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STUDY OF MONOPROPELLANTS FOR ELECTROTHERMAL THRUSTERS

EVALUATION TEST PROGRAM TASK SUMMARY REPORT

J.D. Kuenzly

TRW Systems Group
One Space Park
Redondo Beach, Calif. 90278

MARCH 1974

INTERIM REPORT FOR PERIOD

AUGUST 1973 - FEBRUARY 1974

Prepared for
GODDARD SPACE FLIGHT CENTER
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16. Abstract

An electrothermal thruster designed for operation with MIL-grade hydrazine is suitable for operation with propellants having lower freezing points. These propellants are 76% hydrazine - 24% hydrazine azide, Aerozine-50, 50% hydrazine - 50% monomethylydrazine, and a TRW-formulated mixture of 35% hydrazine - 50% monomethylhydrazine - 15% ammonia. A steady-state specific impulse of 200 sec was exceeded by all propellants. A pulse-mode value of 175 sec specific impulse was exceeded by the azide blend for pulse widths greater than 50 ms and was met by the carbonaceous propellants for pulse widths greater than 100 ms. Longer residence times were required for the carbonaceous propellants; the original thruster design was modified by increasing the characteristic chamber length and density of screen packing. A substantial amount of thermal energy must be supplied to initiate decomposition of propellants containing unsymmetrical-dimethylhydrazine and monomethylhydrazine. The rate controlling factor appeared to be the endothermic removal of methyl radicals. Carbon deposition was minimal with the TRW-formulated mixture whereas that observed with Aerozine-50 may pose problems for long term operation. The original baseline thruster configuration gave non-optimal hydrazine performance. Performance was increased by promoting homogeneous, gas-phase decomposition kinetics in a larger head space. Methods of increasing residence times in the head space should be investigated for the carbonaceous propellants. Alternate injection techniques which could produce an atomized spray appear desirable. The large head space thruster which gave superior performance with hydrazine should be fully exploited.

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PREFACE

The objective of the "Study of Monopropellants for Electrothermal Thrusters" program is to determine the feasibility of operating small thrust level electrothermal thrusters with monopropellants other than MIL-grade hydrazine. The work scope includes analytical study, design and fabrication of demonstration thrusters, and an evaluation test program wherein monopropellants with freezing points lower than MIL-grade hydrazine are evaluated and characterized to determine their applicability to electrothermal thrusters for spacecraft attitude control.

The electrothermal thruster designed for operation with MIL-grade hydrazine is suitable for operation with propellants having lower freezing points. These propellants are 76% hydrazine - 24% hydrazine azide, Aerozine-50, 50% hydrazine - 50% monomethylhydrazine, and a TRW-formulated mixture of 35% hydrazine - 50% monomethylhydrazine - 15% ammonia. The program goal of 200 sec steady-state specific impulse was exceeded by all propellants. The pulsed-mode program goal of 175 sec was exceeded by the azide blend for pulse widths greater than 50 ms and was met by the carbonaceous propellants for pulse widths greater than 100 ms.

Longer residence times were required for the carbonaceous propellants; the original thruster design was modified by increasing the characteristic chamber length and density of screen packing. A substantial amount of thermal energy must be supplied to initiate decomposition of propellants containing unsymmetrical-dimethylhydrazine and monomethylhydrazine. The rate controlling factor appeared to be the endothermic removal of methyl radicals.

Carbon deposition was minimal with the TRW-formulated mixture whereas that observed with Aerozine-50 may pose problems for long term operation.

The original baseline thruster configuration gave non-optimal hydrazine performance. Performance was increased by promoting homogeneous, gas-phase decomposition kinetics in a larger head space.

Methods of increasing residence times in the head space should be investigated for the carbonaceous propellants. Alternate injection techniques which could produce an atomized spray appear desirable. The large head space thruster which gave superior performance with hydrazine should be fully exploited.

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1.0 INTRODUCTION

This report presents the evaluation test program results performed in support of the "Study of Monopropellants for Electrothermal Thrusters." The test program was conducted to evaluate and characterize the applicability of low freezing point monopropellants to electrothermal thrusters for spacecraft attitude control. The work performed during this program period included the initial steady-state characterization of four candidate monopropellants with thrusters designed and baseline tested for operation with MIL-grade hydrazine; an optimization phase wherein the thruster configuration was changed to meet the specific requirements of each propellant. Simulated high altitude performance measurements were obtained for the optimized thruster configurations and compared to operation with MIL-grade hydrazine. Each propellant utilized was subjected to a chemical analysis.

This report presents the characterization and optimization test results, propellant chemical analyses, and describes the test methods and data acquisition equipment used in obtaining the performance measurements.

2.0 EVALUATION TEST PROGRAM

2.1 DESCRIPTION

2.1.1 Propellants

Five propellants other than MIL-grade hydrazine were evaluated during the test program phase. They were monomethylhydrazine (MMH) and a 50-50 mixture of MMH and hydrazine, Aerozine-50 (AERO-50), 76% hydrazine - 24% hydrazine azide (HA), and TRW-formulated mixed hydrazine monopropellant of 35% hydrazine - 50% monomethylhydrazine - 15% ammonia (MHM). These propellants were selected as low freezing point substitutes for MIL-grade hydrazine that do not require an excessive trade-off between freezing point and performance. A separate analytical studies report(1) describes the criteria used in recommending the above propellants.

2.1.2 Thruster

A schematic of the initial demonstration thruster configuration is shown in Figure 1. The thruster design was based on the Electrothermal Hydrazine Thruster (EHT) developed by TRW for NASA/GSFC on NASA Contract No. NAS5-11477.(2) The current thruster design and fabrication phase is described in an earlier report.(3)

2.1.3 Test Methods

Preliminary performance tests with three of the five candidate propellants were performed at the TRW Systems Group Capistrano Test Facility. Simulated high altitude performance measurements were conducted at the main test facility in Redondo Beach. Propellant chemical analyses were performed at both test facilities. The specific requirements for the Evaluation Test Program were presented in an earlier report.(1)

The preliminary sea-level measurements were performed using the equipment shown schematically in Figure 2. The propellants MMH, AERO-50, and HA were supplied in 500 cc interchangeable Type 304 stainless steel sample cylinders. A separate piston tank (Figure 3) was required to prevent the loss of ammonia from the MHM blend. Two additional cylinders of water and alcohol were incorporated in the propellant supply manifold. This enabled the convenient flushing and cleaning of the thruster valve and propellant

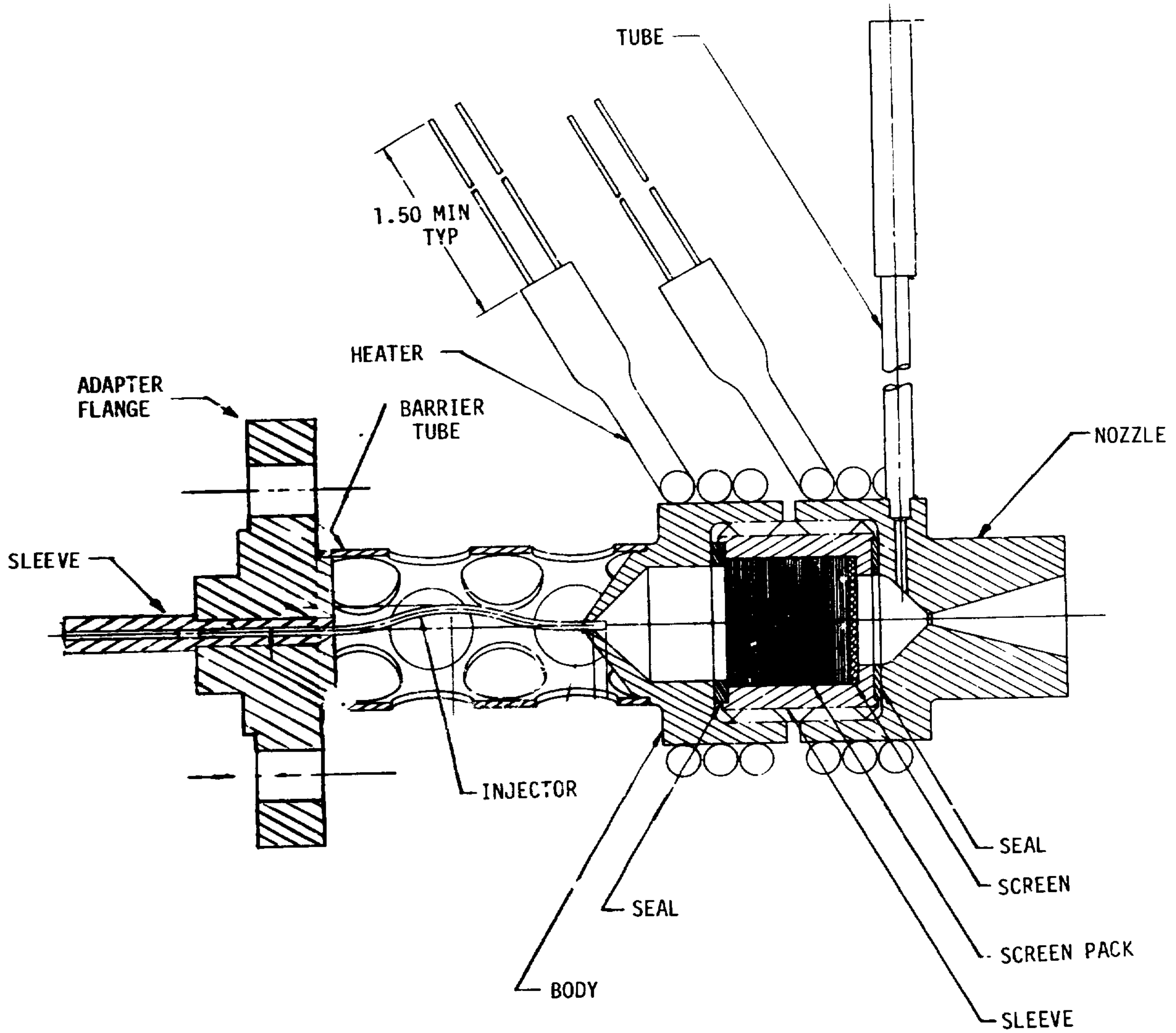


Figure 1. Monopropellant Demonstration Thruster

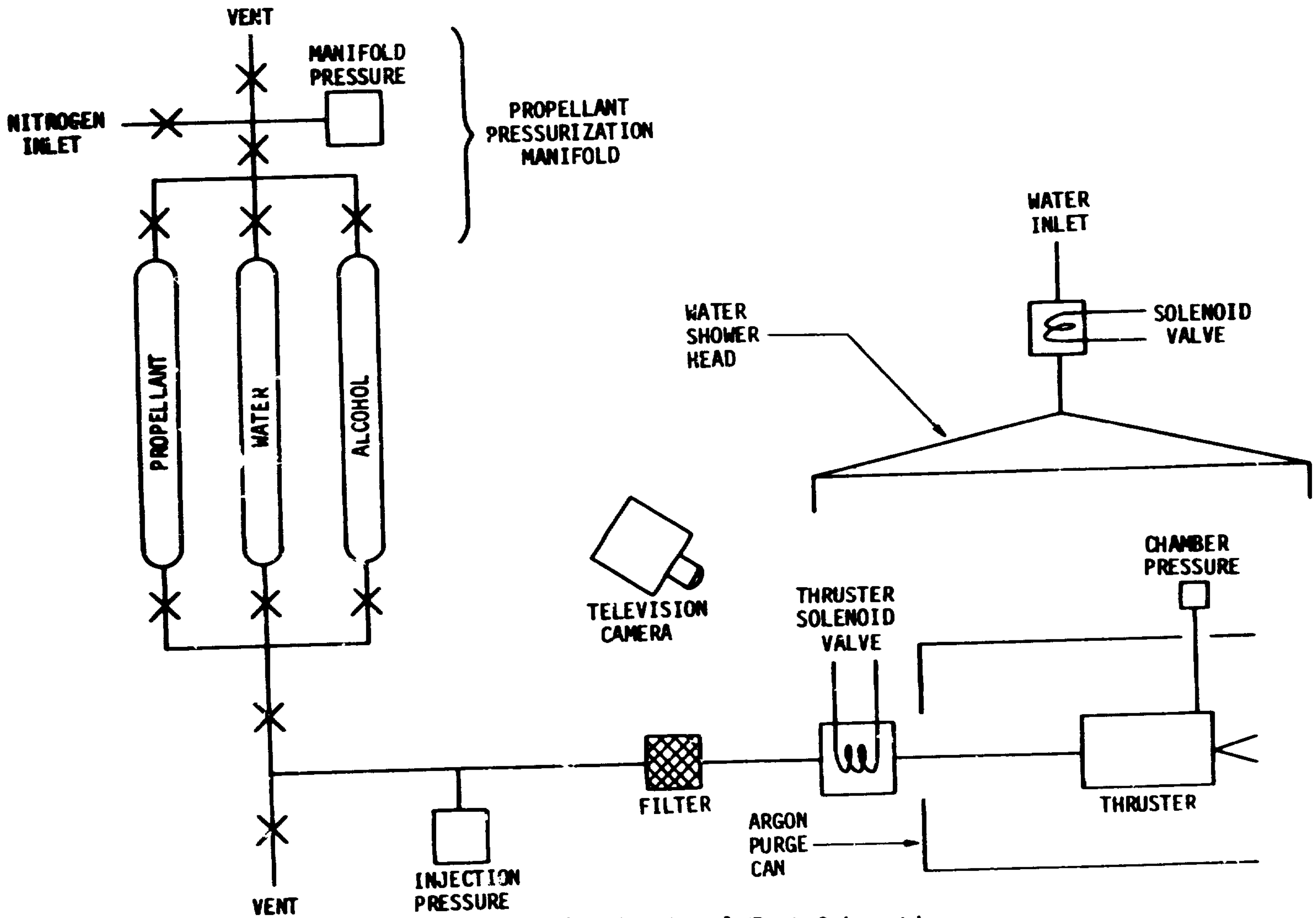


Figure 2. Sea-Level Test Schematic

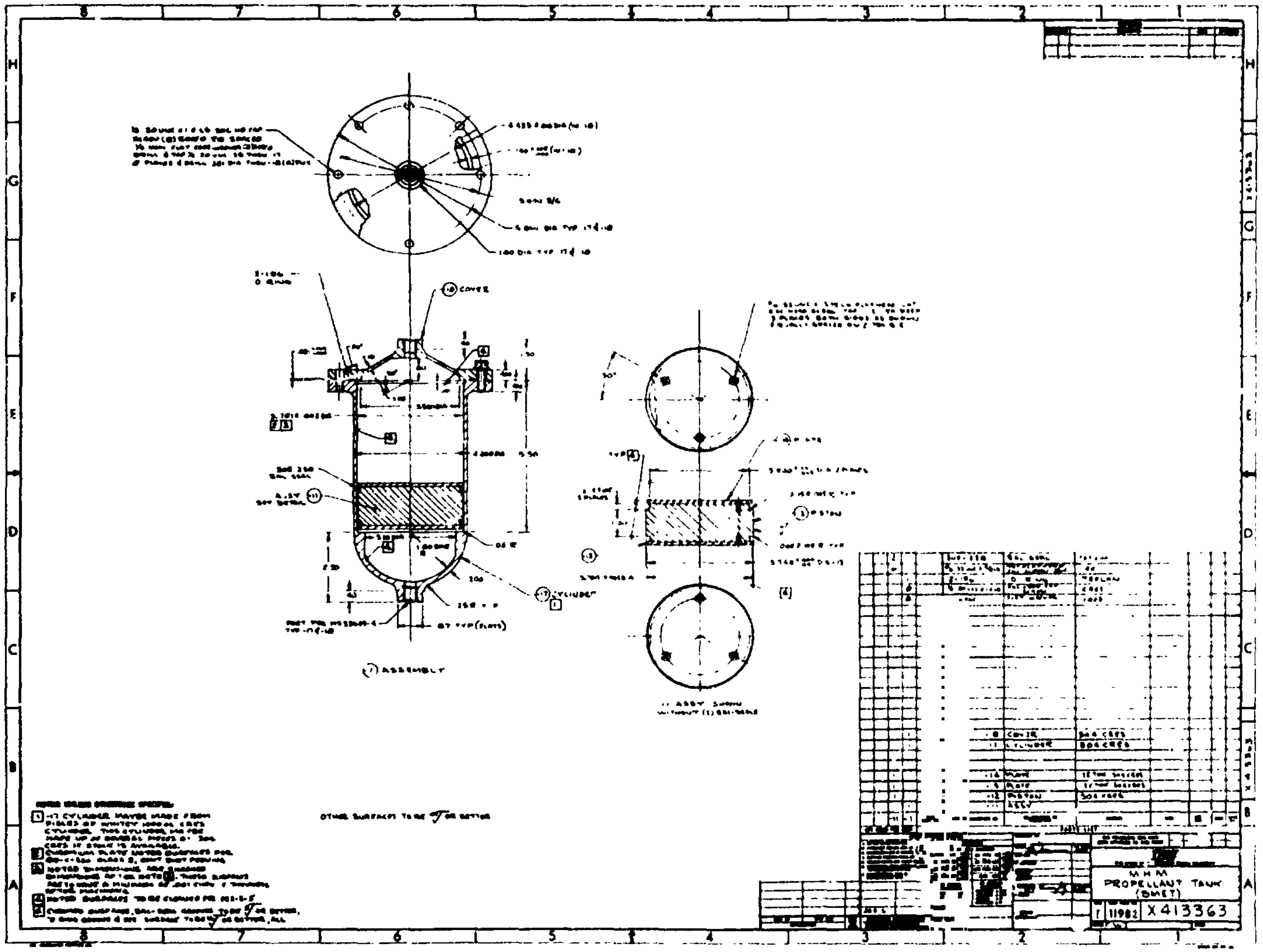


Figure 3. Mixture of Hydrazine Monopropellants (MHM) Piston Tank

lines (thruster removed during such operations). A semi-open canister was mounted around the thruster. Argon was flowed through the canister to reduce oxidation of the thruster components. The thruster, thruster valve and filter were securely attached to an aluminum plate. An insulated and instrumented thruster assembly for sea-level testing is shown in Figure 4. A water shower head was installed directly over the thruster and valve assembly as a precautionary measure in the event of a propellant fire. The sea-level tests were monitored visually by a closed-circuit television hook-up (control block-house located 16 m from test cell). The parameters recorded during sea-level testing were the following:

Manifold Pressure (P_M)

Injection Pressure (P_{INJ})

Chamber Pressure (P_C)

Nozzle Temperature (T_N)

Chamber Temperature (T_C)

Injector Temperature (T_{INJ})

Barrier Tube Temperature (T_B)

Valve Temperature (T_V)

Heater Voltage (V_H)

Heater Current (I_H)

Valve Voltage (V_V)

Valve Current (I_V)

The simulated high altitude performance measurements were conducted in a facility incorporating a 1.22 m x 1.22 m cylindrical vacuum chamber. High vacuum ($< 1.3 \times 10^{-4}$ N/m^2) is maintained by two 0.254 m diffusion pumps. A chevron cyro baffle is mounted at the inlet port of each diffusion pump and is cooled with liquid nitrogen during operation. The diffusion pump assemblies exhaust to a 38 l/s mechanical pump through 5.1 cm tubing. The

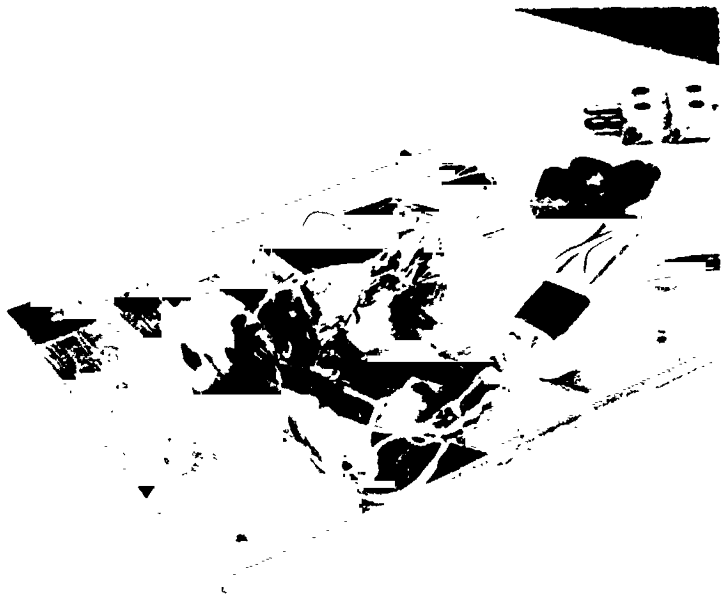


Figure 4. Sea-Level Thruster-Valve Configuration

mechanical pump is used in lieu of the diffusion pumps for steady-state operation and high duty cycle pulsed-mode operation. The mechanical pump maintains the chamber at a pressure of 130 N/m^2 or less during such operations.

The internal chamber configuration is shown in Figure 5. The chamber contains two independent thrust and propellant supply systems (one system was installed during this program reporting interval). The dual systems satisfied the need to test more than one propellant without delays normally encountered in changing propellants. A fully instrumented demonstration thruster is shown mounted on one thrust stand in Figure 6. The propellant supply and mass flow measuring system is represented schematically in Figure 7. Dry, filtered nitrogen is used as the propellant pressurant. The flow measuring device consists of a piston that displaces propellant stored within a small diameter cylinder. The piston displacement is measured by a linear potentiometer.

The data acquisition equipment in Figure 8 was used to obtain performance data. Operating and performance data were recorded on an oscillograph or on magnetic tape. Three additional parameters were recorded for the high altitude tests. They were thrust (steady-state) or integral of thrust (impulse-bit in the case of pulsed-mode), mass flow and integral of chamber pressure.

Original performance measurements were acquired in British Engineering units (foot-pound-second-degree Fahrenheit). The data in this report have been converted to the International System of units (SI) or to more convenient metric units.

The thrusters were routinely disassembled and inspected throughout the test program phase. Several screen pack assemblies were subjected to electron probe microanalysis for the identification of deposits formed on the screens during high temperature operation.

2.2 CHEMICAL ANALYSES

Standard analytical methods were used to determine the chemical composition, particulate weight, particle size distribution and non-volatile residues for the propellants hydrazine, Aerozine-50, monomethylhydrazine,

Figure 5. Vacuum Chamber Test Apparatus

Figure 6. Thruster Mounted for Performance Measurements

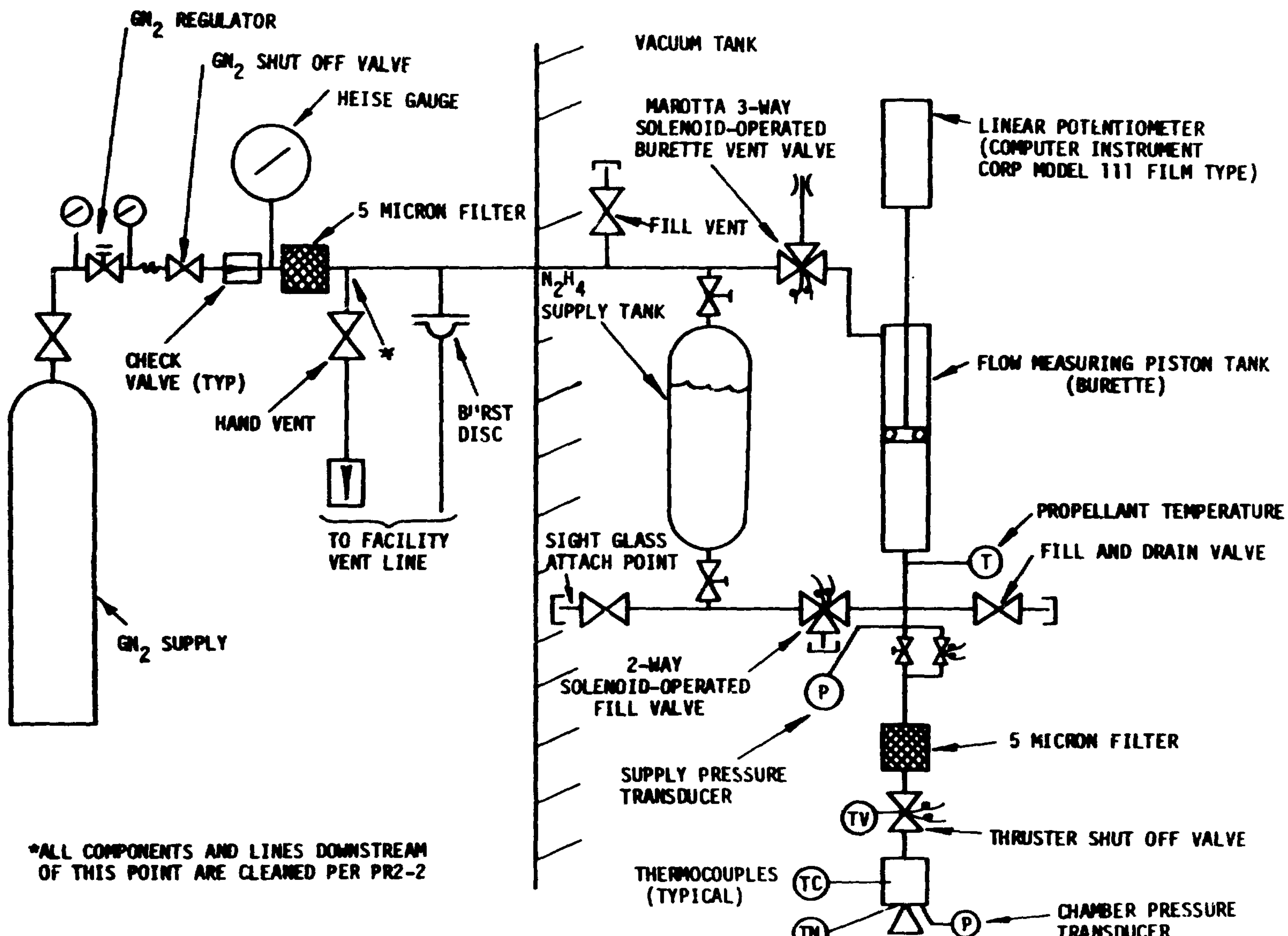


Figure 7. Propellant Supply System

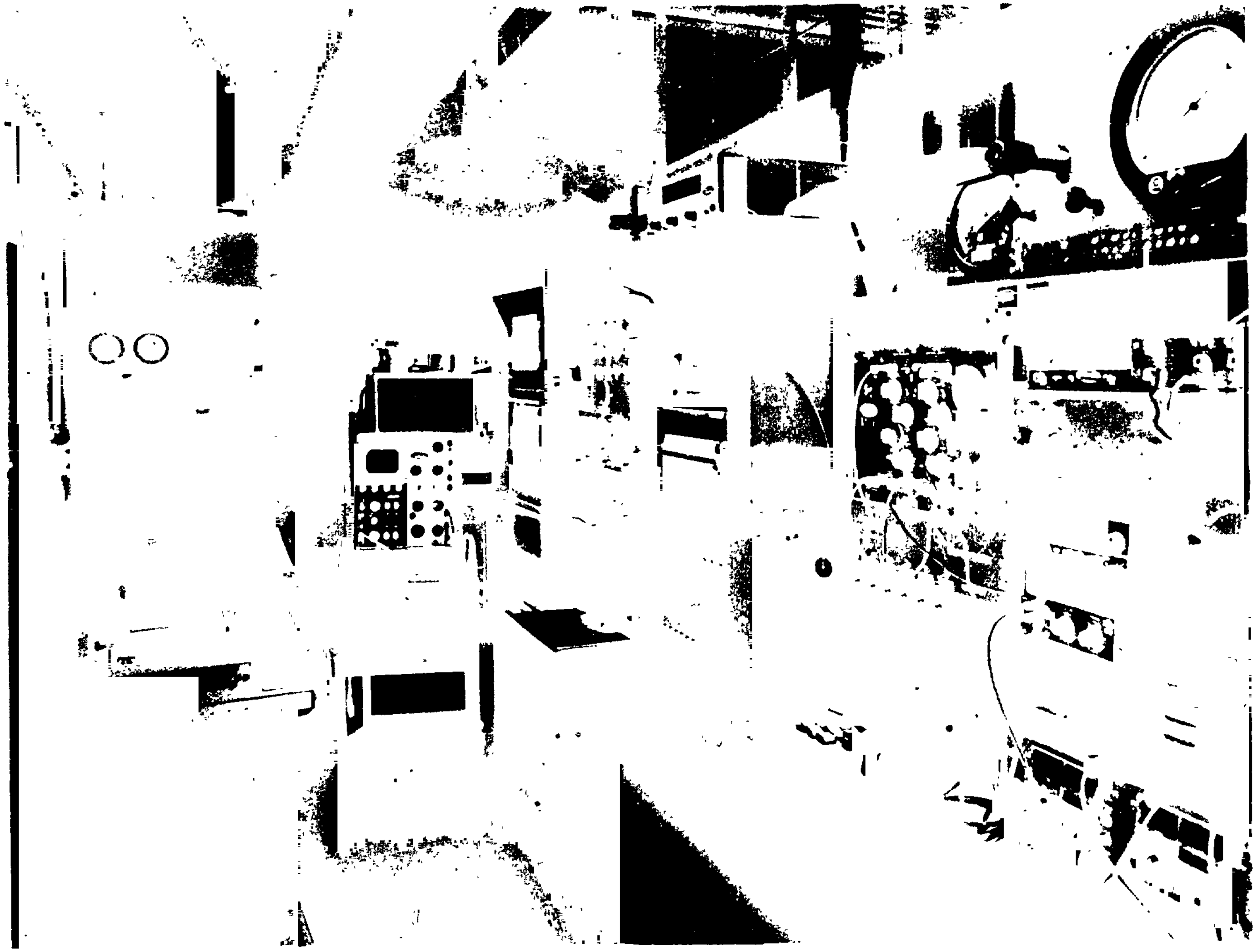


Figure 8. Data Acquisition System

and hydrazine-hydrazine azide. An analysis of the ammonia used for the mixture of hydrazine monopropellants (MHM) was supplied by the manufacturer. The chemical composition of the MHM propellant was determined by the charging sequence. A pre-mixed and weighed charge of hydrazine and MMH was introduced into the piston tank. Both sides of the piston tank were evacuated to remove a protective nitrogen blanket. Ammonia was transferred to the propellant tank in the vapor phase and allowed to saturate the pre-mixed hydrazine and MMH to the vapor pressure corresponding to an aqueous solution content of 15 percent ammonia. Both ends of the propellant tank were then sealed under pressure.

Results of the propellant chemical analyses are presented in Tables 1 through 4 for MIL-grade hydrazine, Aerozine-50, monomethylhydrazine, and hydrazine-hydrazine azide, respectively. The hydrazine azide content was determined by potentiometric titration with 0.1 N NaOH and ammonia liberated from the addition of a weighed sample to acetone. The non-volatile residue (NVR) for the hydrazine-hydrazine azide blend was determined by propellant decomposition with hydrogen peroxide and slow evaporation on a hot plate to dryness. The NVR contents of hydrazine, Aerozine-50 and MMH were determined by weighing the matter remaining after distilling 100 ml of propellant at 313°K and a pressure of 133 N/m^2. The ammonia analysis appears in Table 5.

The NVR contents of hydrazine, Aerozine-50 and MMH were normal for these propellants. However, the high NVR content of the azide blend indicated that the propellant was contaminated. The non-volatile residues of the four propellants were extracted with 3N HCl and subjected to atomic adsorption analyses for iron, nickel and chromium (major storage vessel constituents). The metallic contaminate level of the azide blend (Table 4) was 100 to 200 times that of MIL-grade hydrazine (Table 1). Although hydrazine-hydrazine azide propellants are more reactive than hydrazine, the large difference in contaminate levels should be viewed with caution. The hydrazine test system and storage containers used during the evaluation test program phase were maintained at the highest cleanliness levels applicable to TRW flight-oriented programs. The hydrazine-hydrazine azide blend had been used on a previous program where the cleanliness levels, storage and handling methods were less stringent. The high azide blend contaminate level may have been due to prior handling.

Table 1. Analysis of MIL-grade Hydrazine Propellant

RESULTS	(Ref. 4) SPEC. LIMITS	ANALYSIS
Density at 298°K, g/ml	NR*	1.0047
Hydrazine, %	98 Min	99.50
Unknown, %	NR	trace
Water, %	1.5 Max	0.50

NO. OF PARTICLES PER 100 ml		(Ref. 5)	
6- 10	microns	9700 Max	361
11- 25	microns	2680 Max	247
26- 50	microns	380 Max	133
51-100	microns	56 Max	9
101-250	microns	5 Max	0
Fibers		None	None

Non-volatile Residue, mg/100 ml - 6.0

Element	Analysis, ppm
Fe	0.26
Ni	0.09
Cr	0.11

*NR: Not required

Table 2. Analysis of Aerozine-50 Propellant ($50\%\ N_2H_4$ - 50% UDMH)

RESULTS	(Ref. 6) SPEC. LIMITS	ANALYSIS
Density at 296.9°K, g/ml	NR*	0.8996
N_2H_4, %	51 ± 0.8	51.58
UDMH, %	47 Min	47.81
Ammonia, %	NR	trace
Water, %	1.8 Max	0.61
NO OF PARTICLES PER 100 ml	(Ref. 5)	
6 - 10 microns	9700 Max	960
11 - 25 microns	2680 Max	320
26 - 50 microns	380 Max	108
51 - 100 microns	56 Max	18
101 - 250 microns	5 Max	1
Fibers	None	None

Non-Volatile Residue, mg/100 ml - 24.4

Element	Analysis, ppm
Fe	0.79
Ni	0.22
Cr	0.66

*NR: Not required

Table 3. Analysis of Monomethylhydrazine Propellant

RESULTS	(Ref. 7) SPEC. LIMITS	ANALYSIS
Density at 296.9°K, g/ml	0.870 to 0.874	0.8725
Monomethylhydrazine, %	98.3 Min	99.02
Unknown, %	NR*	trace
Water, %	1.5 Max	0.98

NO. OF PARTICLES PER 100 ml		(Ref. 5)	
6 - 10	microns	9700 Max	1460
11 - 25	microns	2680 Max	520
26 - 50	microns	380 Max	122
51 - 100	microns	56 Max	31
101 - 250	microns	5 Max	4
Fibers		None	None

Non-Volatile Residue, mg/100 mg - 0.8

Element	Analysis, ppm
Fe	0.39
Ni	0.10
Cr	0.03

*NR: Not Required

Table 4. Analysis of Hydrazine-Hydrazine Azide Propellant

RESULTS

Density at 298°K, g/ml	1.0759
Hydrazine Azide, %	24.38
Water, %	trace

NO. OF PARTICLES PER 100 ml	(Ref.5) SPEC LIMITS	ANALYSIS
6 - 10 microns	9700 Max	1220
11 - 25 microns	2680 Max	486
26 - 50 microns	380 Max	130
51 - 100 microns	56 Max	16
101 - 250 microns	5 Max	5
Fibers	None	None

Non-Volatile Residue mg/100 ml - 392.0

Element	Analysis, ppm
Fe	44.8
Ni	7.69
Cr	12.72

Table 5. Analysis of Anhydrous Ammonia

Ammonia, %	99.99 Min
Non-Basic Gas in Vapor Phase	25 ppm Max
Non-Basic Gas in Liquid Phase	10 ppm Max
Water	33 ppm Max
Oil (as soluble in petroleum ether)	2 ppm Max
Salt (calculated as NaCl)	None
Pyridine, Hydrogen Sulfide, Napthalene	None

2.3 BASELINE PERFORMANCE DATA

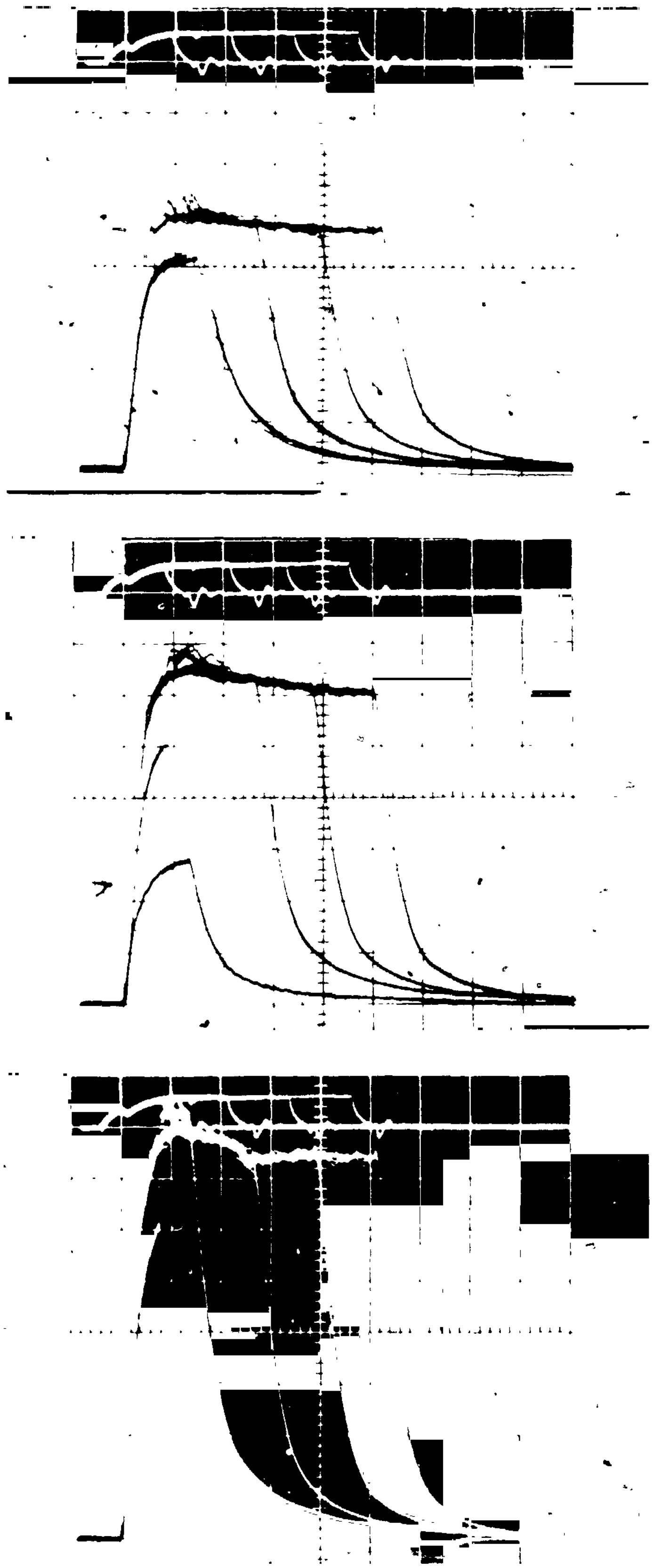
The baseline demonstration thruster configuration (Figure 1) contained sixty 0.5 cm dia. platinum screens (52 mesh, 0.1 mm wire diameter) and one 0.5 cm dia. Haynes 25 retaining screen (40 mesh, 0.28 mm wire diameter). The platinum screens were uniformly compacted to 0.5 cm depth and inserted into a sleeve having the same effective internal length. Performance characterization and baseline testing with MIL-grade hydrazine were performed on five demonstration thrusters prior to operation with the candidate monopropellants.

Typical thruster pulsed-mode characteristics are illustrated by the chamber pressure traces of Figure 9 for inlet pressures of 1.034, 1.379, and 1.724 MN/m^2, with pulse durations of 25, 50, 75 and 100 milliseconds. The pulse rate was 2.5 Hz (one pulse every 0.4 seconds). The trace at the top of each oscilloscope picture represents the propellant control valve current. The delivered specific impulse, rise and decay times as a function of pulse width are presented in Figure 10. An injection pressure of 1.724 MN/m^2 and holding temperature of 810°K were used to obtain the performance parameters. A more realistic pulse repetition rate of one per second was used. Consequently, the temperatures indicated on Figure 10 are lower than those of Figure 9.

The baseline steady-state performance characteristics in Figure 11 were obtained with a holding temperature of 810°K. The data were taken at maximum operating temperatures which varied between 1213 and 1238°K for the range of inlet pressures studied. Nominal design thrust of 0.344 N at 1.724 MN/m^2 feed pressure was met by a delivered thrust of 0.32 N. Chamber pressure roughness varied from $\pm$ 3% to $\pm$ 6% among the five baseline thrusters.

The specific impulse variation between the five baseline thrusters was negligible. Larger variations in thrust and chamber pressure levels due to injector tube flow characteristics were noticed.

One demonstration thruster was disassembled after baseline testing to examine the internal thrust chamber components. This provided a reference point for post-test examinations following operation with other propellants. All interior components revealed minimal reaction with the combustion products. The screen pack remained intact within the sleeve. A dark deposit



P_{INJ} = 1.034 MN/m^2

P_c = 0.172 $MN/m^2/cm$

t = 20 ms/cm

T_c = 1066°K

f = 2.5 Hz

P_{INJ} = 1.379 MN/m^2

P_c = 0.172 $MN/m^2/cm$

t = 20 ms/cm

T_c = 1033-1144°K

f = 2.5 Hz

P_{INJ} = 1.724 MN/m^2

P_c = 0.172 $MN/m^2/cm$

t = 20 ms/cm

T_c = 1089-1144°K

f = 2.5 Hz

Figure 9. Baseline Pulsed-Mode Characteristics

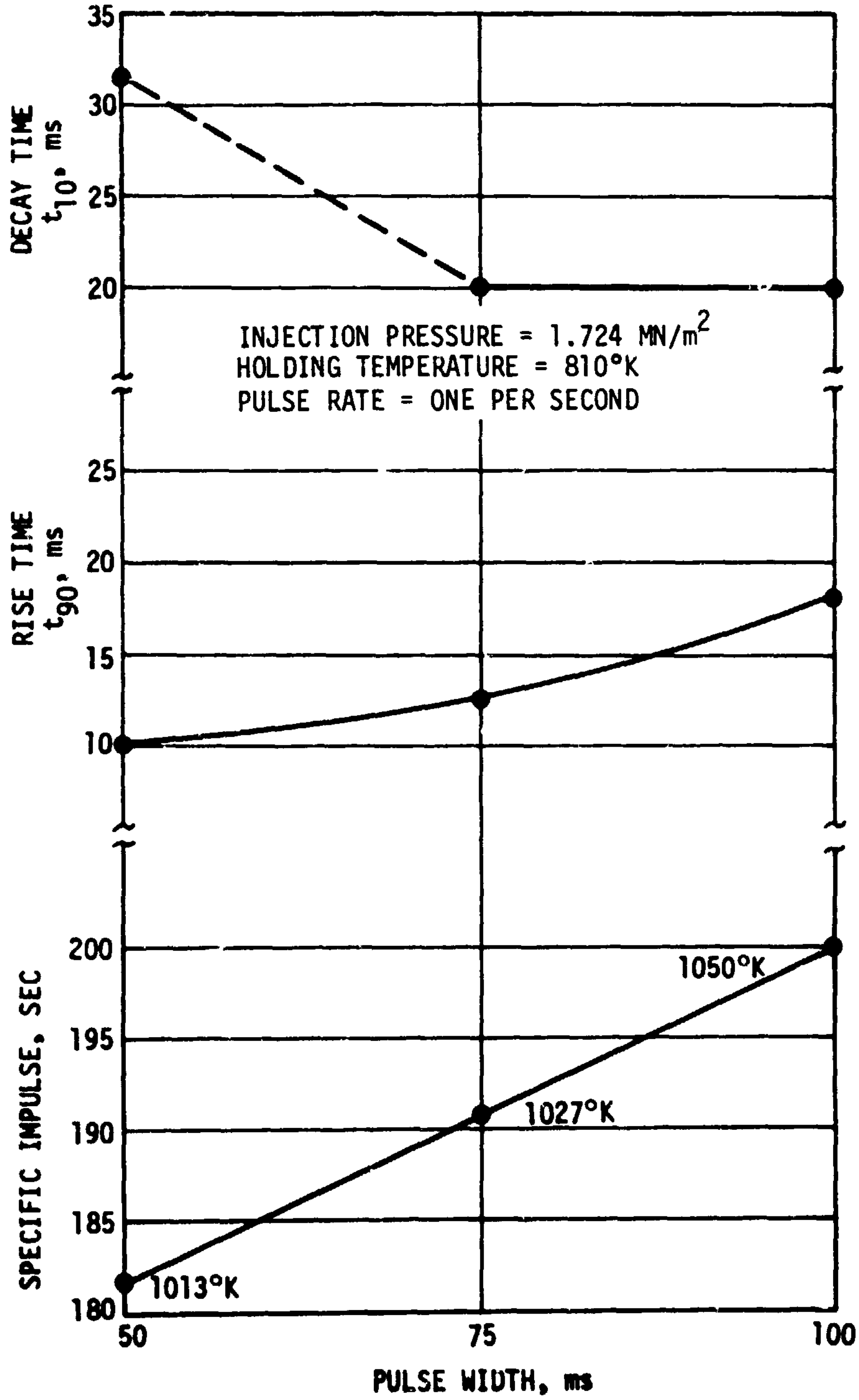


Figure 10. Baseline Pulsed-Mode Performance

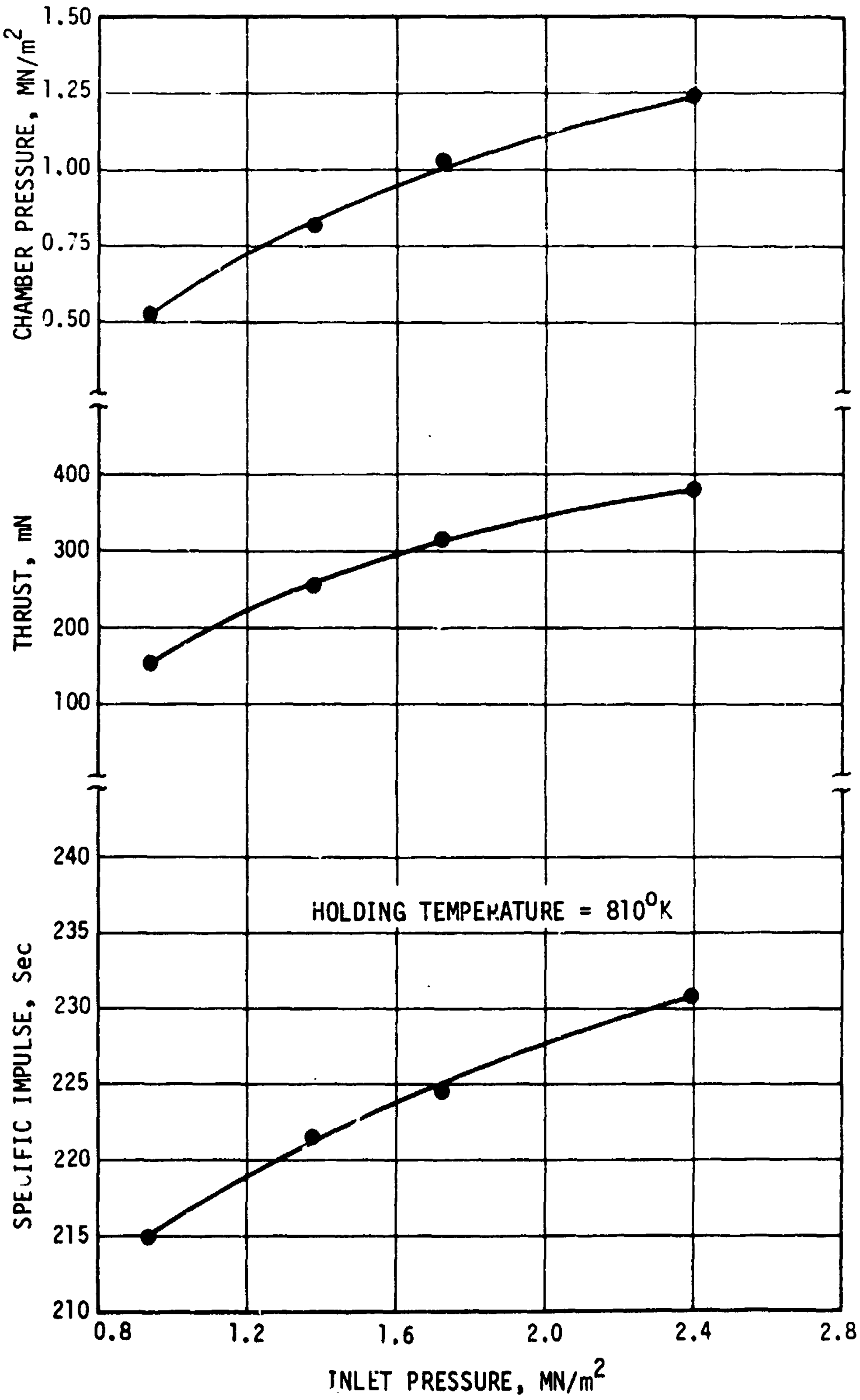


Figure 11. Baseline Steady-State Performance

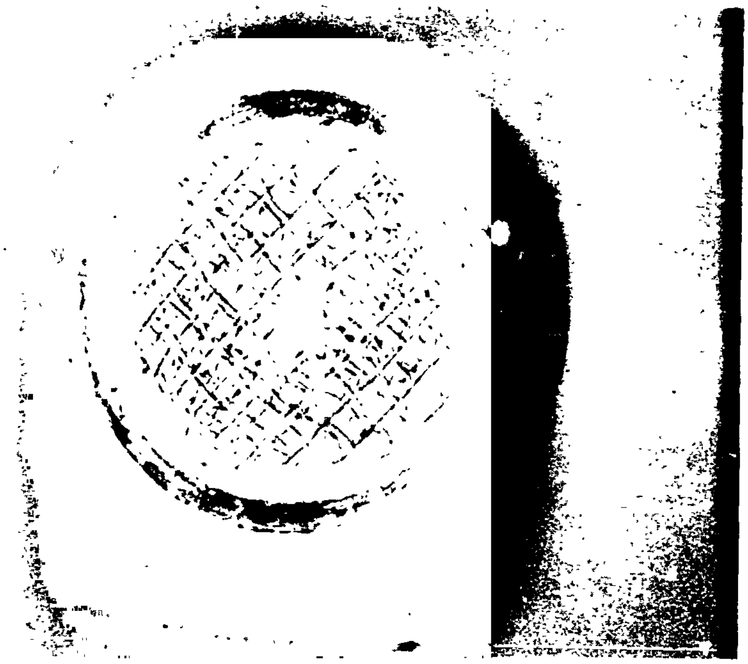
(Figure 12) was noticed on the top platinum screen. The Haynes 25 screen (Figure 13) retained its structural and chemical integrity. The deposit was subjected to electronprobe microanalysis. A backscattered electron micrograph of the top platinum screen center appears in Figure 14. A spectral analysis of the X-rays emitted when the electron beam was positioned directly on the deposit revealed that the major contaminates were Fe, Ni and Cr. The relative intensity of elements present are summarized in Table 6. The Fe content in the screen center was approximately four to five times that measured on the outer periphery of the top screen. An iron K_α X-ray image, Figure 15, confirmed that the iron detected by the spectral analysis was localized on the platinum screen (Figures 14 and 15 are of the same region). The region of highest contamination is at the lower right of each figure.

A spectral analysis of the bottom Haynes 25 retaining screen revealed the presence of W, Ni, Co, Fe, Cr, Mn and Si. The intensity of Fe-K_α radiation from the Haynes 25 screen was considerably smaller than that obtained from the top platinum screen. Iron was present on both screen materials in a disproportionate amount to that possibly present in Haynes 25. The presence of Ti in the top screen deposit indicated that the cause was not due to propellant attack and corrosion of the Haynes 25 thruster materials. The logical sources of contamination are the stainless steel storage vessels, feed lines, filters and propellant valves. The nominal compositions of stainless steels used for propellant handling is given in Table 7. Haynes 25 is included as a reference.

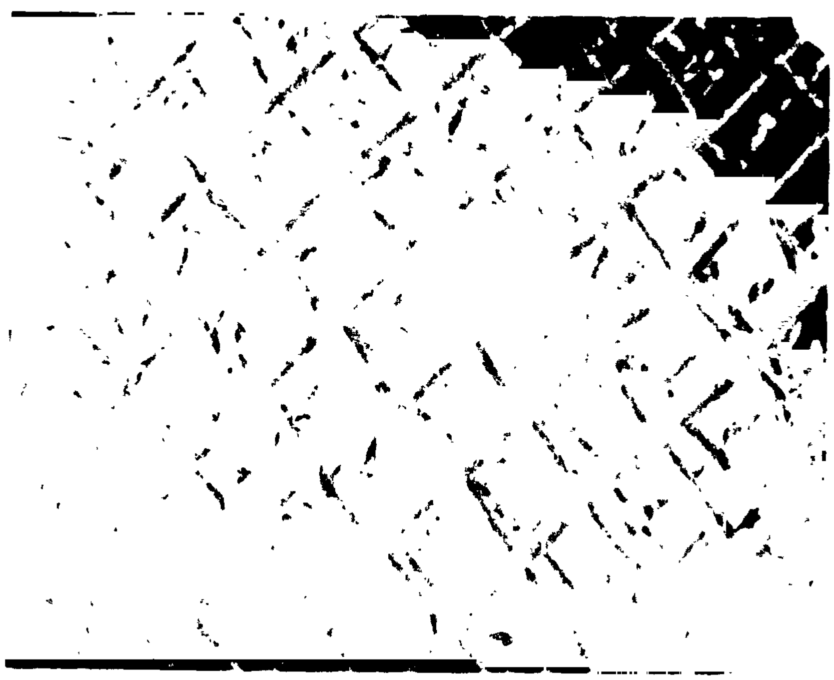
The mechanism of the storage vessel material dissolution into hydrazine has not been well defined. However, a very likely cause is the presence of carbazic acid in propellant grade hydrazine. Carbazic acid can react to form metal or hydrazine salts, e.g., $(N_2H_3COO)_3$ Fe and $N_2H_3COON_2H_5$. These salts will be present as residues after propellant vaporization. The salt residue may undergo subsequent decomposition at the high thruster operating temperatures. This would result in a highly localized metallic concentration.

2.4 PROPELLANT CHARACTERIZATION

This section presents the operating characteristics of hydrazine-hydrazine azide, Aerozine-50 and monomethylhydrazine with the baseline thruster configuration (Sec. 2.3). Initial tests with these three propellants were performed under sea-level conditions. Initial characterization tests with



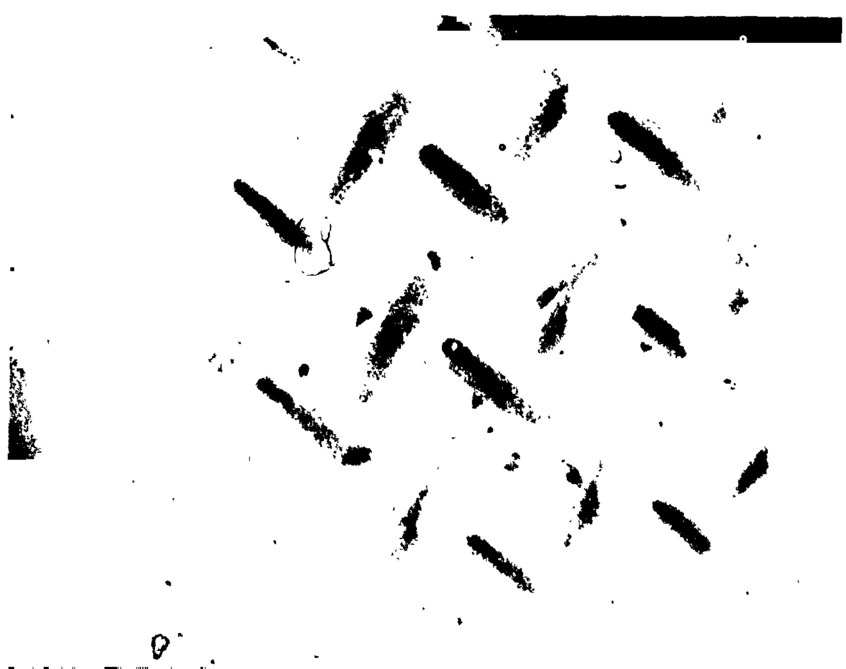
(a) 10X



(b) 27X

Figure 12. Deposit on Top Platinum Screen

(a) 10X



(b) 27X

Figure 13. Haynes 25 Retaining Screen

Figure 14. Backscattered Electron Image of the Top Platinum Screen Center

Table 6. Spectral Analysis of Platinum Screen Deposit

RELATIVE X-RAY INTENSITY

Very Strong	Strong	Medium	Weak	Trace
Pt	Fe	Cr	Ti	Ca
	Ni		Co	Si
				Cl
				S
				Na
				Mn

NOTE: Carbon below instrument detection limits.
Oxygen below instrument detection limits.

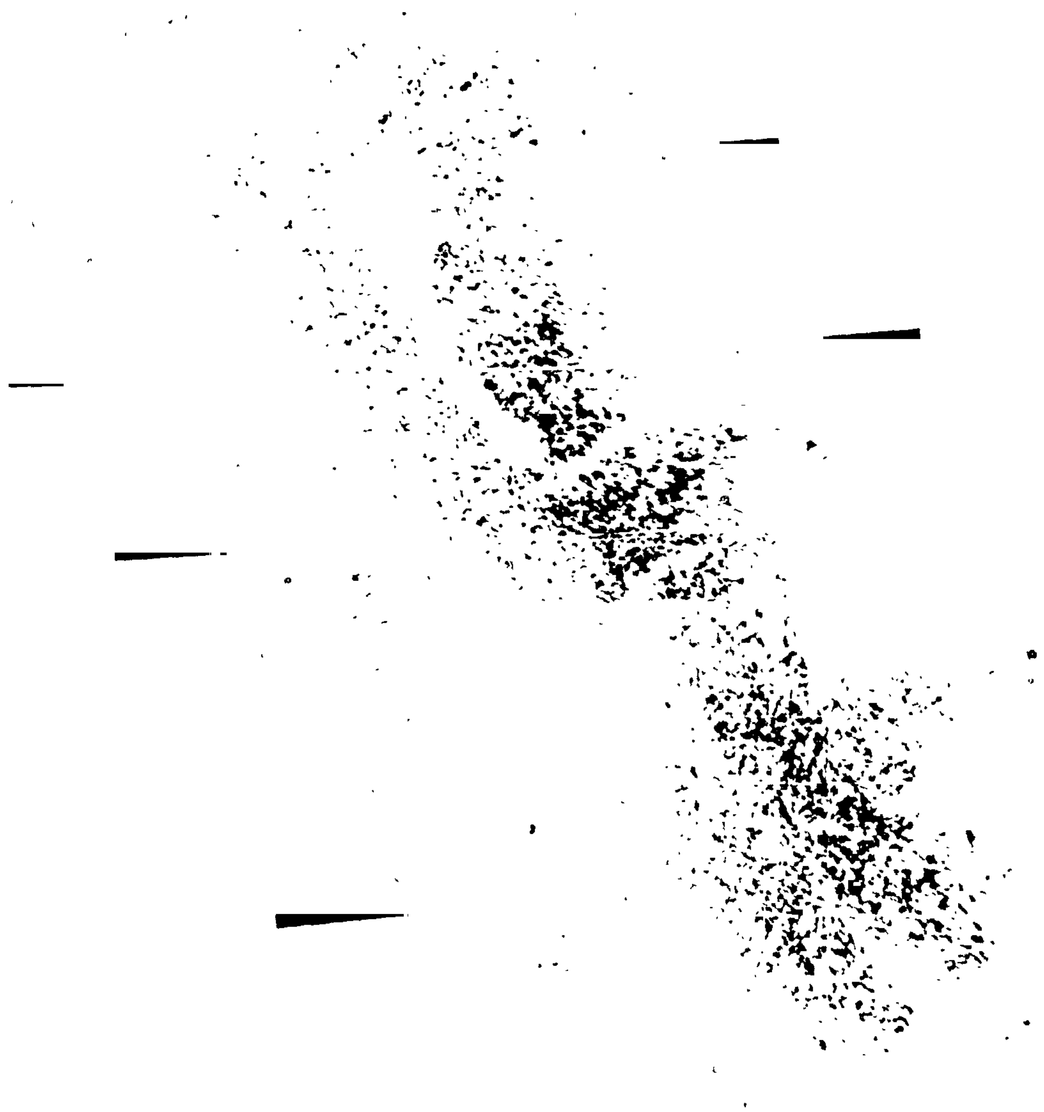


Figure 15. Iron K_α X-ray Image of the Top Platinum Screen Center

Table 7. Nominal Compositions of Stainless Steels and Haynes 25

Steel	C	Cr	Ni	Mn	Si,max	P,max	S,max	Others
303	0.015 max	17.00-19.00	8.00-10.00	2.00 max	1.00	0.02	0.15 min	0.060 max Mo(a)
304	0.08 max	18.00-20.00	8.00-12.00	2.00 max	1.00	0.045	0.03	...
321	0.08 max	17.00-19.00	9.00-12.00(b)	2.00 max	1.00	0.045	0.03	5 x C min Ti

Haynes 25, 0.10C, 20Cr, 10Ni, 15W, 1.5Mn, 0.5Si, balance Co.

(a) Optional

(b) A nickel content of 9 to 13% is permitted for tubular products.

50% MMH-50% N_2H_4 and MHM were performed during the later stages of the evaluation test program with thruster configurations derived from satisfactory operation with Aerozine-50. The test results with these propellants are included in the performance optimization section.

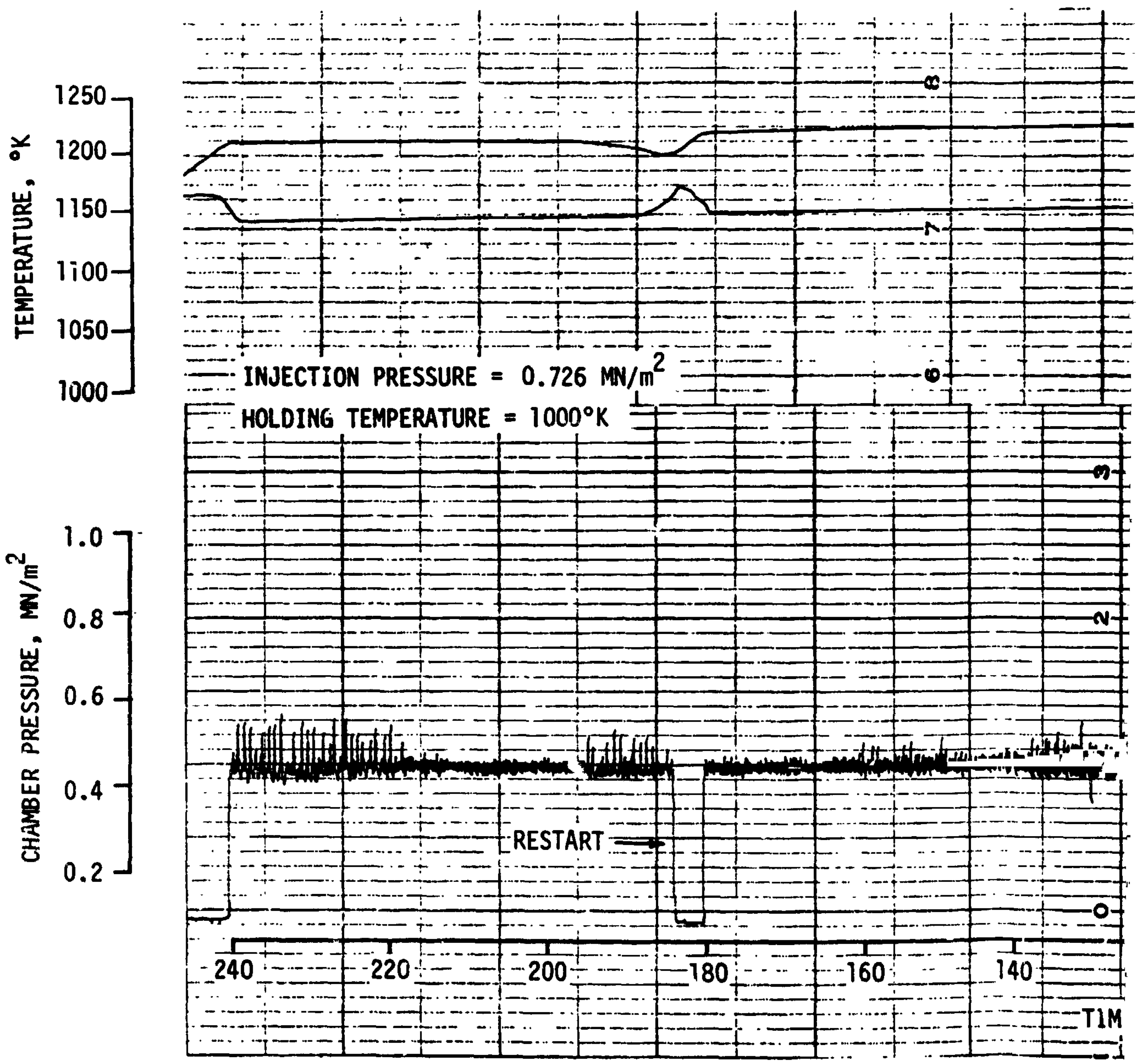
2.4.1 Hydrazine-Hydrazine Azide

A total of 23.5 minutes steady-state operation was accumulated before testing was terminated by an injector failure (revealed by post-test inspection). The thruster exhibited metastable operation during this period. This mode is illustrated by the chamber pressure trace in Figure 16. Ignition at the holding temperature of 1000°K was very erratic. The large chamber pressure fluctuations were significantly reduced when the energy supplied by decomposition raised the thruster temperature to 1155°K. Chamber pressure roughness continued to decrease with time. High speed oscillograph chamber pressure traces reproduced in Figure 17 illustrate the roughness decrease.

Stable operation could not be achieved at injection pressure above 0.83 MN/m^2. The injection pressure was reduced to 0.72 MN/m^2 and an additional 18 minutes steady-state time was accumulated when an abrupt loss of chamber pressure occurred. Operation during this period was characterized by smooth and very rough behavior. The chamber pressure trace just prior to and at injector failure is shown in Figure 18. Post-test inspection revealed that the injector ruptured at the first portion of the thermal relief bend (Figure 19).

Disassembly of the thruster revealed a considerable amount of screen pack rearrangement and compaction (Figure 20). A two-zoned contamination region is indicated in the plan view (Figure 20a). The individual screen wires were bent and kinked from their original geometry. The oblique view in Figure 20b illustrates the screen pack compaction. These effects were caused by the large chamber pressure fluctuations which occurred during unstable operation. Negligible chamber corrosion was observed. An interior view of the nozzle end appears in Figure 21a. The Haynes 25 retaining screen (Figure 21b) remained intact during testing.

An electron microprobe analysis of the post-test screen pack condition indicated that the major contaminate was iron. A backscattered electron



FOLDOUT FRAME

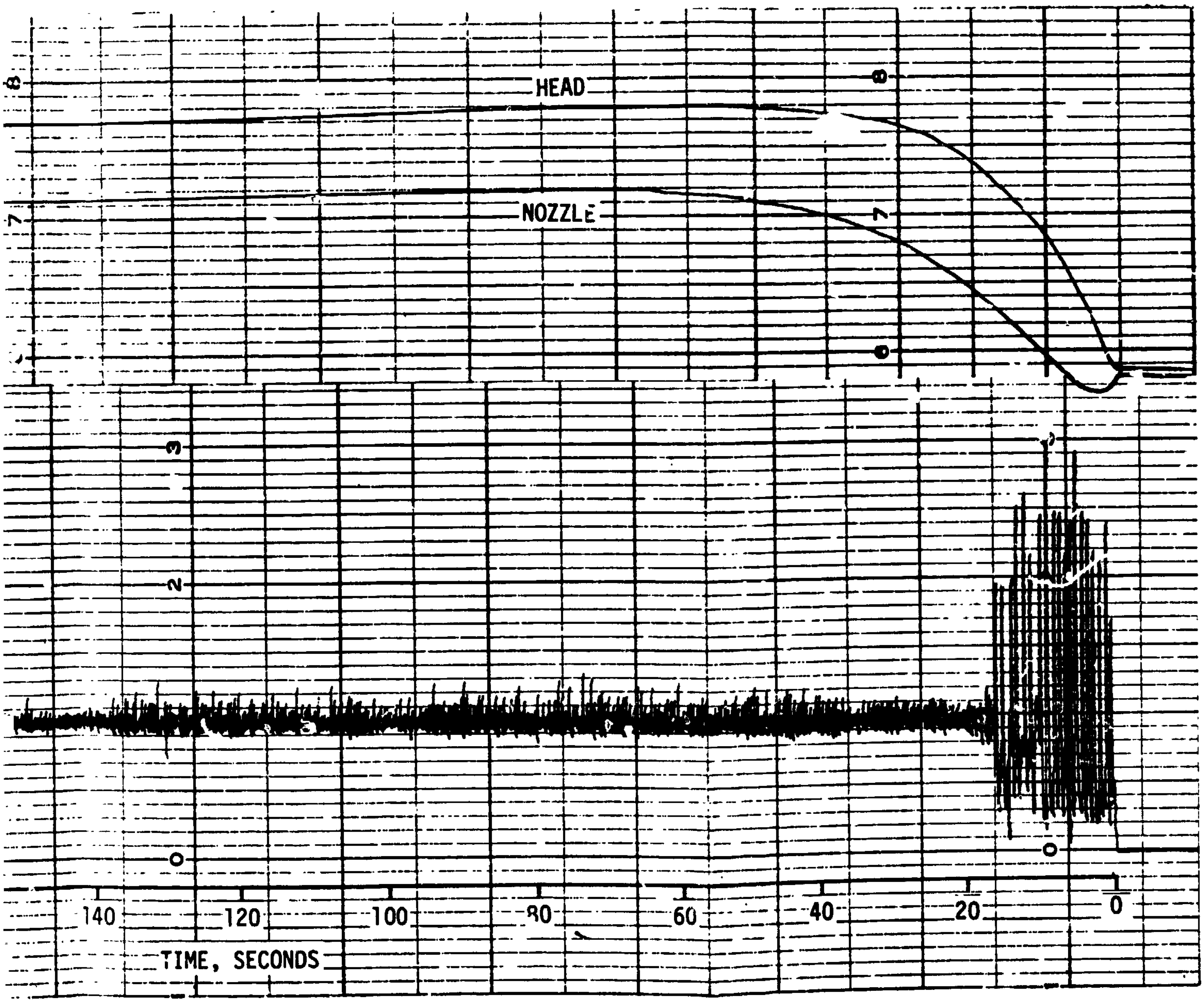


Figure 16. Preliminary Sea-Level Steady-State Operation with 76 Percent Hydrazine — 24 Percent Hydrazine Azide

FOLDOUT FRAME 2

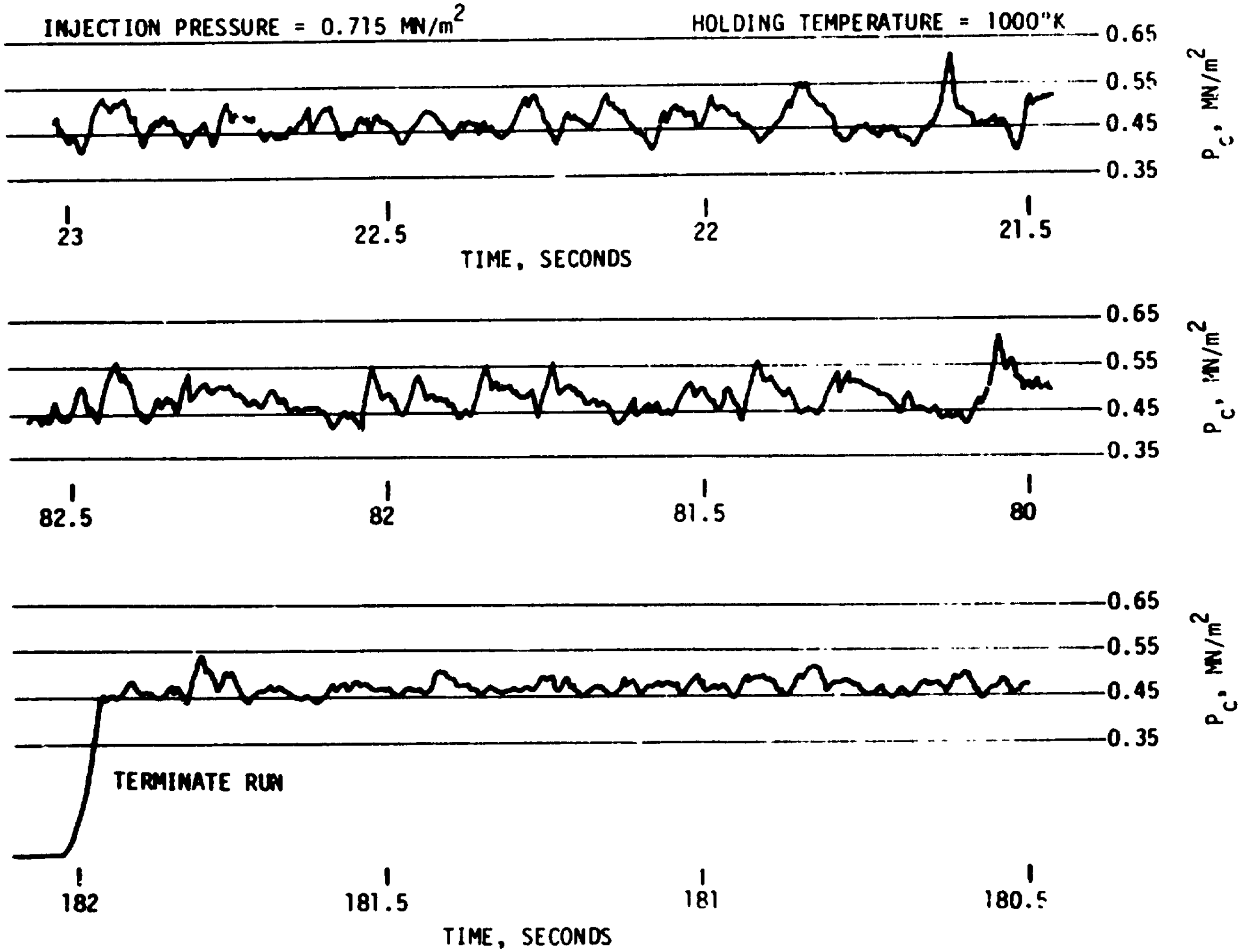


Figure 17. Steady-State Oscillograph Chamber Pressure Traces at Times Corresponding to Those of Figure 16

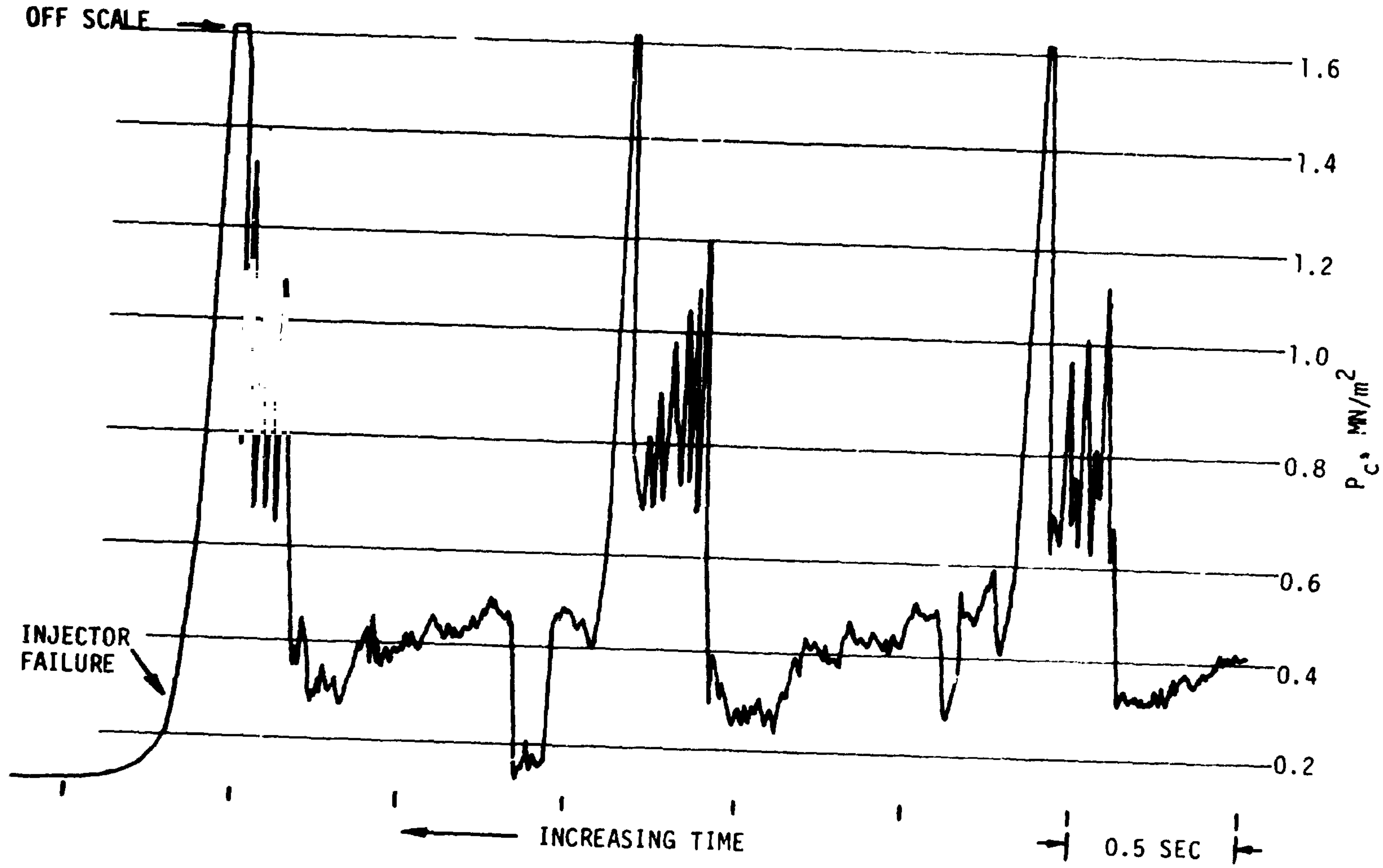
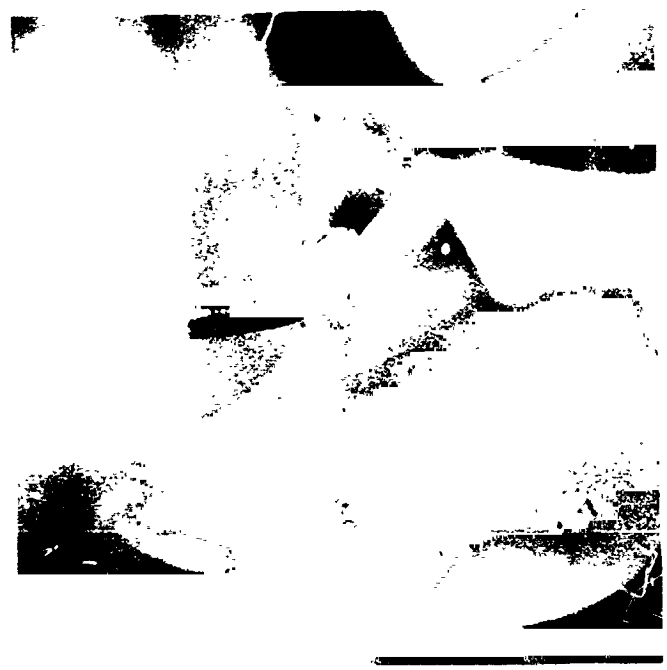


Figure 18. Oscillograph Trace of Chamber Pressure Prior to and at Injector Failure



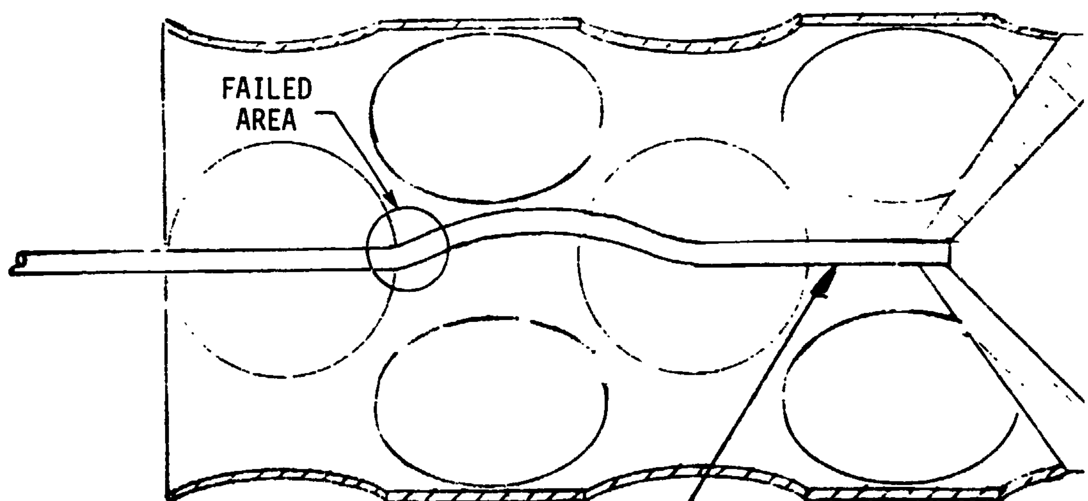
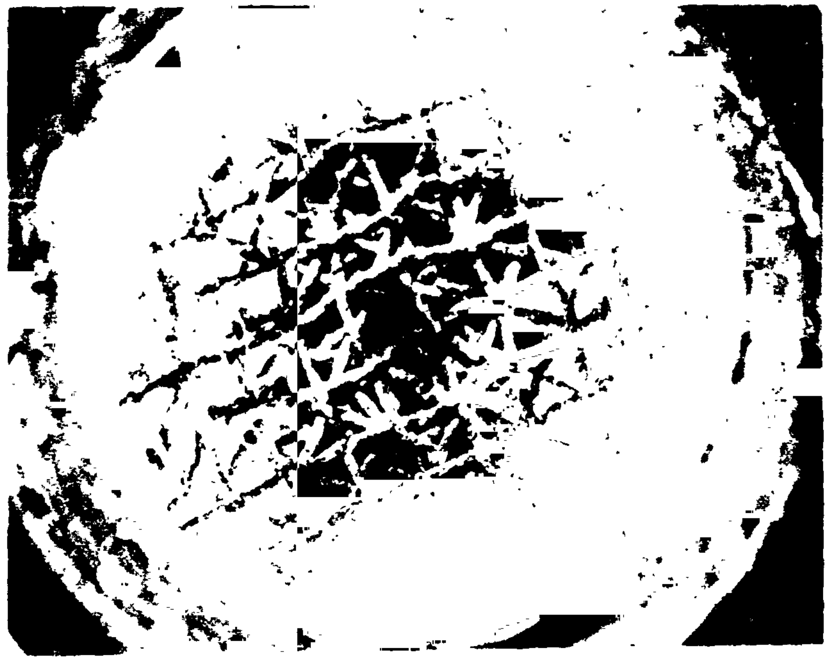
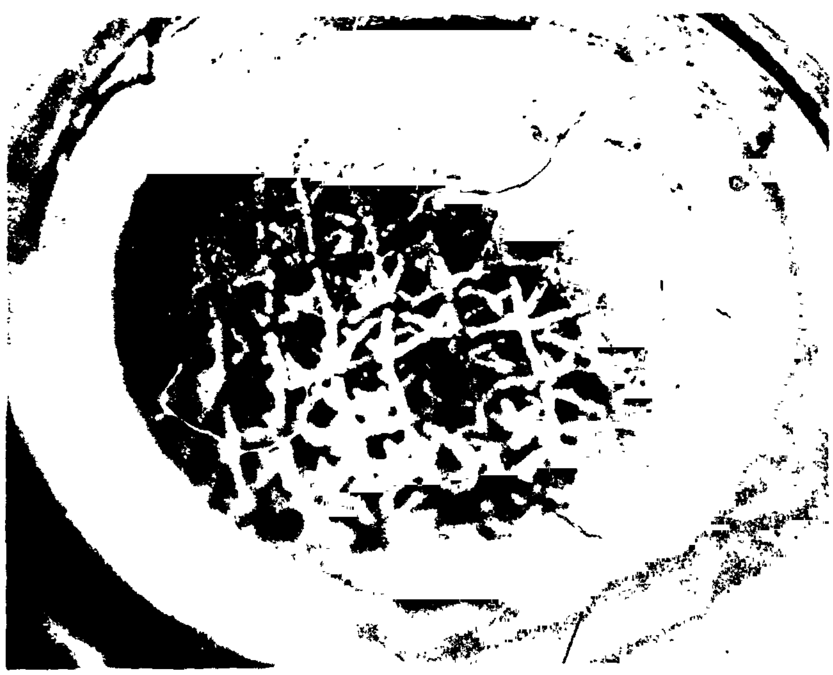


Figure 19. Injector Failure



(a) Plan View



(b) Oblique View

Figure 20. Post-Test Condition of Screen Pack From Thruster Operated on 76 Percent Hydrazine - 24 Percent Hydrazine Azide

(a) Interior View of Nozzle End and Throat

(b) Haynes 25 Retaining Screen

Figure 21. Downstream Thrust Chamber Components of Thruster Operated on 76 Percent Hydrazine - 24 Percent Hydrazine Azide

image of the central area of Figure 20a appears in Figure 22. An Fe-K_{α} X-ray image of the same area is shown in Figure 23. A spectral analysis also revealed the presence of chromium, nickel and cobalt. The iron content was significantly higher than that observed on the hydrazine baseline thruster's screen pack.

2.4.2 Aerozine-50

A total of seven minutes steady-state operation was accumulated with the baseline thruster configuration. Injection pressures were varied between 0.31 and 1.03 MN/m^2 and initial holding temperatures of 993 and 1073°K were used. The thruster exhibited stable operation under all test conditions. Ignition could not be sustained for any reasonable length of time with injection pressures above 0.31 MN/m^2 at either holding temperature. Chamber pressure (P_c) traces during steady-state operation are illustrated in Figure 24 for an injection pressure of 1.03 MN/m^2 and holding temperatures of 993 and 1073°K, respectively. Large chamber pressure fluctuations were absent. The gradual decrease in P_c after two seconds run time was accompanied by a decrease in thruster temperature (monitored visually on digital readout). Limited decomposition occurred at a low injection pressure of 0.31 MN/m^2 for about 45 seconds before the thruster temperatures were observed to decrease.

Post-test thruster disassembly and inspection revealed negligible chamber corrosion. Carbon deposition was not observed on the chamber walls or in the nozzle section. No evidence of carbon deposition was noticed on the platinum screens. The bottom Haynes 25 retaining screen had a dark deposit buildup. The top and bottom portions of the screen pack appear in Figure 25. X-ray imaging in the electron microprobe confirmed that the deposit on the retaining screen was carbon.

2.4.3 Monomethylhydrazine

Preliminary sea-level steady-state operation with MMH was similar to that with Aerozine-50. The rate of decrease in thruster temperature was more severe than that with Aerozine-50. This rapid performance degradation is illustrated in Figure 26. Screen pack flooding also occurred at lower injection pressures and higher holding temperatures. The only difference was the time required to produce the same level of thruster quench. The

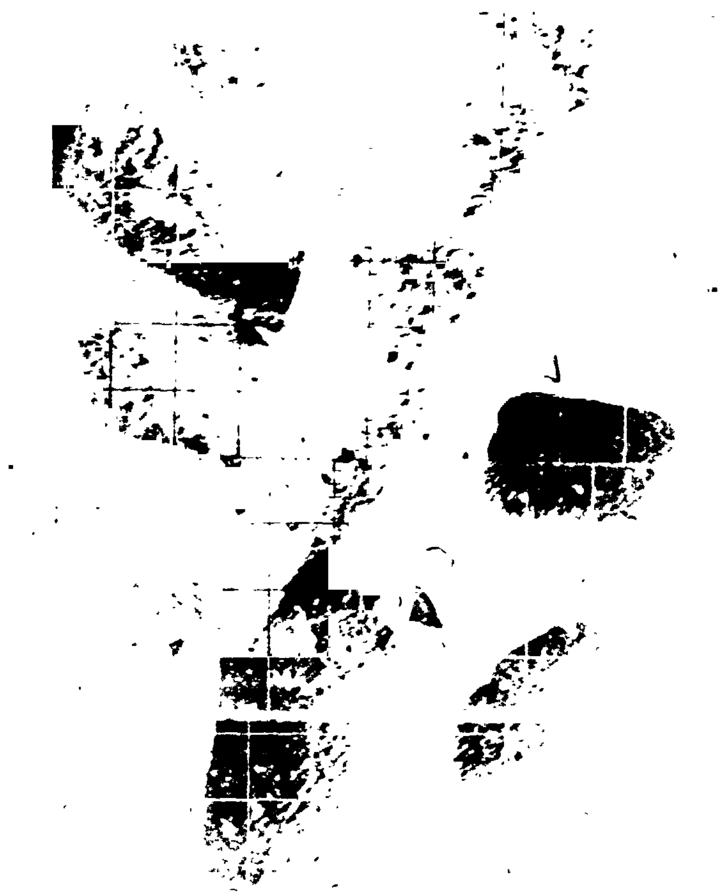


Figure 22. Backscattered Electron Image of the Top Platinum Screen Center From Thruster Operated With Hydrazine-Hydrazine Azide

Figure 23. Iron K_α X-Ray Image of the Top Platinum Screens of Figure 22

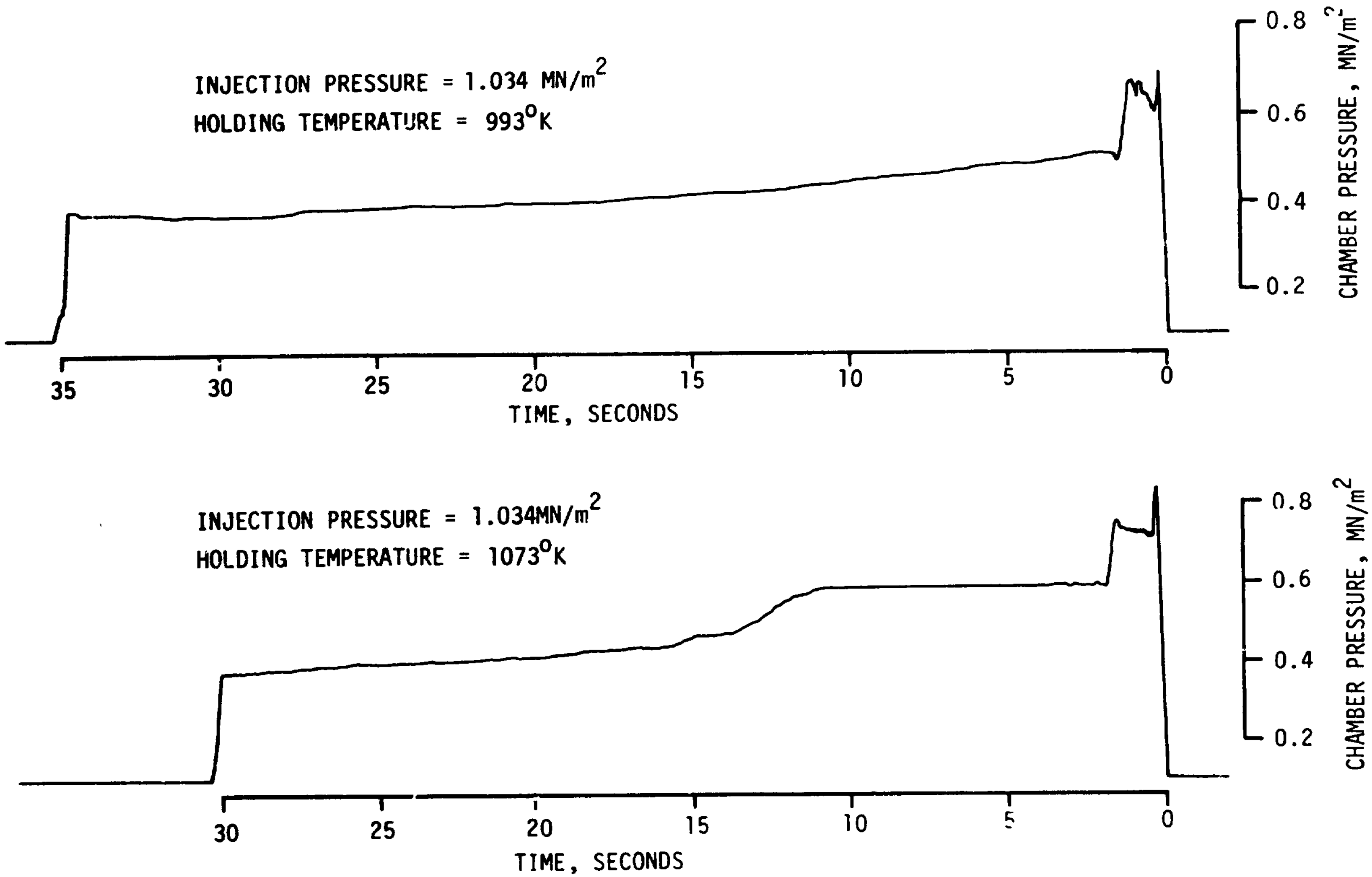
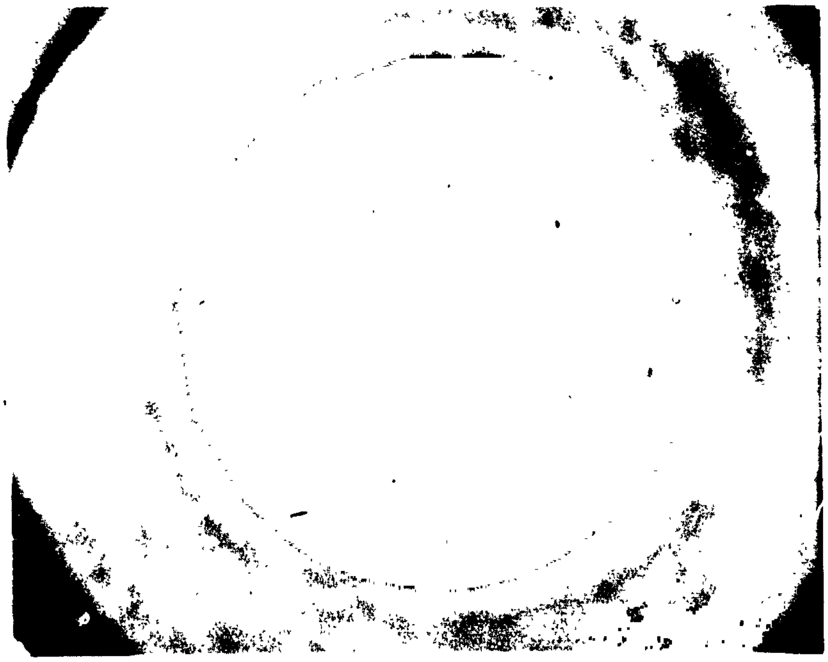


Figure 24. Preliminary Sea-Level Steady-State Thruster Operation With Aerozine-50

(a) Top Platinum Screens, 20X



(b) Haynes 25 Retaining Screen, 20X

Figure 25. Aerozine-50 Post Test Screen Pack Appearance

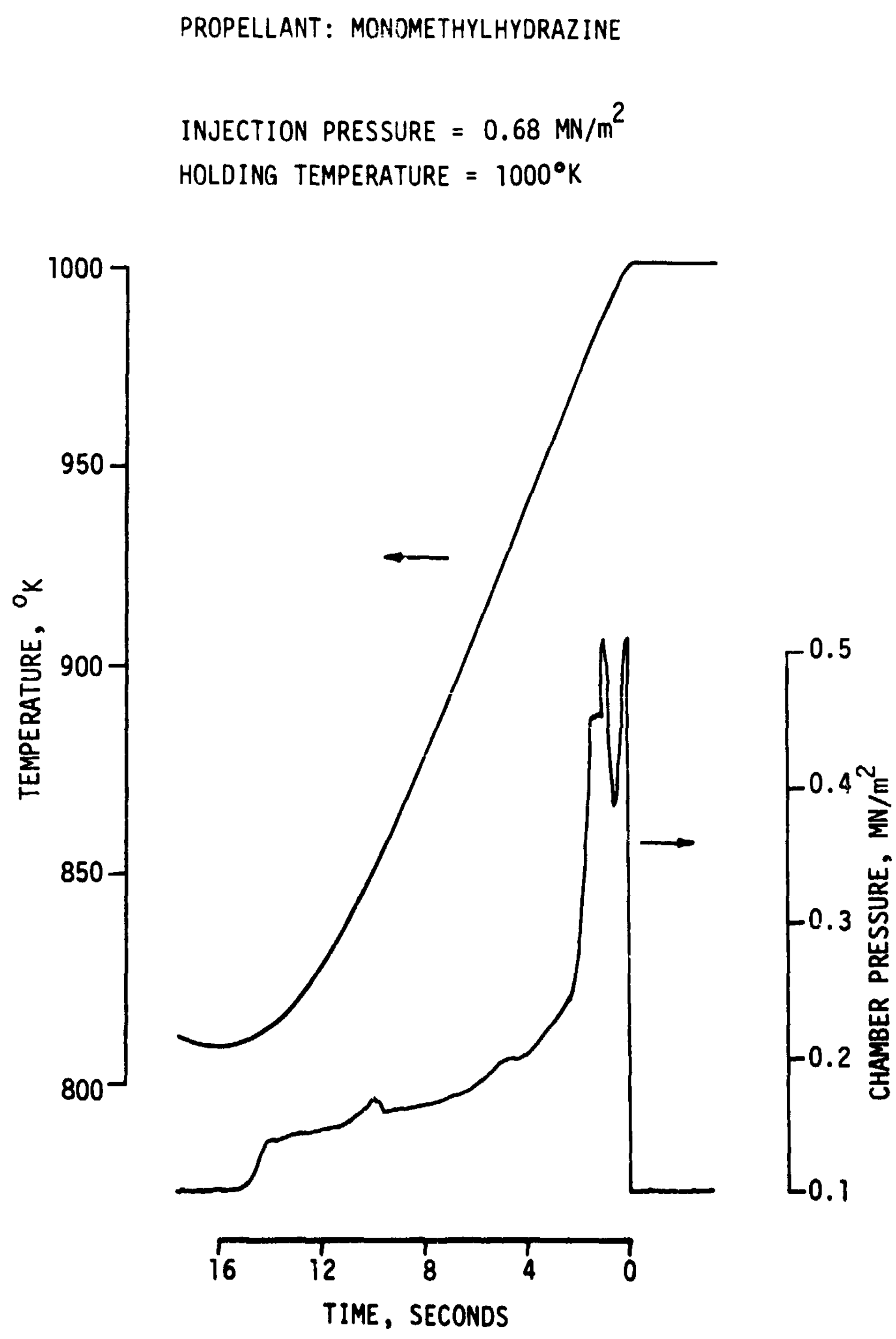


Figure 26. Preliminary Sea-Level Steady-State Thruster Operation With Monomethylhydrazine

steady-state tests were terminated prior to the condition of liquid propellant flow through the nozzle. The total steady-state operation amounted to about five minutes.

The thruster was pulsed (50 ms pulse, one pulse per second) with an injection pressure of 0.34 MN/m^2 and holding temperatures of 1000, 1061 and 1144°K, respectively. Two hundred pulses were accumulated at holding temperatures of 1000 and 1061°K (one hundred each). There were no indications of abnormal operation at these temperatures. Rapid chamber pressure degradation occurred after ten pulses at the high holding temperature of 1144°K. Post-test inspection revealed that the injector was plugged with carbon. Thermal soakback between pulses was sufficient to cause vaporization and decomposition in the injector. No carbon deposits were observed on any of the interior thrust chamber surfaces.

2.5 PERFORMANCE OPTIMIZATION

The initial characterization tests (Section 2.4) indicated that the baseline thruster configuration was marginal for stable operation with the azide blend and inadequate for operation with the carbonaceous propellants (AERO-50, MMH). Subsequent tests revealed that the propellants' reactivity in a thermal environment decreased in the following order: Hydrazine-Hydrazine azide, Hydrazine, Aerozine-50, 50% N_2H_4-50% MMH, MHM, MMH. This fact required a different thruster configuration for each propellant in order to accommodate the varying decomposition characteristics. The resulting thruster configurations were obtained by varying the internal screen pack geometries. The head and nozzle sections were not changed.

Each new thruster configuration was baselined with hydrazine prior to operation with the candidate propellant. A substantial amount of performance data was gathered for operation with hydrazine. One thruster configuration appeared to offer considerable performance increases over the baseline thruster. A complete analysis of hydrazine performance with the configurations derived for operation with other propellants will appear as a separate section in the Data Correlation portion of the Final Project Report. The data from those thruster configurations are presented in this section for comparative purposes.

2.5.1 Hydrazine-Hydrazine Azide

The unstable operation which led to an injector failure with the baseline thruster configuration indicated that undecomposed propellant traversed a considerable length of the screen pack. Subsequent decomposition of this propellant caused a pressure wave front to rapidly move towards the injector end of the thruster. The intensity of this wave front promoted rapid decomposition of propellant remaining in the head space. The end result of this process was a large pressure spike.

A series of tests were initiated to determine the relationship between stable modes of operation, screen pack density and characteristic chamber length, L^*. Results indicated that the head space "reactivity" controls the overall thruster performance. Two thruster configurations which resulted in very unstable operation are briefly described. The configurations were the following:

1. Large head space: 60 screens compacted 0.5 cm in a 0.75 cm sleeve.
2. High Density Screen Pack: 80 screens in a 0.5 cm sleeve, standard head space.

Both thruster configurations resulted in unstable decomposition in the head space; one by virtue of the larger physical volume and the other by a larger pressure drop across the screen pack.

A configuration using a variable density screen pack reduced the head space "reactivity." Sixty screens were packed in a 0.5 cm sleeve with the packing density at the head end approximately twice that at the nozzle end. Stable steady-state operation was obtained at an injection pressure of 1.034 MN/m^2 and a holding temperature of 923°K. This represented a considerable improvement over the standard screen pack geometry for which stable operation was marginal at a low injection pressure of 0.717 MN/m^2 and a holding temperature of 998°K. Slight instabilities were observed after 80 seconds of steady-state operation but large chamber pressure variations were absent.

Performance measurements with hydrazine for this thruster configuration were similar to the original baseline configuration. Values of delivered specific impulse were five percent lower. Steady-state perfor- measurements for the azide blend are given in Figure 27.

A higher holding temperature of 923°K was used after the start characteristics at 810°K were rough. Chamber pressure roughness varied from ± 9% at 1.034 MN/m^2 injection pressure to ± 15% at 1.724 MN/m^2 injection pressure. Operation at the high injection pressure of 2.413 MN/m^2 resulted in metastable operation similar to that obtained with the baseline configuration. The data at this injection pressure are approximate. The pulsed-mode performance characteristics are presented in Figure 28. The low value of delivered specific impulse and large rise time to 90% P_c for the 50 ms pulse indicated that vaporization was occurring in the feed tube.

2 5.2 <u>Aerozine-50</u>

The inability to sustain steady-state ignition with the baseline configuration suggested that the thrust chamber resident times were too short. Residence times could be increased by a longer screen pack assembly (larger L^*) or by a higher pressure drop across an existing screen pack (baseline L^*). The latter option was adopted. A 0.5 cm length sleeve was packed with 80 platinum screens. The free volume fraction within the pack was decreased from the baseline configuration value of 0.576 to 0.434. The thruster was sea-level baseline tested on hydrazine and then operated with Aerozine-50. Simulated high altitude performance measurements were later obtained with an identical thruster configuration operating with both propellants.

Thirty minutes sustained steady-state ignition was obtained using Aerozine-50 with the modified screen pack. An injection pressure of 1.034 MN/m^2 and holding temperature of 810°K were used. The chamber pressure

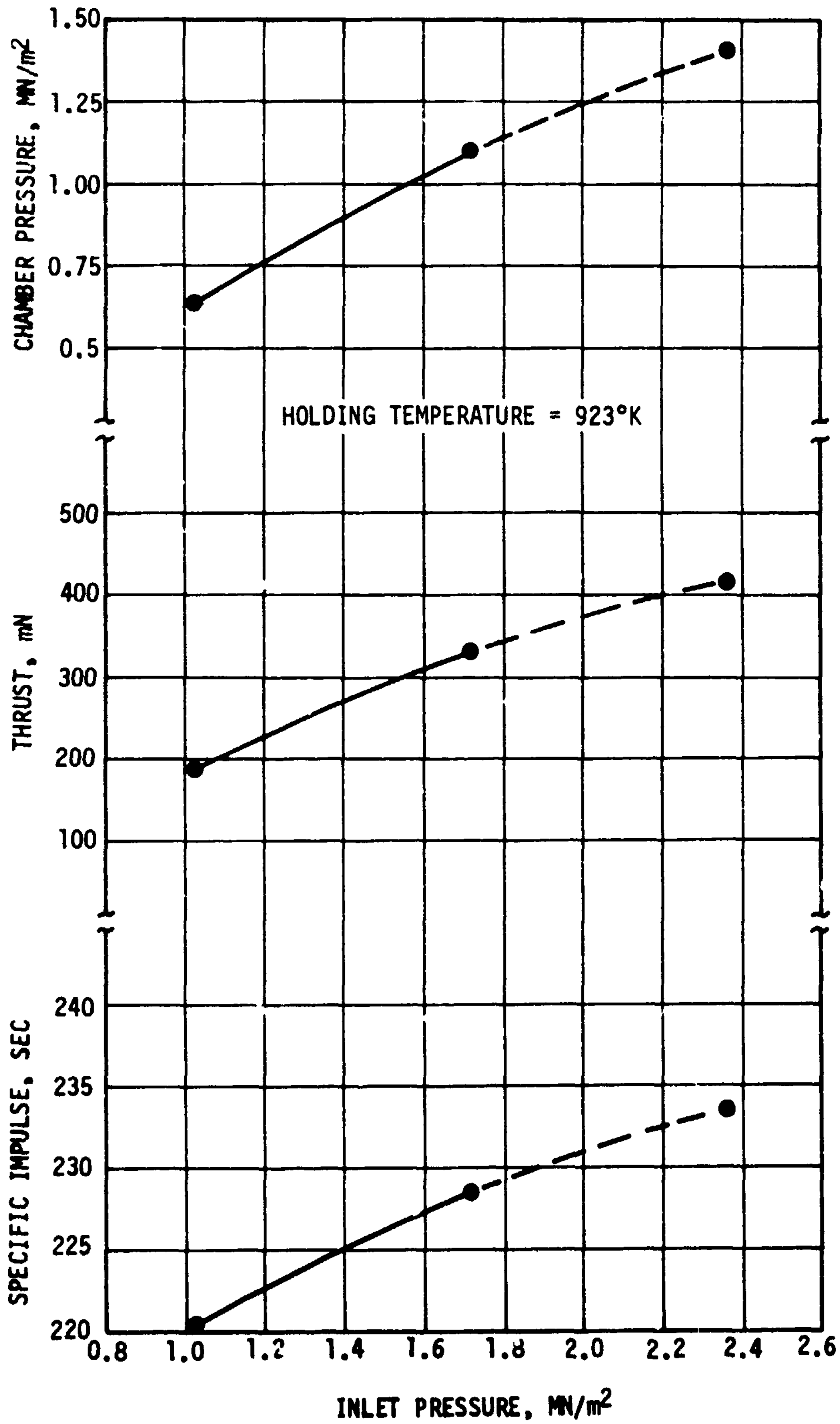


Figure 27. Hydrazine-Hydrazine Azide Steady-State Performance

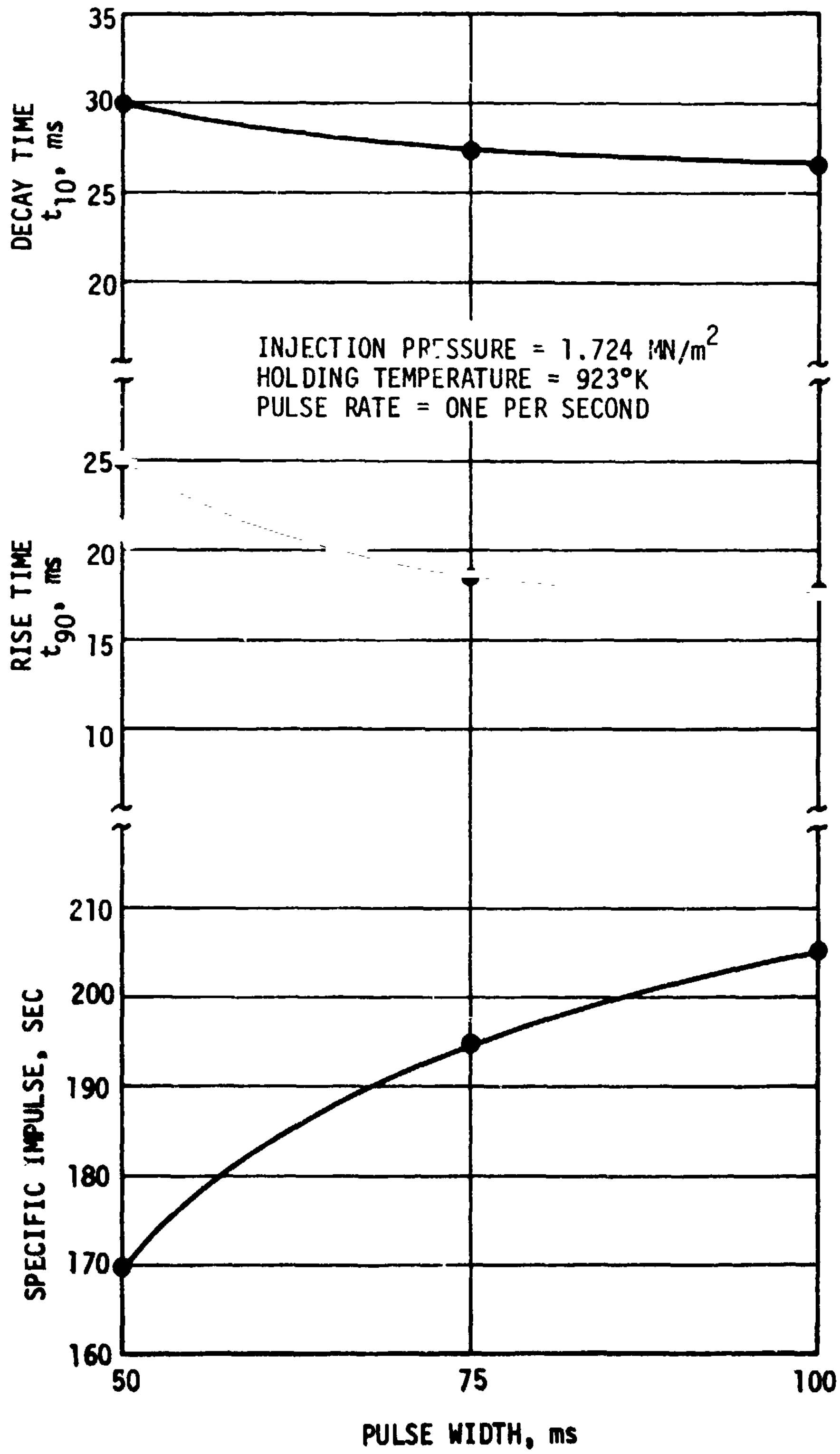


Figure 28. Hydrazine-Hydrazine Azide Pulsed-Mode Performance

roughness was ± 3.5 percent at an average value of 0.637 MN/m^2. The chamber temperature rose to 977°K. The steady-state test was terminated when response from the chamber pressure transducer became sluggish. At this time, however, the thruster was still operating in a normal mode as judged from the chamber temperature traces. The thruster was removed from the test stand and disassembled. The slow transducer response was caused by a thin layer of carbon buildup in the nozzle section. The nozzle section is shown in Figures 29a and 29b as internal and external views, respectively. The nozzle throat showed no evidence of carbon accumulation; the pre and post-test diameters were identical. Carbon deposits were also observed on the walls of the head space and within the screen pack. The injector showed no signs of carbon buildup. The carbon deposited in the form of a fine powder.

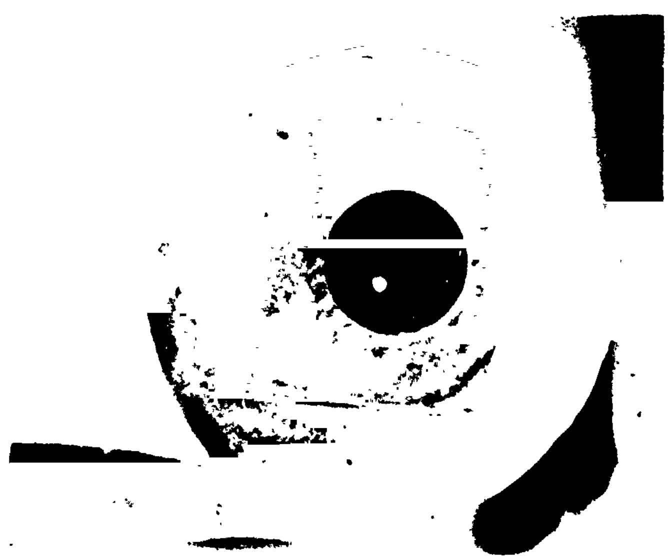
Steady-state performance parameters for Aerozine-50 are compared to those for hydrazine in Figure 30 with the modified thruster configuration. Temperature measurements indicated that considerable decomposition was occurring near the nozzle. The nozzle block and chamber head temperatures were 1061°K and 1027°K, respectively (injection pressure was 1.724 MN/m^2). The corresponding nozzle and head temperatures for operation with hydrazine were 1205°K and 1239°K, respectively. Chamber pressure roughness was ± 7% for hydrazine and ± 6% for Aerozine-50.

The pulsed-mode performance of hydrazine versus Aerozine-50 appears in Figure 31. The operating parameters for these data were injection pressure = 1.724 MN/m^2; holding temperature = 810°K; pulse rate = one per second. The maximum thruster temperatures are indicated at each datum point. An oscillograph recording of the pulsed-mode analog data is reproduced in

Pressure Tap

Heater Lead

(a) Interior View of Nozzle Section



(b) Exterior View of Nozzle Section

Figure 29. Post-Test Appearance of Nozzle Section From Thruster Operated 30 Minutes Steady-State With Aerozine-50

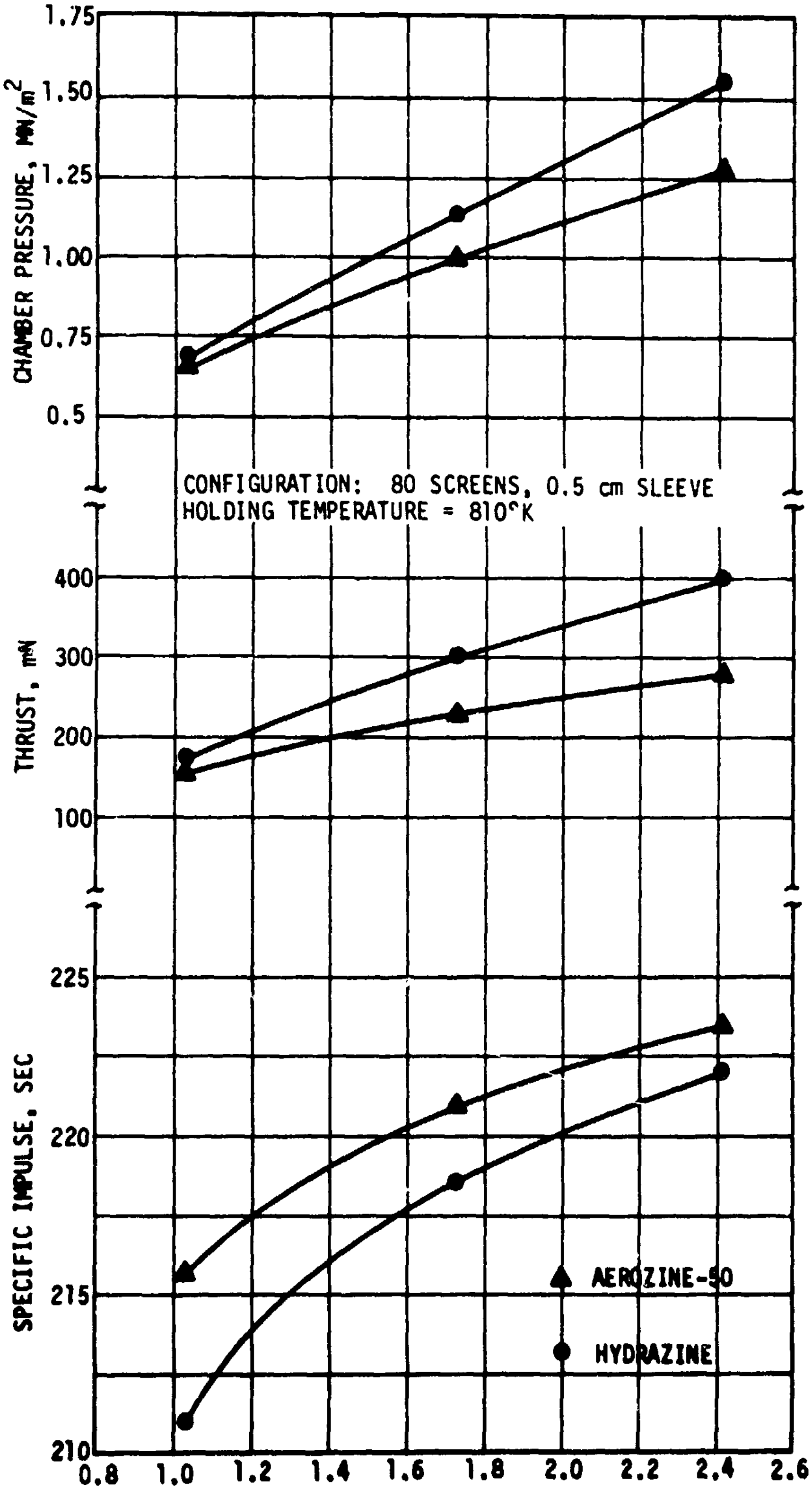


Figure 30. Steady-State Performance Measurements With Aerozine-50

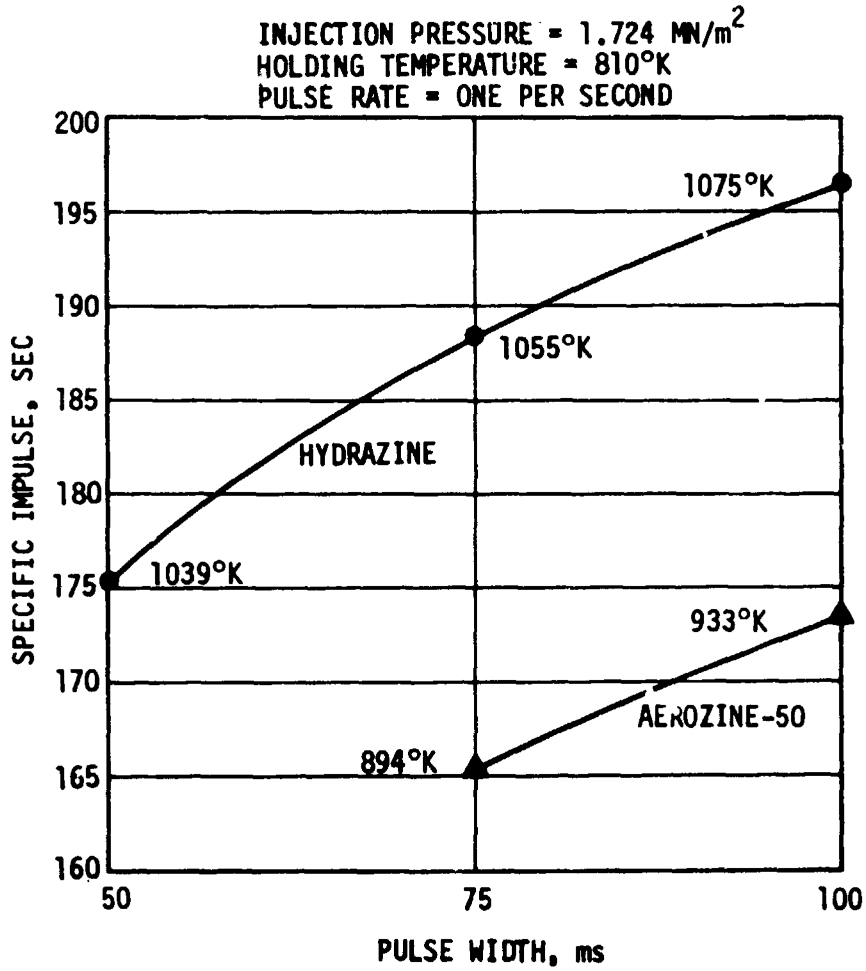


Figure 31. Pulsed-Mode Performance With Aerozine-50

Figure 32 for a 100 ms pulse. The rise and decay times to 90% and 10% P_c were 28 ms and 75 ms, respectively. A 42 ms centroid shift from the command pulse was calculated.

Post-test disassembly and inspection revealed a similar level of carbon deposition as was observed after sea-level testing.

2.5.3 Monomethylhydrazine

Attempts to obtain sustained steady-state decomposition with the Aerozine-50 thruster configuration were unsuccessful. A 1.02 cm sleeve was packed with 160 platinum screens to provide a higher screen pack pressure drop (increased residence times). An additional heater element was wrapped around the longer sleeve to prevent temperature gradients along the thruster assembly. A separate power supply was used to equalize the temperature distribution. Steady-state operation was marginal at a holding temperature of 1198°K and an injection pressure of 1.034 MN/m^2. The nozzle section temperature rose to 1263 °K and the head quenched to 773°K after five minutes of operation. Longer run times resulted in "flooding." Prior to this condition, the thrust level was 154 mN with a delivered specific impulse of 229 sec.

Hydrazine was mixed in a 1:1 ratio with MMH in order to reduce the high holding temperatures necessary to initiate MMH decomposition. Two screen pack configurations were used. One configuration was similar to that used with MMH. The 1.02 cm sleeve was packed with 180 screens. The second thruster had 360 screens packed in a 2.54 cm sleeve. Marginal steady-state decomposition was obtained at a lower holding temperature of 1033°K with the former thruster configuration. The thruster's temperature-time history indicated that the decomposition front was towards the nozzle end. Sustained steady-state decomposition was obtained for ten minutes with the long (2.54 cm)

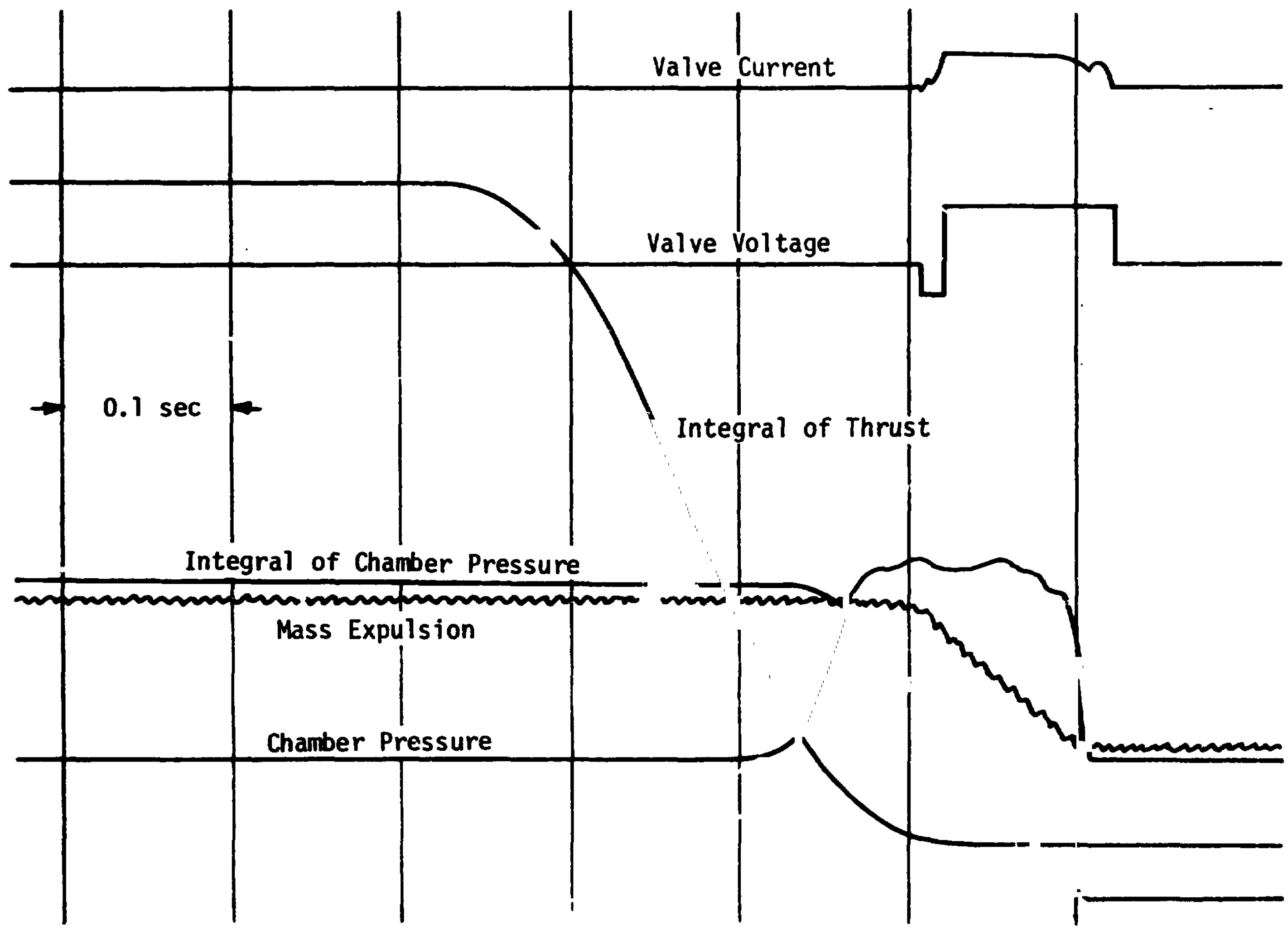


Figure 32. Aerozine-50 Pulsed Mode Analog Data Recording

screen pack assembly at a holding temperature of 1033°K and injection pressure of 1.034 MN/m^2. Thrust and chamber pressure degradation were noticed after ten minutes. The thrust decreased from 168 mN to 52 mN. The specific impulse decreased from 221 sec. to 206 sec. A decrease in thruster temperature from 1143°K to 1083°K was recorded. During thrust degradation, the primary decomposition front appeared to move from the middle of the screen pack to the head end. These observations indicated that a high pressure drop was created in the nozzle section. Post-test inspection revealed a substantial carbon deposit on the Haynes 25 retaining screen. Heavy carbon deposits were not noticed elsewhere on the internal thrust chamber components. Pre and post-test injector water flow characteristics were identical. It was concluded that the thrust degradation was caused by carbon buildup on the Haynes 25 retaining screen.

Limited pulsed-mode data was obtained for the 50/50 N_2H_4-MMH mixture with the 2.54 cm screen pack. A specific impulse of 171 sec. was obtained for a 100 ms pulse at a holding temperature of 1033°K and an injection pressure of 1.034 MN/m^2. The pulse rate was one per second; the thruster temperature rose to 1089°K.

2.5.4 Mixture of Hydrazine Monopropellants

The MHM blend was the last propellant investigated during the evaluation test program. Previous tests with Aerozine-50, MMH and the N_2H_4 - MMH mixture indicated that worthwhile data would not be obtained using the baseline thruster configuration. Accordingly, longer screen pack assemblies were used to characterize the MHM blend. The 180 screen, 1.02 cm sleeve was used to obtain data for comparison with MMH and 50% N_2H_4 - 50% MMH. The final configuration consisted of 400 screens in a 2.54 cm sleeve. Both thruster configurations were steady-state baseline tested with hydrazine. The steady-state baseline characteristics are shown in Figure 33. Very high thruster head temperatures were recorded during these tests. The thruster temperatures as a function of inlet pressure are shown in Figure 34.

A holding temperature of 1143°K was necessary to sustain MHM decomposition with the shorter screen pack (180 screens, 1.02 cm sleeve) at an injection pressure of 0.965 MN/m^2. Operation at higher injection pressures resulted in "flooding." The steady-state data in Figure 35 shows performance degradation at an injection pressure of 1.655 MN/m^2. The nozzle and head section temperatures remained at the holding temperature while the middle screen pack temperature rose to 1223°K. Fifteen minutes steady-state operation was accumulated with the 1.02 cm screen pack. Post-test disassembly revealed a minimal amount of carbon deposition. Carbon accumulation was not observed in the head space or on the platinum screens. Little to no carbon was noticed in the nozzle section. However, a small deposit was noticed on the Haynes 25 retaining screen.

Operation with the 2.54 cm sleeve containing 400 platinum screens resulted in a reduced holding temperature necessary to initiate and sustain MHM decomposition. The holding temperature was reduced from 1143°K to 1033°K. The maximum thruster temperature (1094°K) at an injection pressure of 1.034 MN/m^2 occurred at the middle of the screen pack. The decomposition front moved towards the nozzle section as the injection pressure was increased. At 1.724 MN/m^2 injection pressure, marginal operation resulted. At higher injection pressures, decomposition could not be maintained and "flooding" occurred. Post-test thruster inspection revealed little carbon deposition. Steady-state performance data for the 2.54 cm screen pack configuration appears in Figure 36. Pulsed-mode data at an injection pressure of 0.81 MN/m^2 were

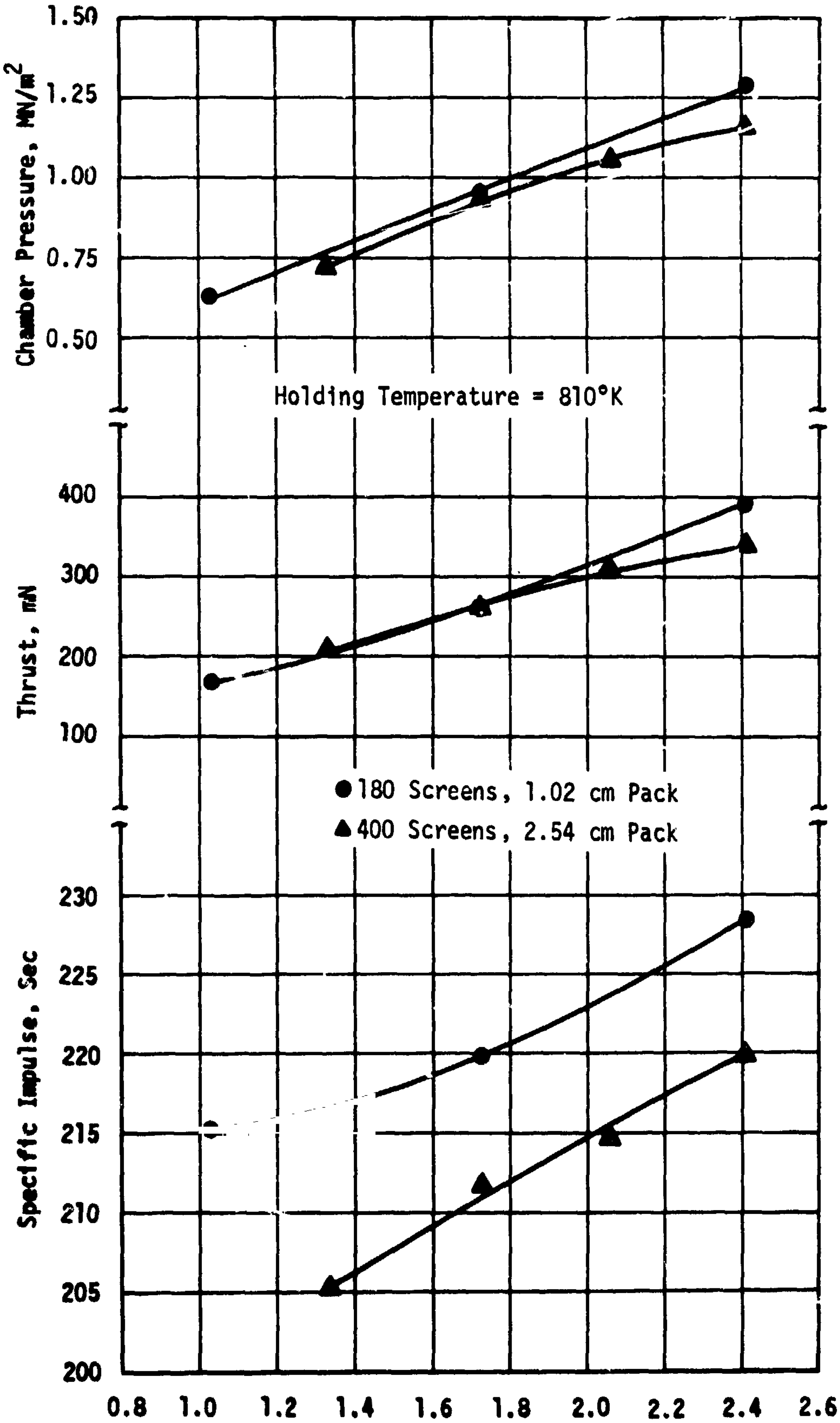


Figure 33. Steady-State Performance of Hydrazine With Long Screen Packs

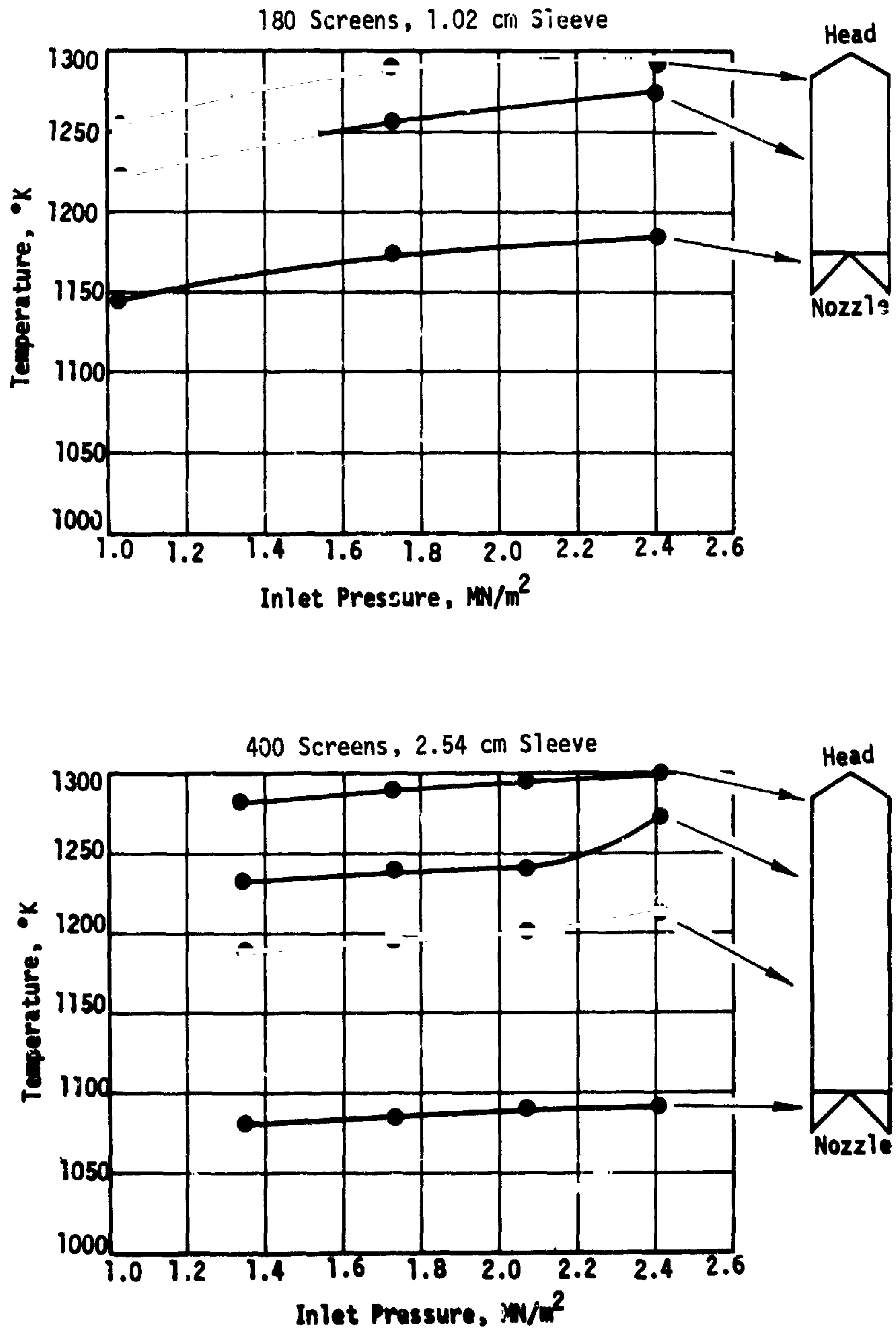


Figure 34. Thruster Temperature Distributions with Long Screen Packs

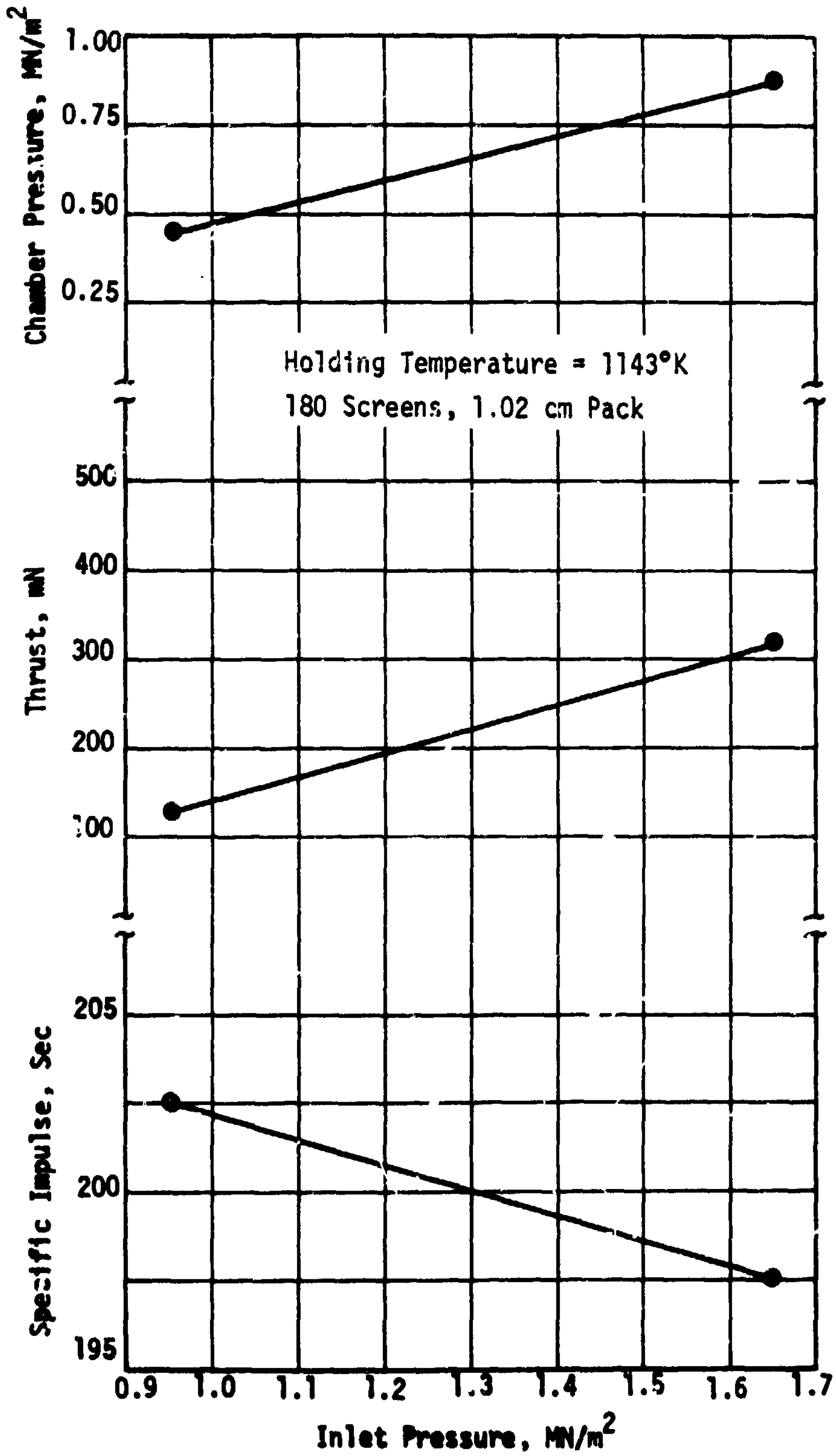


Figure 35. MHM Steady-State Performance with 1.02 cm Screen Pack

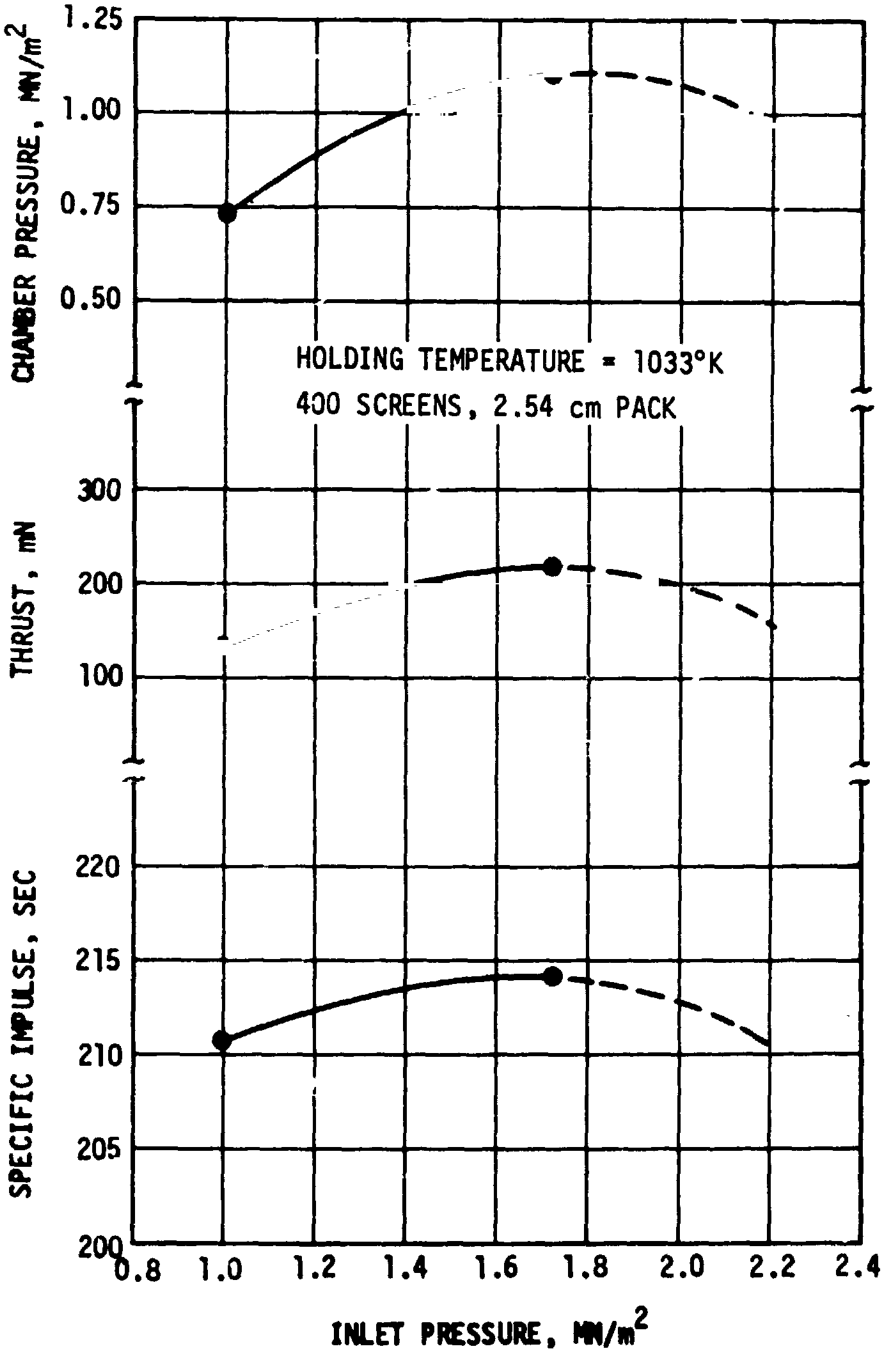


Figure 36. MHM Steady-State Performance With 2.54 cm Screen Pack

obtained for pulse widths of 75 and 100 ms. The delivered specific impulse at 75 ms was 162 sec. and 174 sec. for the 100 ms pulse. The rise and decay times were slightly longer than those observed for Aerozine-50.

3.0 DISCUSSION OF RESULTS

3.1 BASELINE PERFORMANCE

The steady-state and pulsed-mode performance characteristics for the standard 60 screen 0.5 cm sleeve were comparable to those obtained with the EHT [2]. The additional thrust chamber and nozzle mass associated with the modular, three piece design increased the times to reach holding and steady-state temperatures. Holding power levels of 8 to 9.1 watts were required to maintain the thruster temperature at 810°K under simulated high altitude conditions. The power requirement for a flight configuration thruster with proper insulation, no pressure tap and only one heater lead has been previously demonstrated to be less than 5 watts [2].

Hydrazine performance measurements with the modified screen packs indicated that the baseline configuration (60 screens, 0.5 cm sleeve) was non-optimal. Comparative data on four configurations are presented in Table 8. The data are for steady-state at an injection pressure of 1.724 MN/m^2 and a holding temperature of 810°K. A 3.5% increase in delivered specific impulse for the large head space thruster over the baseline configuration is significant. The higher thruster head temperatures with the modified configurations suggested that homogeneous, gas phase decomposition kinetics were promoted in the head space. The lower performance levels of the longer screen pack configurations indicated that substantial amounts of ammonia were dissociated within the screen pack. This was reflected by a decrease in nozzle temperature with an increase in screen pack length (medium versus long screen pack). The pulsed-mode performance levels also decreased with the longer screen pack configurations.

Table 8. Configurational Hydrazine Performance Data (Steady-State)

Designation	Configuration	Injection Pressure = 1.724 MN/m^2, Holding Temperature = 810°K: Thrust mN	Specific Impulse Sec	Temperatures, °K: Head	Middle	Nozzle
Large Head	60 screens, 0.76 cm sleeve additional 0.25 cm head space	315	232	1255	-	1222
Baseline	60 screens, 0.5 cm sleeve	314	224	1233	-	1200
Medium Pack	180 screens, 1.02 cm sleeve	267	220	1289	1255	1171
Long Pack	400 screens, 2.54 cm sleeve	259	212	1289	1217	1083

3.2 CANDIDATE MONOPROPELLANTS

A comparison of the delivered steady-state specific impulse for the candidate monopropellants is presented in Figure 37. The configurations and holding temperatures for each propellant are summarized. Reference data for hydrazine are included. The general performance levels are in reasonable agreement with the predictions of the Analytical Task Summary Report [1] except the datum point for MMH. The high holding temperature (1198°K) resulted in a somewhat inflated specific impulse value. The steady-state program goal of 200 sec. specific impulse was met by all propellants studied. A similar comparison of the pulsed-mode specific impulse appears in Figure 38. Large differences in steady-state and pulsed-mode performance levels for short and long (or high density) screen packs are apparent by comparing Figures 37 and 38. The ratios of pulsed-mode to steady-state specific impulse for 75 and 100 ms pulses are presented in Table 9. Pulsed-mode performance for Aerozine-50 and MHM was compromised in order to obtain adequate steady-state operation. Longer or higher density screen pack assemblies were required to satisfy the heat transfer conditions necessary to initiate decomposition of the carbonaceous propellants. The ease of initiating decomposition decreased in the following order: Aerozine-50, 50% N_2H_4-50% MMH, MHM and MMH. Sustained steady-state operation with Aerozine-50 (50% N_2H_4-50% UDMH) was obtained with an 80 screen, 0.5 cm screen pack at a 810°K holding temperature, whereas a long screen pack (360 screens, 2.54 cm sleeve) and 1033°K holding temperature were required to decompose the 50% N_2H_4-50% MMH propellant. The addition of hydrazine to UDMH and MMH effectively reduces the holding temperature necessary to initiate pure UDMH or MMH decomposition. The energy liberated by hydrazine decomposition is made available to assist UDMH or MMH decomposition.

PROPELLANT	SCREENS	CONFIGURATION SLEEVE LENGTH, CM	HOLDING TEMPERATURE, °K
Azide	60	0.5	923
AERO-50	80	0.5	810
MHM	400	2.54	1033
50 N_2H_4 - 50 MMH	360	2.54	1033
MMH	160	1.02	1198
N_2H_4	60	0.5	810

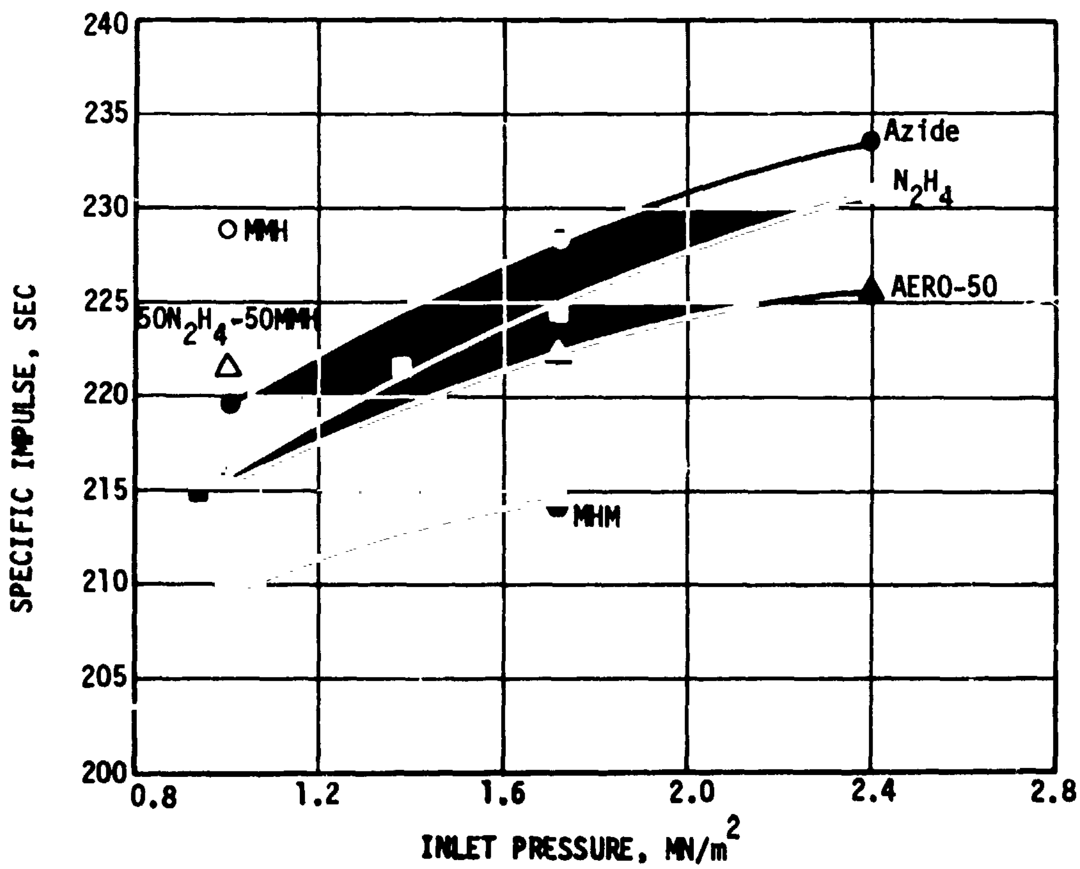


Figure 37. Steady-State Performance Data of Five Candidate Monopropellants

PROPELLANT	INJECTION PRESSURE MN/m^2	HOLDING TEMPERATURE °K
HA	1.724	923
MHM	0.807	1033
AERO-50	1.034	810
50 N_2H_4 - 50 MMH	1.034	1033
Hydrazine	1.724	810

(PULSE RATE = ONE PER SECOND)

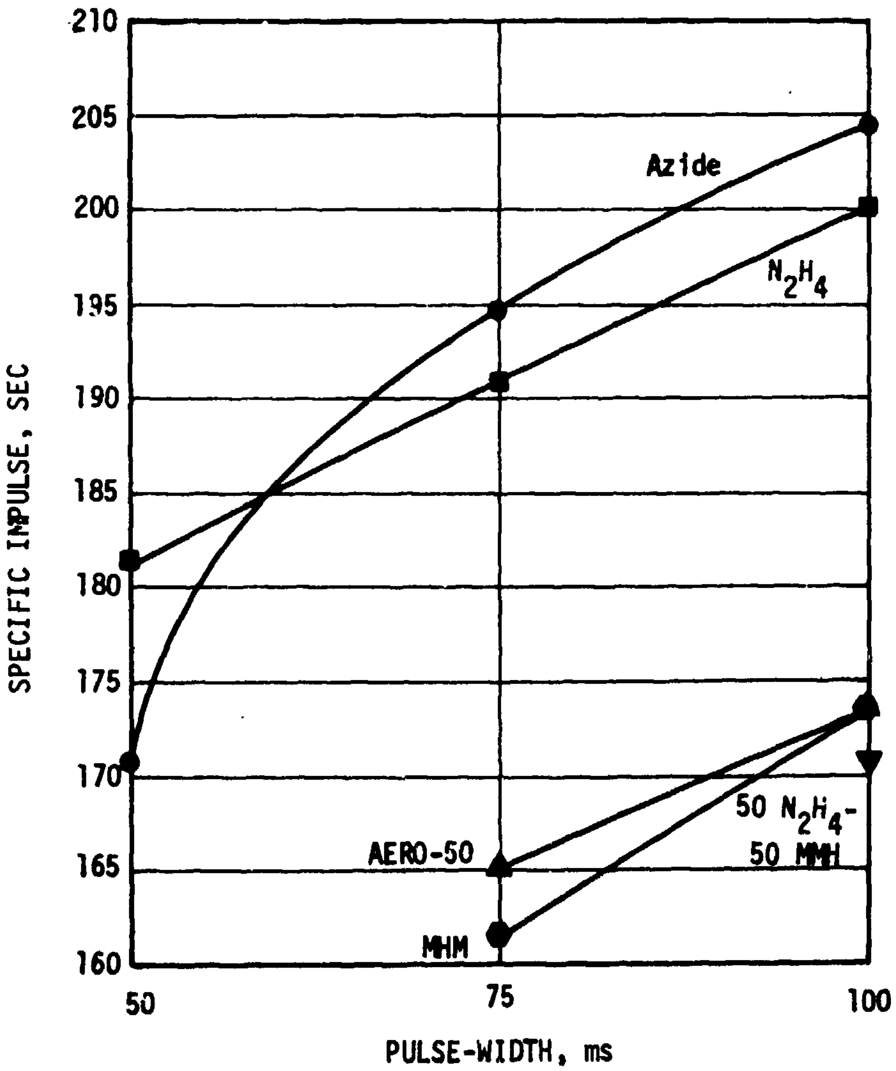


Figure 38. Pulsed-Mode Performance Data of Four Candidate Monopropellants

Table 9. Comparison of Pulse-Mode to Steady-State Specific Impulse

Propellant	Ratio of Pulsed-Mode to Steady-State Specific Impulse		Remarks
	75 ms	100 ms	
Hydrazine-Hydrazine Azide	0.853	0.895	Short Screen Pack
Hydrazine	0.847	0.884	Short Screen Pack
Aerozine-50	0.766	0.804	High Density Screen Pack
MHM	0.773	0.829	Long Screen Pack

Carbon deposited on the Haynes 25 retaining screen in a disproportionate amount to that observed on the other interior thrust chamber components. A striking example of this behavior is noticed in Figure 25 (Aerozine-50, preliminary sea-level characterization). Carbon deposited only on the Haynes 25 retaining screen. The heat transfer characteristics in the vicinity of the retaining screen would not be sufficient to cause localized propellant decomposition. A logical explanation would be a higher level of catalytic activity of Haynes 25 than that of platinum.

4.0 NEW TECHNOLOGY

The electrothermal thruster concept has been demonstrated to be feasible for operation with propellants other than MIL-grade hydrazine. The modular design of the monopropellant demonstration thruster allowed the rapid evaluation of candidate propellants at significant cost savings.

A secondary task of the Evaluation Test Program was to obtain baseline hydrazine performance data for all new thruster configurations. One thruster configuration provided substantial performance increases over previous electrothermal hydrazine thrusters. The data generated from the several configurations are amenable to analytical investigation which will increase the level of understanding hydrazine decomposition processes.

5.0 PROGRAM FOR THE NEXT REPORTING INTERVAL

The work scope during the next reporting interval includes the Final Project Report preparation. An integral part of that report is the Task IV Data Correlation phase. The Data Correlation objective is to propose specific recommendations for the work required to design and develop flight worthy electrothermal thrusters using low freezing point monopropellants for spaceflight applications. Results of the Tasks II and III phases will be critically reviewed and analyzed in order to formulate a development program to meet the Task IV objective.

6.0 CONCLUSIONS

The electrothermal thruster designed for operation with MIL-grade hydrazine is suitable for operation with propellants having lower freezing points. Internal thrust chamber modifications were required to accommodate the different decomposition characteristics of each propellant. The propellant's tendency to readily decompose in a thermal environment dictated the extent of modification. All modifications were performed on the screen pack assembly; the head end and nozzle section were unchanged. The propellants' reactivity decreased in the following sequence: 76% N_2H_4 - 24% N_5H_5 > N_2H_4 > Aerozine - 50 > 50% N_2H_4 - 50% MMH > MHM > MMH. The induction time to initiate decomposition was increased by additions of UDMH and MMH to hydrazine. Thruster configurations employing longer and/or higher density screen packs were required to obtain steady-state decomposition. The program goal of 200 sec. steady-state specific impulse was exceeded by all propellants tested. The pulsed-mode program goal of 175 sec. was exceeded by the azide blend for pulse widths greater than 50 ms and was met by the carbonaceous propellants for pulse widths greater than 100 ms.

A substantial amount of thermal energy must be supplied to initiate decomposition of propellants containing UDMH and MMH. The rate controlling step appeared to be the endothermic removal of methyl radicals. Propellants containing MMH required greater heat input than that containing UDMH.

Carbon deposition from the TRW-formulated mixture (MHM) was minimal. Carbon accumulation resulting from long term operation with Aerozine-50 may result in performance degradation with the configuration derived for its operation. An appraisal of detrimental carbon deposition resulting from 50% N_2H_4 - 50% MMH decomposition was masked by the apparent high catalytic activity of the Haynes 25 retaining screen.

The original baseline configuration gave non-optimal hydrazine performance. Performance was increased by promoting homogeneous, gas phase decomposition kinetics in a larger head space.

The Evaluation Test Program results indicated that the basic thruster concept was applicable to the several monopropellants. However, the thruster configurations for specific propellants will differ in order to yield optimum performance.

7.0 RECOMMENDATIONS

The process of optimizing performance concentrated on the internal screen pack geometry. Methods of increasing residence times in the head space should be investigated for the carbonaceous propellants. This would reduce heat losses associated with the long screen packs. Alternate injection techniques which could render the incoming propellant stream unstable appear desirable. The net effect would increase the surface to volume ratio and allow a greater quantity of heat to be transferred to the propellant at injection.

The large head space thruster which gave superior performance with hydrazine should be fully exploited.

8.0 REFERENCES

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7. "Propellant, Monomethylhydrazine," Military Specification MIL-P-27404A, Amendment 2, June 1970.