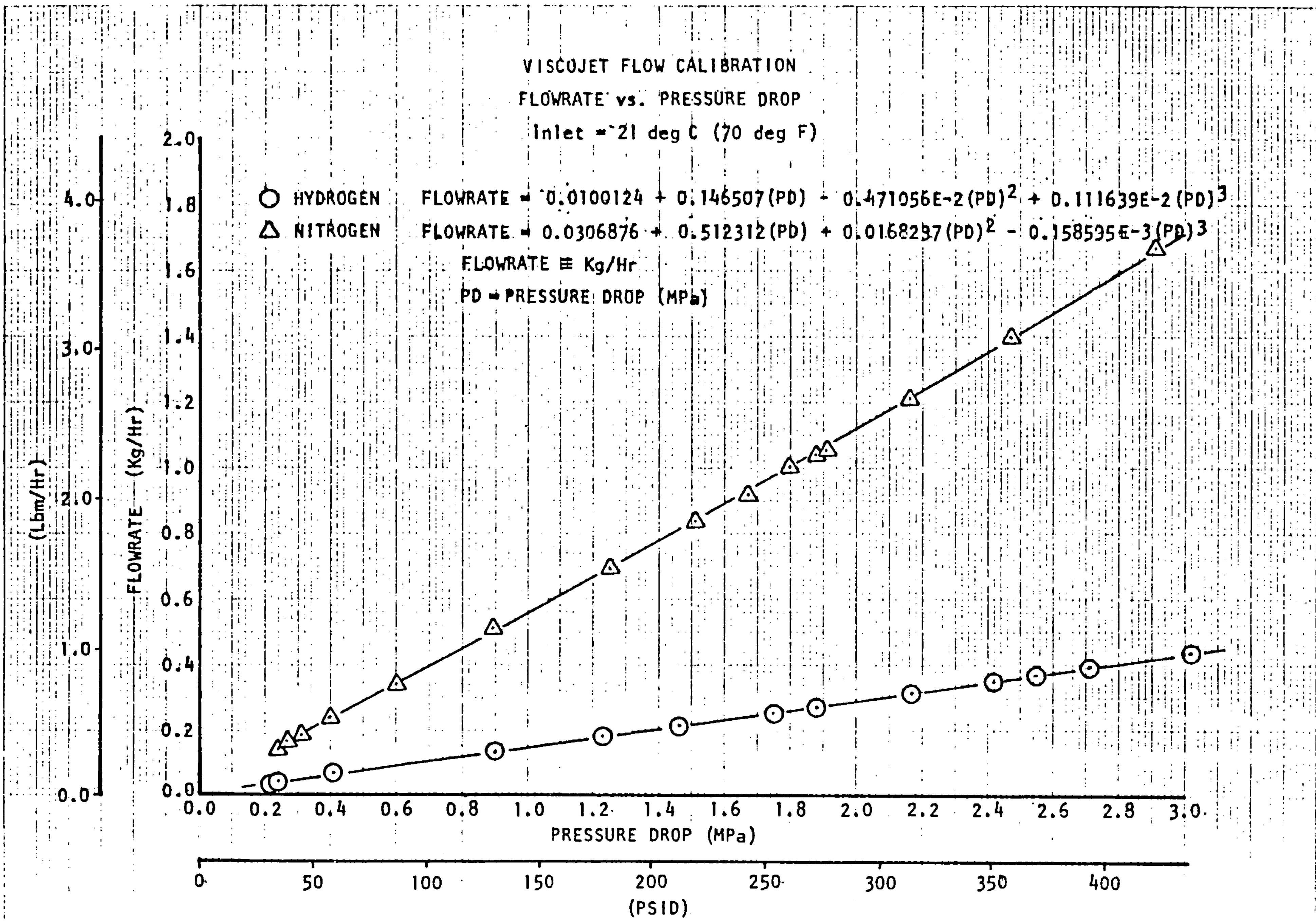
B.4 SPECIFIC POWER

Specific power is the ratio of augmentation power applied to thrust delivered.

$$P_{sp} = \text{Hpow}\ F_{vac}$$

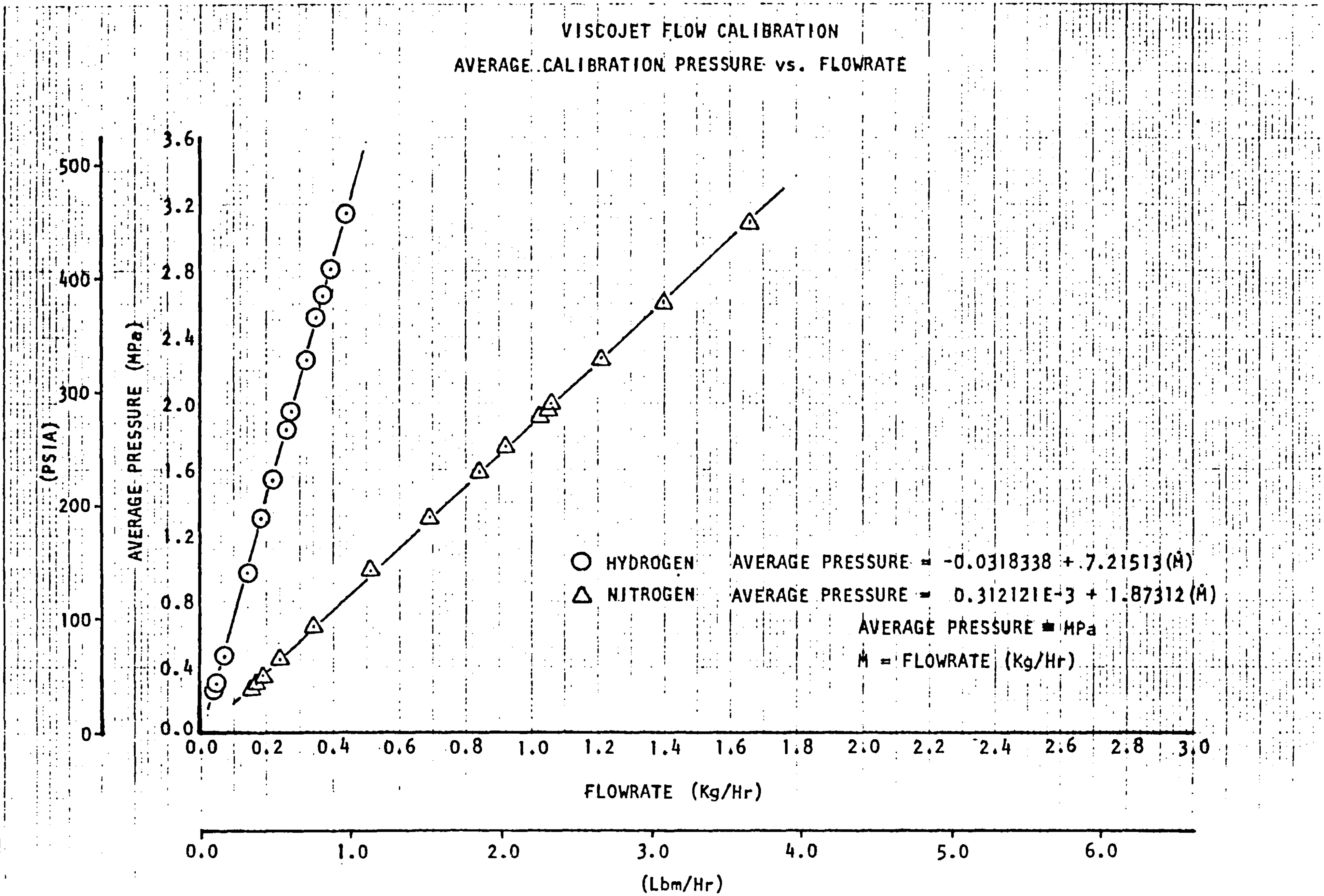
where,

P_{sp}	=	Specific power
Hpow	=	Augmentation heater power calculated from the product of heater voltage and current.



VISCOJET FLOW CALIBRATION
FLOWRATE vs. PRESSURE DROP
Inlet = 21 deg C (70 deg F)
HYDROGEN FLOWRATE = 0.0100124 + 0.146507(PD) - 0.471056E-2(PD)^2 + 0.111639E-2(PD)^3
NITROGEN FLOWRATE = 0.0306876 + 0.512312(PD) + 0.0168237(PD)^2 - 0.158595E-3(PD)^3
FLOWRATE ≡ Kg/Hr
PD = PRESSURE DROP (MPa)
FLOWRATE (Kg/Hr)
(Lbm/Hr)
PRESSURE DROP (MPa)
(PSID)

Figure B-1



VISCOJET FLOW CALIBRATION
AVERAGE CALIBRATION PRESSURE vs. FLOWRATE
(PSIA)
AVERAGE PRESSURE (MPa)
FLOWRATE (Kg/Hr)
(Lbm/Hr)
HYDROGEN AVERAGE PRESSURE = -0.0318338 + 7.21513(Ṁ)
NITROGEN AVERAGE PRESSURE = 0.312121E-3 + 1.87312(Ṁ)
AVERAGE PRESSURE = MPa
Ṁ = FLOWRATE (Kg/Hr)

Figure B-2

CEESI

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P.O. Box 41
Nunn, Colo. 80648
Phone: 303—897-2340

CALIBRATION OF A ROCKET RESEARCH FLOWMETER
SERIAL NUMBER: NONE
FOR: ROCKET RESEARCH CO. ORDER: 86066-500
DATA FILE: 84R[illegible]C1 DATE: 2 MARCH 1984
INLET DIA: 0.5 INCHES THROAT DIA: 0.0094 INCHES
TEST GAS: NITROGEN STD DENSITY= 0.072448 LBM/CU-FT
AT STANDARD CONDITIONS OF 529.69 DEG R, AND 14.696 PSIA
DIFF: DIFFERENTIAL PRESSURE IN PSI
E PRESS: EXIT PRESSURE IN PSIA
K FACTOR: DISCHARGE COEFFICIENT
REY NO: THROAT REYNOLDS NUMBER
LBM/HR: MASS FLOWRATE IN POUNDS PER HOUR
PRESS: INLET PRESSURE IN PSIA
TEMP: INLET TEMPERATURE IN DEGREES RANKINE
RATIO OF SPECIFIC HEATS: 1.4
FOR EXP FACTOR, SEE ASME FLUID METERS, 5TH, P 126

L	DIFF	E PRESS	K FACTOR	REY NO	LBM/HR	PRESS	TEMP
1	44.999	28.009	1.0685	16131.	0.42248	73.009	530
2	35.3	22.894	1.0814	13112.	0.34315	58.194	529.5
3	39.327	25.015	1.0769	14395.	0.37672	64.342	529.5
4	58.976	35.285	1.0512	20369.	0.53332	94.261	529.8
5	39.278	24.994	1.0752	14350.	0.37565	64.272	529.7
6	87.463	50.002	1.0342	28964.	0.7589	137.47	530.3
7	130.03	78.25	1.0112	43290.	1.1348	208.28	530.6
8	181.78	99.996	1.0254	58404.	1.5316	281.78	530.9
9	219.35	120.6	1.0275	70622.	1.852	339.94	530.9
10	240.56	132.37	1.0289	77566.	2.0347	372.94	531.1
11	182.07	100.07	1.0261	58466.	1.5339	282.14	531.2
12	87.559	49.986	1.0348	28935.	0.75902	137.55	531.1
13	271.74	150.	1.0318	87906.	2.308	421.74	531.7
14	313.13	173.53	1.035	101840.	2.6739	486.66	531.7
15	359.35	200.02	1.0394	117680.	3.0897	559.37	531.7
16	277.21	152.86	1.0328	89734.	2.3556	430.08	531.6
17	272.34	150.16	1.0325	88122.	2.3133	422.5	531.6
18	262.2	144.68	1.0303	84945.	2.226	406.88	530.4
19	358.59	199.88	1.0376	117690.	3.0842	558.47	530.4
20	422.67	236.75	1.0421	139930.	3.6636	659.42	529.8

AVERAGE VALUES FOR ABOVE RESULTS:
P= 302.96 PSIA DENSITY= 1.4966 LBM/CU-FT
T= 530.67 DEG R VISCOSITY= 9.8637E-7 LBM/INCH-SEC
Z= 0.99648 COMPRESSIBILITY FACTOR

Figure B-3

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INC.

OFFICE:

FED

LABORATORY:
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Nunn, Colo. 80648
Phone: 303—897-2340

```
SERIAL NUMBER: NONE
DATA FILE: 84RBC1                          DATE: 2 MARCH 1984

X POINTS EXCLUDED FROM AVERAGES.   K(AVE)= 1.0411    %DEV FROM K(AVE);
 L(O) R/1000 MTR READ L(O)-10          -5         0         +5       +10%
                                  0 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 0
   2    13.11      35.3           ............................O............
   5    14.34      39.278    3    ...........................O.............
   1    16.13      44.999         .........................O...............
   4    20.36      58.976         ......................O..................
  12    28.93      87.559    6    ...................O.....................
   7    43.28      130.03         ..............O..........................
   8    58.4       181.78    11   .................O.......................
   9    70.62      219.35         .................O.......................
  10    77.56      240.56         ..................O......................
  18    84.94      262.2          ..................O......................
  13    87.9       271.74    17   ..................O......................
  16    89.73      277.21         ..................O......................
  14    101.84     313.13         ...................O.....................
  15    117.68     359.35    19   ...................OO....................
  20    139.92     422.67         ....................O....................

SCALE,? 10
LO: 1.31 E+4   R  5.54 E+4     K= 1.05418 E+0      K/K(AVE)=  1.01252
STD DEV= 0.25 E-1              % STD DEV= 2.414    BASED ON   8 DATA PTS
MAX DEV= -.43 E-1              % MAX DEV=-4.072    AT L= 7    CHAUV= 1.474
MD: 5.54 E+4   R  9.77 E+4     K= 1.02943 E+0      K/K(AVE)=  0.98874
STD DEV= 0.29 E-2              % STD DEV= 0.283    BASED ON   8 DATA PTS
MAX DEV= -.41 E-2              % MAX DEV=-0.395    AT L= 8    CHAUV= 2.607
HI: 9.77 E+4   R  1.40 E+5     K= 1.03853 E+0      K/K(AVE)=  0.99748
STD DEV= 0.30 E-2              % STD DEV= 0.288    BASED ON   4 DATA PTS
MAX DEV= 0.35 E-2              % MAX DEV= 0.342    AT L=20    CHAUV= 1.881

R(AVE)= 63622              K(AVE)= 1.0411

R(LO)= 22443.   R(MD)= 76971.   R(HI)= 119290.

K = A + B*R + C*R*R
A= 1.0763    B=-1.1407E-6    C= 6.9083E-12

K = X + Y*(MTR READ) + Z*(MTR READ)*(MTR READ)
X= 1.0748    Y=-3.6301E-4    Z= 7.2413E-7
BASED ON ABOVE TEST DATA (P,T,GAS)
  AND ASSUMING K CORRELATES WITH MTR READ

THIS CALIBRATION IS TRACEABLE TO NBS.
THE FLOW MEASUREMENT ACCURACY IS ESTIMATED TO BE:±.5%
COLO ENGINEERING EXPERIMENT STATION INC,BX 41,NUNN CO 80648
```

Figure B-3 (Concluded)

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CALIBRATION OF A ROCKET RESEARCH FLOWMETER
SERIAL NUMBER: NONE
FOR: ROCKET RESEARCH CO. ORDER: 86066-500
DATA FILE: 84RRC1A DATE: 5 MARCH 1984
INLET DIA: 0.5 INCHES THROAT DIA: 0.0094 INCHES
TEST GAS: HYDROGEN STD DENSITY= 0.005209 LBM/CU-FT
AT STANDARD CONDITIONS OF 529.69 DEG R, AND 14.696 PSIA
DIFF: DIFFERENTIAL PRESSURE IN PSI
E PRESS: EXIT PRESSURE IN PSIA
K FACTOR: DISCHARGE COEFFICIENT
REY NO: THROAT REYNOLDS NUMBER
LBM/HR: MASS FLOWRATE IN POUNDS PER HOUR
PRESS: INLET PRESSURE IN PSIA
TEMP: INLET TEMPERATURE IN DEGREES RANKINE
RATIO OF SPECIFIC HEATS: 1.4
FOR EXP FACTOR, SEE ASME FLUID METERS, 5TH, P 126

L	DIFF	E PRESS	K FACTOR	REY NO	LBM/HR	PRESS	TEMP
1	130.77	75.266	1.0446	23373.	0.30736	206.04	529
2	178.88	99.927	1.0345	31105.	0.40903	278.81	529
3	212.5	117.34	1.0308	36566.	0.48071	329.84	528.8
4	179.3	100.22	1.0331	31178.	0.40973	279.52	528.5
5	254.92	139.26	1.0275	43457.	0.57095	394.19	528.3
6	273.04	148.73	1.027	46442.	0.61001	421.77	528.1
7	315.79	170.85	1.0259	53414.	0.7014	486.64	527.9
8	273.06	148.79	1.0266	46481.	0.61021	421.85	527.7
9	351.85	189.94	1.0261	59451.	0.78018	541.78	527.4
10	370.88	199.97	1.0262	62619.	0.82155	570.86	527.2
11	393.1	211.88	1.027	66381.	0.87078	604.98	527.1
12	438.95	236.38	1.0284	74094.	0.97184	675.33	527
13	393.18	211.93	1.0267	66420.	0.87096	605.11	526.8
14	31.018	22.451	1.1284	6748.4	0.08916	53.469	532.7
15	35.385	25.001	1.1215	7549.9	0.099761	60.386	532.8
16	59.243	38.949	1.0884	11789.	0.15578	98.192	532.8
17	35.306	24.96	1.1226	7541.	0.099656	60.266	532.9

AVERAGE VALUES FOR ABUVE RESULTS:
P= 358.18 PSIA DENSITY= 0.12503 LBM/CU-FT
T= 529.05 DEG R VISCOSITY= 4.948E-7 LBM/INCH-SEC
Z= 1.0147 COMPRESSIBILITY FACTOR

SUBSONIC VENTURI: FLOW NOZZLE PROG 10

Figure B-4

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```
EXCLUDED FROM AVERAGES: 1  POINTS.  SCALE:? 10
  L     R      % DEV
 12   74093   -2.16

SERIAL NUMBER: NONE
DATA FILE: 84RRC1A                    DATE: 5 MARCH 1984

X POINTS EXCLUDED FROM AVERAGES.   K(AVE)= 1.0511    %DEV FROM K(AVE):
 L(O)   R     MTR READ L(O) -10            -5              0            +5          +10%
                               0 9 8 7 6 5 4 3 2 1 0 1 2 3 4 5 6 7 8 9 0
   14  6748.4    31.018        ...................................O....
   17  7541.     35.306    15  .................................OO......
   16  11789.    59.243        ..............................O.......
    1  23373.    130.77        ....................O..................
    2  31105.    178.88     4  ..................O....................
    3  36566.    212.5         ................O......................
    5  43457.    254.92        ................O......................
    6  46442.    273.04     8  ...............O.......................
    7  53414.    315.79        ...............O.......................
    9  59451.    351.85        ...............O.......................
   10  62619.    370.88        ...............O.......................
   11  66381.    393.1          ...............O.......................
 X 12  74094.    438.95    13  ...............O.......................
                               ................X......................

SCALE,? 10
LO: 6.75 E+3  R  2.66 E+4    K= 1.10111 E+0      K/K(AVE)= 1.04761
STD DEV= 0.35 E-1            % STD DEV= 3.205    BASED ON  5 DATA PTS
MAX DEV= -.57 E-1            % MAX DEV=-5.136    AT L= 1   CHAUV= 1.101
MD: 2.66 E+4  R  4.65 E+4    K= 1.02992 E+0      K/K(AVE)= 0.97988
STD DEV= 0.34 E-2            % STD DEV= 0.329    BASED ON  6 DATA PTS
MAX DEV= 0.46 E-2            % MAX DEV= 0.447    AT L= 2   CHAUV= 2.09
HI: 4.65 E+4  R  6.64 E+4    K= 1.02640 E+0      K/K(AVE)= 0.97653
STD DEV= 0.45 E-3            % STD DEV= 0.044    BASED ON  5 DATA PTS
MAX DEV= 0.62 E-3            % MAX DEV= 0.060    AT L=11   CHAUV= 1.714

R(AVE)= 37532              K(AVE)= 1.0511

R(LO)= 11400.    R(MD)= 39205.    R(HI)= 61657.

K = A + B*R + C*R*R
A= 1.1517    B=-4.9809E-6    C= 4.7828E-11

K = X + Y*(MTR READ) + Z*(MTR READ)*(MTR READ)
X= 1.1426    Y=-7.8526E-4    Z= 1.2794E-6
BASED ON ABOVE TEST DATA (P,T,GAS)
  AND ASSUMING K CORRELATES WITH MTR READ

THIS CALIBRATION IS TRACEABLE TO NBS.
THE FLOW MEASUREMENT ACCURACY IS ESTIMATED TO BE: ±.5%
COLO ENGINEERING EXPERIMENT STATION INC,BX 41,NUNN CO 80648
```

Figure B-4 (Concluded)

B.5 OVERALL EFFICIENCY

Overall efficiency is the ratio of the exit jet power to total input power. Total input power consists of the electrical augmentation power and the chemical energy of the propellant. Overall resistojet efficiency is defined as,

$$\eta = P_{out}/P_{in} = F\ I_{sp}/(2(Hpow + \dot{m}\ h))$$

where,

P_{in}	=	Input power (chemical and electrical)
P_{out}	=	Useful output power
$\dot{m}$	=	Mass flow rate
Hpow	=	Augmentation power
h	=	Propellant inlet enthalpy (Reference condition $0^{o}K$)
F	=	Thrust
I_{sp}	=	Specific impulse
η	=	Overall efficiency

B.6 HEATER WIRE TEMPERATURE

Augmentation heater wire temperature may be determined from its electrical resistance. A temperature-resistance calibration was obtained by optical pyrometer temperature measurements during component level testing.

Temperature is estimated as a linear function of resistance. Figure B-5 shows temperature versus resistance for the heater used in testing.

11153-18

RESISTOJET HEATER TEMPERATURE CALIBRATION

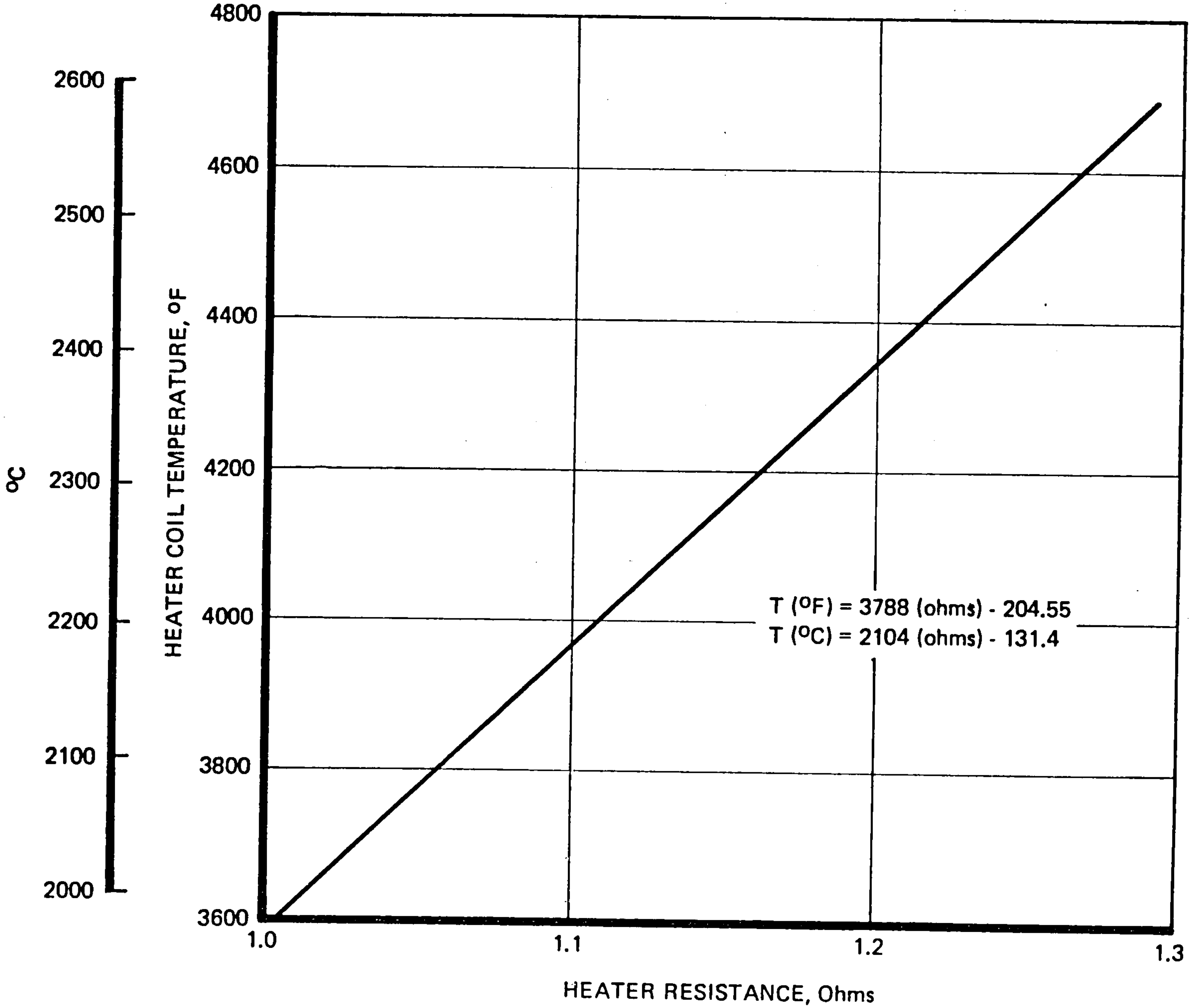

Figure B-5

1. Report No. NASA CR-174763	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Radiative Resistojet Performance Characterization Tests		5. Report Date September 1984 6. Performing Organization Code
7. Author(s) C. I. Miyake		8. Performing Organization Report No. 84-R-958 10. Work Unit No.
9. Performing Organization Name and Address Rocket Research Company 11441 Willows Road Redmond, Washington 98052-1012		11. Contract or Grant No. NAS3-23868 13. Type of Report and Period Covered Contractor Report
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code 506-55-28

15. Supplementary Notes

Final report. Project Manager, James S. Sovey, Space Propulsion Technology Division, NASA Lewis Research Center, Cleveland, Ohio 44135.

16. Abstract

This report describes the test article, test approach, data analysis and results of a study undertaken to characterize performance of the augmentation section of the Rocket Research Company Augmented Catalytic Thruster as a gas resistojet using hydrogen, nitrogen and ammonia as propellants. This renewed interest in resistojets is a result of propulsion systems definition studies which indicate potential application to space station auxiliary propulsion.

17. Key Words (Suggested by Author(s)) Spacecraft propulsion Electric propulsion Auxiliary propulsion	18. Distribution Statement Unclassified - unlimited STAR Category 20

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