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HIGH PERFORMANCE STORABLE PROPELLANT RESISTOJET

Contract NAS3-24652

91-R-1553

FINAL REPORT

Prepared for:
NASA Lewis Research Center
Cleveland, OH 44135

January 17, 1992

(NASA-CR-191128) HIGH PERFORMANCE
STORABLE PROPELLANT RESISTOJET
Final Technical Report (Rocket
Research Corp.) 314 p

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ROCKET RESEARCH COMPANY

REDMOND, WASHINGTON

Olin *AEROSPACE DIVISION*

HIGH PERFORMANCE STORABLE PROPELLANT RESISTOJET

Contract NAS3-24652

Prepared for:

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Prepared by:

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Report No. 91-R-1553

Date: January 17, 1992

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SUMMARY

From 1965 until 1985 resistojets were used for a limited number of space missions. Capability increased in stages from an initial application using a 90 W gN_2 thruster operating at 123 sec specific impulse (Isp) to a 830 W N_2H_4 thruster operating at 305 sec Isp. Prior to 1985 fewer than 100 resistojets were known to have been deployed on spacecraft.

Building on this base NASA embarked upon the High Performance Storable Propellant Resistojet (HPSPR) program to significantly advance the resistojet state-of-the-art. Higher performance thrusters promised to increase the market demands for resistojets and enable space missions requiring higher performance.

The program goals were ambitious. At the beginning of the program the performance goals were to produce a resistojet design capable of producing 50 to 100 mlbf of thrust with an Isp of 380 seconds utilizing no more than 1500 watts of electrical power. The goals were refocused to the changing needs of users and a changing status of technology throughout the program. The performance goals during successive phases are summarized below:

Phase	Goals	Achieved
II	Isp = 380 sec	348 sec, vented cavity, radiative heater 322 sec, sealed cavity, radiative heater
	1500 W	Reduced to 750 prior to test
	50 – 100 mlbf	39 – 62 mlbf at 500 to 850 W, vented cavity, radiative heater 37 – 56 mlbf at 500 to 850 W, sealed cavity, radiative heater
III	Isp = 315 sec	322 sec, immersed heater
	Power < 750 W	763 W
	100,000 lb-sec	Never attempted, mass loss was excessive at 315 + I_{sp}

The key technology limitation turned out to be the tungsten wire temperature. For all configurations tested the wire temperatures required to achieve the desired performance resulted in excessive sublimation rates or in adverse chemical reactions resulting in filament mass loss. In addition, heat exchanger material creep drove throat diameter up. This diameter increase resulted in a lower nozzle efficiency and hence lower overall performance.

During the program three resistojets were fabricated and tested. High temperature wire and coupon materials tests were completed. A life test was conducted on an advanced gas generator.

The following are the notable accomplishments of the HPSPR program over its 5-year history. These items are also summarized graphically in Figure 1.

1. Advanced the understanding of low Reynolds number nozzles. Fabricated nozzles for NASA cold gas study and performed analysis in support of the study. Resulted in NASA TM-89858.
2. Comprehensive performance mappings of vented cavity, sealed cavity, and immersed filament resistojets were completed. Performance limits of each configuration were determined. An extensive data base in the moderate power (500 to 850 W) range for Isp, thrust efficiency, and thermal performance was obtained for the three thruster configurations.
3. High temperature tungsten filaments for three resistojet configurations were characterized. Material loss rates and mechanisms were investigated.
4. A better understanding of refractory metals was obtained. The mechanisms of attack of N_2H_4 decomposition products were explored. The effects of high temperature atomic oxygen were investigated. Metals studied included rhenium, tungsten, Mo/41Re, and Mo/3Re.
5. Conducted a life test of an advanced low flow gas generator. The life test ultimately achieved 887 hours and the gas generator demonstrated reduced feed tube plugging compared to all previous designs.

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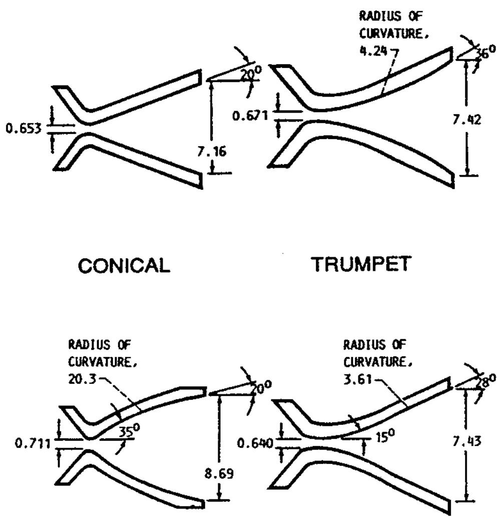
HPSPR Prog

LOW REYNOLDS NUMBER NOZZLES

NOZZLE GEOMETRIES
All Dimensions are in Millimeters



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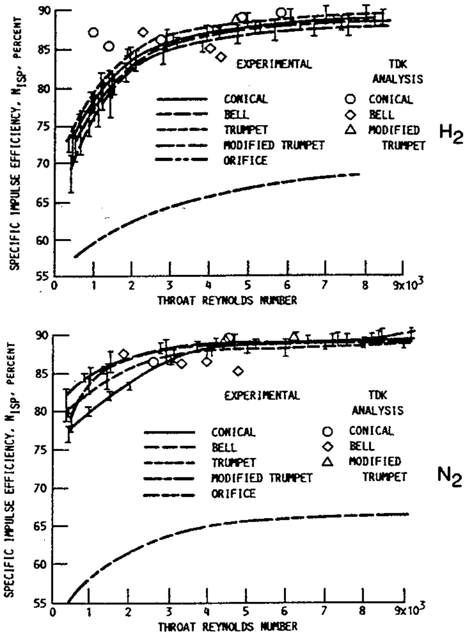
SPECIFIC IMPULSE EFFICIENCY AS A FUNCTION OF THROAT REYNOLDS NUMBER FOR gH_2 & gN_2. Experimental Data & Two-Dimensional Kinetics (TDK) Nozzle Analysis



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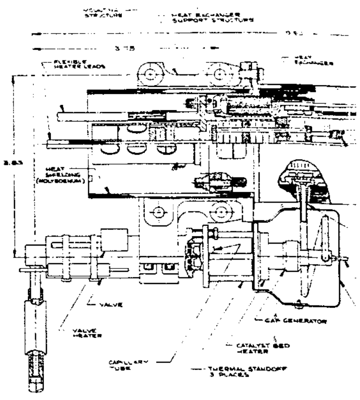
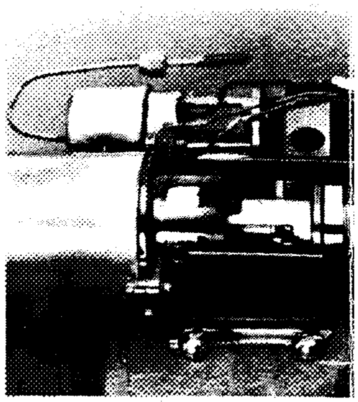
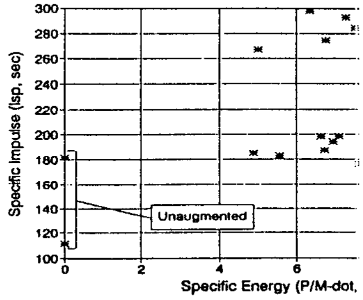
RESISTOJET DESIGN/F



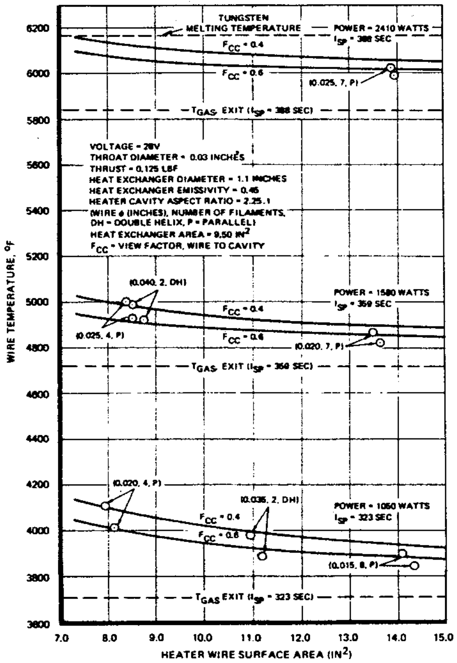


HIGH PERFORMANCE RE
Sealed Cavity Dat



TUNGSTEN FILAMENT BEHAVIOR

HIGH PERFORMANCE RESISTOJET HEATER SIZING STUDIES

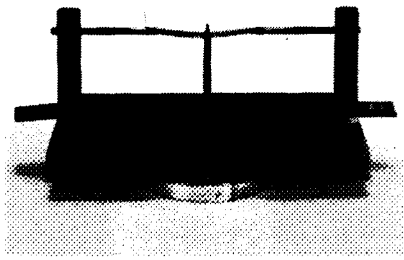


11177-12

5300°F WIRE SAG TEST FIXTURE & RESULTS

3037-3

BEFORE



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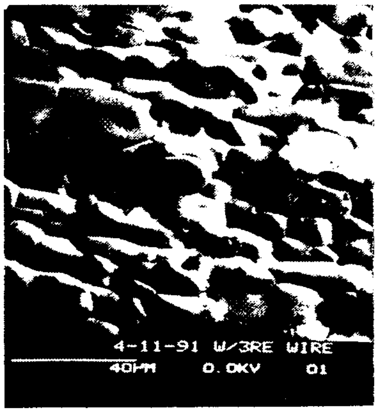
AFTER

11232-38

REFRACTORY METAL

W/3 Re



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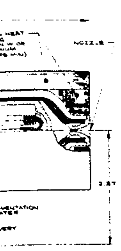
m Highlights

RICATION & TESTING



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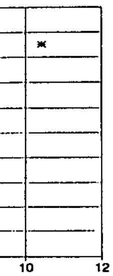
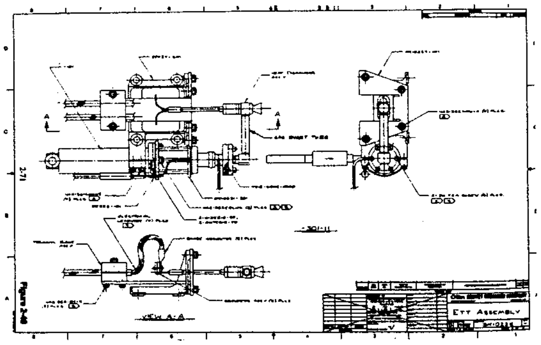
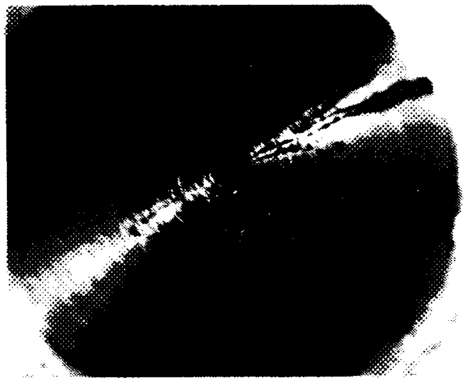
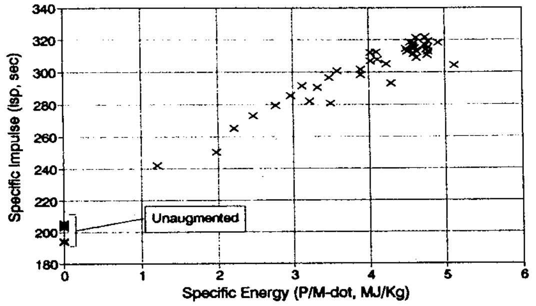
JET







HIGH PERFORMANCE RESISTOJET
TRW-ETT Heater On/Off



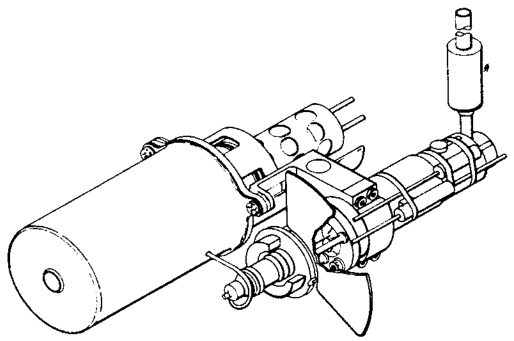
TESTING @ 2100°F WITH 1% MOISTURE IN AMMONIA

Sample	103 Hrs % Wt Gain	493 Hrs % Wt Gain
IrCVDW	+0.0078	+0.026*
W/25Re	+0.0087	0
Mo/41Re	-0.205	-0.366
Re	+0.0038	+0.015
W100	-0.022	-0.026

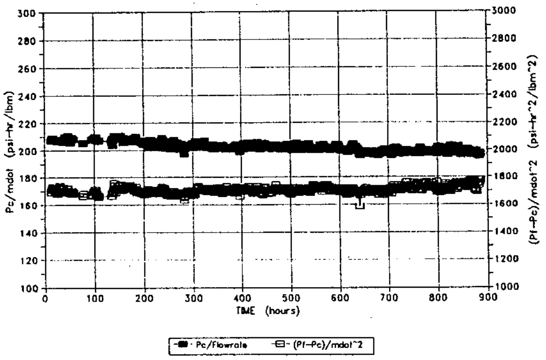
* Ir CVD W sample was split after the 103-hour test for metallograhic analysis and exposed tungsten surface underwent a different reaction (turned black).

Sample	Appearance
IrCDVW	• Ir coating unchanged. Bare W shows dull greying. Fractured surface is black. no visible cracks.
W/25Re	• Polished surface still has some reflective properties. No visible cracks.
Mo/41Re	• Polished surface still has some reflectivity. Sample has cracks that appear to penetrate through the piece, i.e. cracks continue from one surface into the adjoining surface.
Re	• Strip has original appearance, reflective. No visible cracks.
W100	• Polished surface totally nonreflective, dull, grey. No visible cracks.

ADVANCED GAS GENERATOR



NASA FLIGHT DEVELOPMENT GG
(Pf-Pc) / Flowrate^2 & Pc / Flowrate



HIGH PERFORMANCE RESISTOJET
Preliminary Performance Specification

• Mission	• N-S stationkeeping geosynchronous communication satellite
• Life	• 10 years (250-hour total firing time)
• Thrust level	• 0.125-lbf nominal design point
• Total impulse	• 117,000 lbf-sec
• Specific impulse	• 360 lbf-sec/lbm average over feed pressure blowdown range (300 — 100 psia)
• Power requirement	• Direct operation from S/C bus. Simple current surge limiter circuit on start-up desirable but not required
	• Regulated or battery voltage let-down
	• 28 vdc nominal peak. adjustable as required
	• 1600 watt at P_f = 300 psia; 1400 watt at 100 psia
• Propellant pressure	• Blowdown 300 to 100 psia
	• Regulated 150 psia minimum
• Thrust repeatability	• ±5%
• Vibration	• Spectrum 0.2 g^2/Hz, 20 — 20,000 Hz
	• Overall 13.0 g rms
• Spacecraft heat rejection	• TBD

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Figure 1

1.0 INTRODUCTION

This is the Final Technical Report for Contract NAS3-24652 entitled "High Performance Storable Propellant Resistojet" (HPSPR). The program technical effort began in January, 1986 and concluded in May, 1991.

1.1 HISTORY OF RESISTOJETS

In the early 1960's resistojets were one of several electric propulsion devices developed for a wide variety of space missions. Avco and Giannini developed resistojets concurrently with early research on arcjets. Power levels ranged from less than one watt to over 60 kW. High thrust efficiency and Isp up to 846 sec were measured. Most of these resistojets operated on NH_3 or H_2 (Jahn, 1970). The minimal available electrical power in early spacecraft, poor integration into ACS and delta-V propulsion systems, and finally a dearth of missions requiring the level of performance offered resulted in few space applications.

The earliest resistojet used in space propulsion was in 1965 when the Vela spacecraft carried two gN_2 resistojets into orbit. These thrusters used 90 W of electrical power and produced an Isp of 123 sec compared to 70 sec for a cold gas gN_2 system (Jackson, 1966). Other early flight systems included NH_3 fueled micro-lbf class thrusters developed for the Naval Research Laboratory and low-power, low thermal inertia resistojets flown as experiments on the ATS spacecraft series (Pugmire, 1971). While mission models indicated that increased performance was desirable in low thrust engines it was clear that a practical resistojet would have to be fully integrated into the ACS propulsion of a spacecraft. The need for lighter weight, long life, station keeping propulsion systems for Geosynchronous Equatorial Orbit (GEO) communication satellites provided the first user requirements that demanded technology advancements such as resistojets (Sackheim, 1979).

The technology was significantly advanced again in the late 1970's when a TRW team designed (Grabbi, 1976) and completed the qualification of the High Performance Electrothermal Hydrazine Thruster (HiPEHT) hydrazine resistojet (Dressler, 1981). The HiPEHT thruster was qualified for the Intelsat-V spacecraft. This thruster used N_2H_4 propellant and was fully integrated with the catalytic thruster ACS propulsion system. This design used a decomposition heater in a separate chamber to break down the N_2H_4 into N_2, H_2, and NH_3, and an immersed tungsten filament to super-heat the decomposition gases in a vortex heat exchanger. The thrust range of this resistojet was 50 to 110 mlbf with a power requirement of 5 W per mlbf delivering an Isp of 295 sec. The thruster suffered from early heater failures and deposition of nonvolatile residue in the feed tube in the decomposition chamber.

Starting in 1981 Rocket Research Company (RRC) was involved in a series of developments extending resistojet technology further with an emphasis on flight hardware. The design approach used a catalytic gas generator (based on a 0.1 lbf thruster) to decompose the N_2H_4 into N_2, H_2, and NH_3. The decomposition gases were super heated within a refractory metal heat exchanger. The heat exchanger and heater filament were radiatively coupled with the filament centrally located in an evacuated cavity within the heat exchanger. This feature allowed the heater filament to be hotter, but decreased the thrust efficiency.

RRC conducted a series of resistojet programs. In 1981 RRC was awarded a contract from RCA for the design, qualification, and production of an Augmented Catalytic Thruster (ACT). Qualification and first flight hardware deliveries of the MR-501 thruster were completed in about 13 months. This ACT flew on SATCOM F-1, Spacenet, G-Star, ASC I-III, and BS-3. Additional technology programs included an effort for AFRPL in which a gas generator was operated for 500 hours (equivalent to 130,000 lbf-sec of impulse). In a contract with Intelsat, RRC completed a comprehensive design study of scaling effects for electrothermal thrusters in the 0.5 to 5 N thrust range. For NASA-LeRC, RRC completed a demonstration program to map resistojet performance up to 1 kW using the ACT heat exchanger with gH_2, gN_2, and NH_3. In another NASA-LeRC program, RRC fabricated an all rhenium heat exchanger to withstand higher temperatures and yield longer life times.

These programs resulted in a qualified flight thruster, the MR-501, and advanced technology in heaters, heat exchangers, materials, and gas generators. All of these efforts formed the technology basis for the HPSPR program. This background is summarized in Figure 1-1.

1.2 HPSPR PROGRAM GOALS/PLANS

The purpose of the HPSPR program was to advance the technology of resistojets used for auxiliary propulsion. The performance of resistojet thrusters to this point in time had been limited primarily by material temperature limits, heat exchanger and nozzle performance, and by propellant thermodynamics. The program was intended to establish a technology focus and provide for the design and demonstration of a resistojet with significantly improved performance using storable propellants.

At the beginning of the program there was a performance goal to produce a resistojet design capable of producing 50 to 100 mlbf of thrust with an Isp of 380 seconds utilizing no more than 1500 watts of electrical power. The total delivered impulse was to have been 70,000 lbf-sec. In the original program concept there were to have been four phases in which one development and two proto-flight thrusters were to have been built.

To meet these goals RRC originally planned a four phase program to investigate the fundamental physical limits to resistojet performance, identify and test key components necessary to overcome existing performance limits, and build and test an advanced resistojet thruster incorporating the design features identified.

Figure 1-2 provides a graphical summary of the original program plan. As will be discussed, this plan was changed significantly as results were obtained and user community requirements changed. These changes are also illustrated in Figure 1-2.

There were 3 key decision points during the program. First, at the end of Phase I an assessment was made of whether to proceed to conceptual design of the candidate thruster. The material data were inadequate to support commitment to a design. It was judged that

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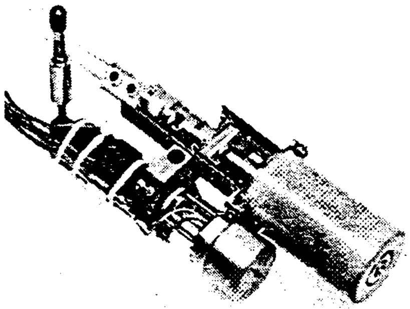
Rocket Research (

UNPARALLED TECHN(

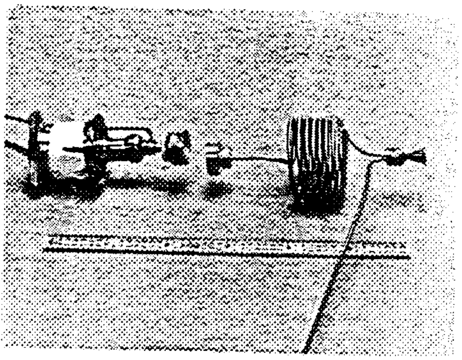
AUGMENTED CATALYTIC THRUSTER



2635

- RCA-FUNDED CONTRACT
- EMPLOYS RADIATIVE HEAT EXCHANGER
- DEMONSTRATED PERFORMANCE:
  - – MISSION AVG I_{sp} = 293 sec
  - – TOTAL IMPULSE = 76,000 lbf-sec
- 64 FLIGHT ENGINES DELIVERED

HIGH TEMPERATURE AUGMENTED HYDRAZINE THRUSTER



2658

- AFRPL-FUNDED CONTRACT
- COILED TUBE HEATER
- DEMONSTRATED PERFORMANCE
  - – 430 HRS OF LIFE
  - – AVERAGE I_{sp} OF 293 sec

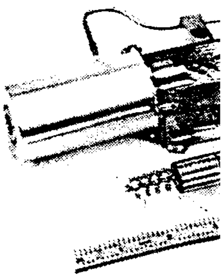
HIGH TEMPERATURE REFRACTORY METAL CHARACTERIZATION

- RRC IRAD PROGRAM
- TESTING AT BATTELLE
- RRC METHODOLOGY

ACT APPLICATION TO SBS-1A SATELLITE

- HUGHES-FUNDED CONTRACT
- DEMONSTRATED OVER 500 HRS OF AUGMENTATION HEATER OPERATION IN A 2.6 "g" FIELD

RADIATIVE R



2793-1

- NASA/LeRC-FUNDE
- MEASURED PERF V N_2, N_2 AND NH_3 F(LEVELS UP TO 1 kV
- DEMONSTRATED T UP TO 0.2 lbf
- EXCELLENT PERF(DELIVERED FOR E

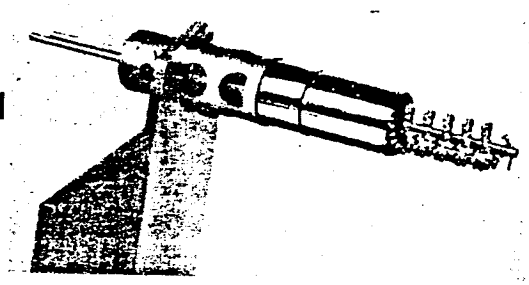
EHT SCALING STU

- INTELSAT-FUNDED C
- DEFINED SCALING & CRITERIA FOR AUGM THRUSTERS IN THE 0 THRUST RANGE
- THERMAL/PERFORM/ DEVELOPED FOR 3 G OF RESISTOJETS

LONG-LIFE GAS GENERATOR DEVELOPMENT

- RRC IRAD PROGRAM
- DEMONSTRATED CATALYTIC GAS GENERATOR LIFE IN EXCESS OF 500 HRS

ADVANCED HEATER DEVELOPMENT



- RRC IRAD PROGRAM
- 90-g rms RANDOM VIB TEST
- EMPLOYED SAG-RESISTANT COIL MATERIAL
- TESTING INCLUDED 500-HR LIFE TEST

AC IMPR(

- RRC IRAD P
- DEMONSTR CAPABILIT\ GAS GENER OF HYDRAZ
- EMPLOYED ENVIRONMI
- 120°F PROP
- STEADY-ST/ DUTY CYCL

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npany Resistojet Experience

OGY AND FLIGHT EXPERIENCE

FOLDOUT FRAME 2

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AM
THROUGHPUT
ADVANCED
OF 430 lbm

TOJET THERMAL

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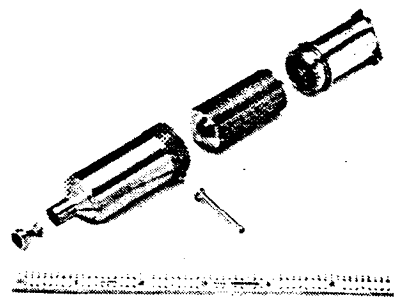
ND OFF-PULSING

RHENIUM RADIATIVE RESISTOJET



2867

- NASA/LeRC-FUNDED CONTRACT
  OBTAINING PERF MAP OF RHENIUM RESISTOJET USING GASEOUS DECOMPOSITION PRODUCTS OF HYDRAZINE
- RHENIUM FABRICATION EXPERIENCE

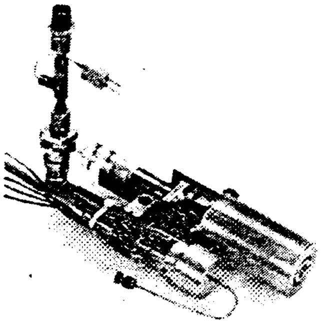
HOT ISOSTATIC PRESSURE OF RHENIUM POWDER

- RRC IRAD PROGRAM
- SUBCONTRACT TO BATTELLE

HIGH THRUST (2N) ELECTROTHERMAL HYDRAZINE THRUSTER

- INTELSAT-FUNDED CONTRACT
- PROGRAM INCLUDES DESIGN, FAB, PERF VERIFICATION & LIFE TESTING OF A 2-N, 2 kW HYDRAZINE RESISTOJET

ACT PERFORMANCE IMPROVEMENT



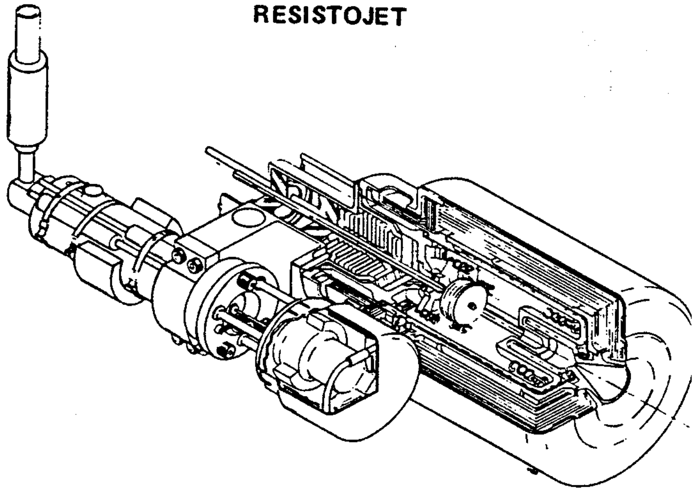
2748-2

- RRC IRAD PROGRAM
- DEMONSTRATED I_{sp} IN EXCESS OF 310 sec IN THE 0.04- TO 0.20-lbf THRUST RANGE
- EXTENSIVE PERF MAPPING

ACT PRODUCT IMPROVEMENT

- RRC IRAD PROGRAM
- DEMONSTRATED HIGHER PERF OF ACT W/INCREASED HEATER POWER (600 W)
- REFINED THERMAL & THERMO-MECHANICAL MODELS
- CHARACTERIZED GROUND TEST EFFECTS

HIGH PERFORMANCE RESISTOJET



- FLIGHT PROVEN DESIGN HERITAGE
- SPECIFIC IMPULSE CAPABILITY IN EXCESS OF 400 lbf-sec/lbm
- MINIMUM IMPACT TO USER SPACECRAFT
- LOGICAL EXTENSION OF CONTINUING EFFORTS

Figure 1-1

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HPSPRJ OVERALL PROGRAM FLOW

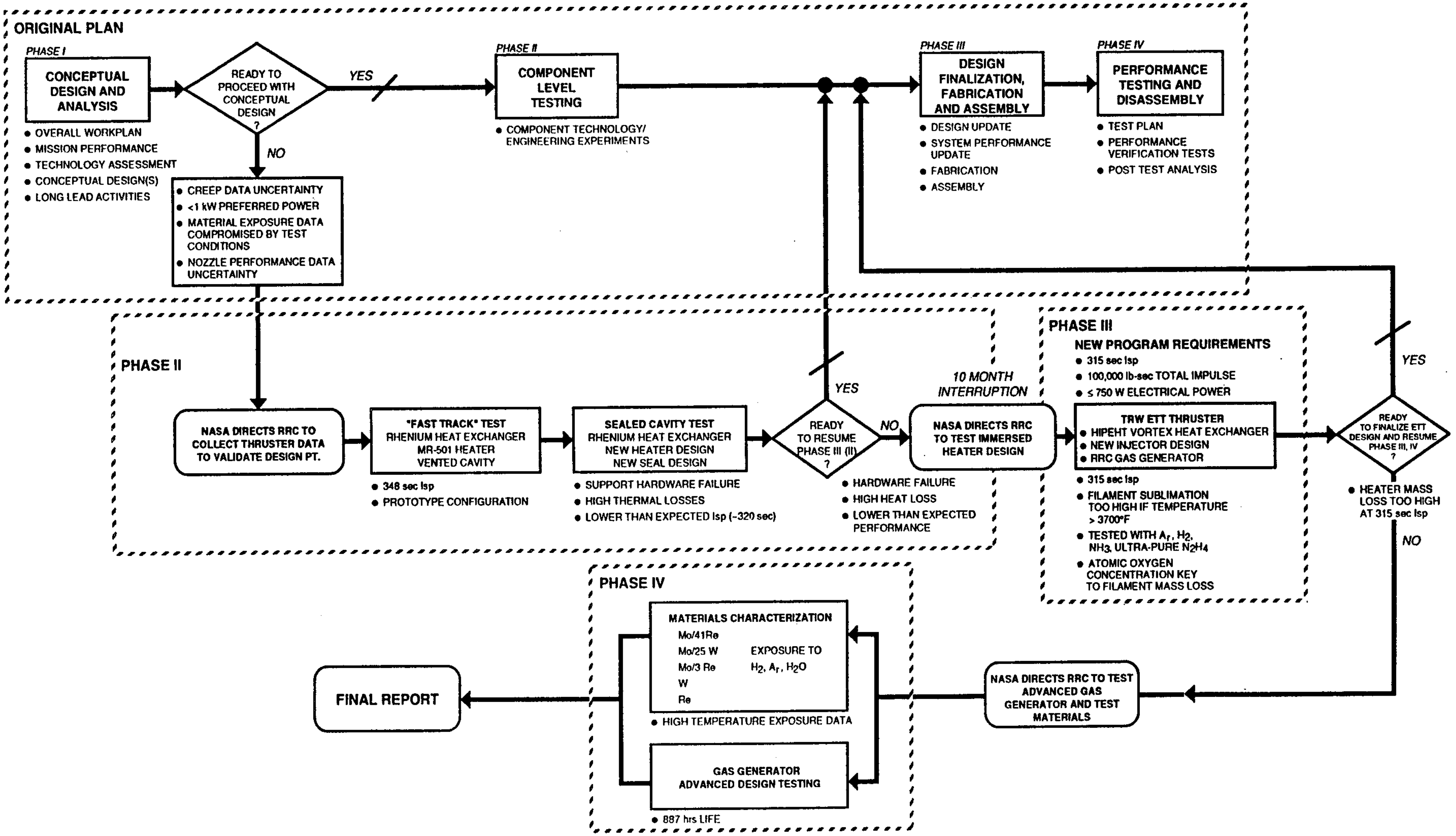


Figure 1-2

collection of data directly from thrusters was the best way to clarify the issues. Second, following the thruster testing a decision was made that the performance did not merit a detailed design. Following an interval of 10 months the program was redirected to investigate an immersed heater design. The final decision was whether to finalize the proto-flight design based on the immersed heater configuration. Again, the performance did not merit a final design. Additional material data were determined to be more useful to the user community.

1.3 OUTLINE OF PROGRAM HISTORY

The following is a summary of the four phases of the program.

1.3.1 Phase I — Program Initiation

This phase of the program was conducted as planned. Materials characterizations proved to be more difficult than originally thought. Both the creep characterization of heat exchanger materials and the wire compatibility tests were unable to achieve temperature ranges beyond 4500°F due to facility limitations. Thermal and structural modelling that depended on material data required extrapolations and therefore were subject to some uncertainty.

There were three specific design problems. First, the creep behavior of heat exchanger bodies was excessive for the higher temperatures required for higher performance. Second, a sealed cavity resulted in exposing the heater wire to N_2H_4 decomposition products and there was an inadequate materials data base. A sealed cavity was proposed as a means of increasing life and performance by decreasing the filament mass loss rates. Finally, there was no seal design to implement a sealed cavity

1.3.2 Phase II — Radiative Heater Thruster Experiments

Due to the lack of a test facility to collect creep data over the desired temperature range and the presence of water in the wire exposure tests there was considerable uncertainty at the end of Phase I regarding whether available materials would support the design features needed for performance improvements. To alleviate the uncertainty, Phase II was restructured to proceed immediately to thruster testing. Direct measurement of actual thruster performance promised to provide creep data on heat exchanger materials, wire compatibility data, nozzle performance data, and verification of thermal and structural models. In addition, thruster testing provided direct verification of performance estimates for component improvements identified in Phase I.

Two radiative heat exchanger thruster configurations were tested. The first was a vented cavity heat exchanger (filament in a vacuum) operating at a higher temperature than existing designs. The second was a sealed cavity thruster using the same heat exchanger design with the volume surrounding the filament pressurized with decomposition gases.

1.3.3 Phase III — Immersed Heater Thruster Experiments

Phase II results indicated great difficulty in limiting performance losses due to heat conduction away from the thruster. There was also a support hardware failure in the second of the two tests. Requirements of the potential user community were also changing. Because of these factors the program was restructured for a second time starting in Phase III. The new requirement was for a thruster delivering 315 sec Isp using 750 W of electrical power and providing 100,000 lbf-sec total delivered impulse. An immersed heater thruster based on the HiPEHT thruster was tested. A catalytic gas generator was substituted to obviate the feed tube nonvolatile residue problem previously encountered with thermal decomposition, and the vortex injector was redesigned to improve heat transfer. Two of these thrusters were tested on the program.

1.3.4 Phase IV — Materials and Gas Generator Experiments

Following Phase III, the program embarked on a study of advanced materials and gas generator designs that would be required to extend the life of resistojets. Coupon and wire samples of a range of refractory metals were tested with N_2H_4 decomposition gases and other gases. A life test of an advanced gas generator was performed.

The following sections provide a detailed report of the program activities.

2.0 HARDWARE DEVELOPMENT REPORT

2.1 PHASE 1 — PROGRAM INITIATION

The objectives of this phase were to assess technologies to improve resistojet performance. The leading candidate design at the beginning of the program was a sealed cavity radiative heater concept with a super heater just upstream of the nozzle illustrated in Figure 2-1. Preliminary analysis indicated the sealed cavity heater filament could be operated at higher temperature with no increase in mass loss rate. A super heater could further enhance performance by adding more enthalpy to the flow. There were three technology areas that were of particular concern for this candidate thruster.

First, the creep behavior of heat exchanger bodies was excessive for the higher temperatures required for higher performance. The creep of the Mo/41Re heat exchanger in the MR-501 was measurable over the life of the thruster. Excessive creep would result in ballooning leading to rupture of the heat exchanger outer wall, or in shorting out the heater filament against the heat exchanger due to pressure from the outside forcing the heat exchanger in toward the filament. Engineering judgement was that there was no margin for increased temperature. A rhenium heat exchanger with superior creep life had been fabricated in a previous program. There were limited creep data for Mo/41Re and rhenium. The maximum temperature of the available data was 4100°F. Extrapolation was required for heat exchanger temperatures of >5000°F.

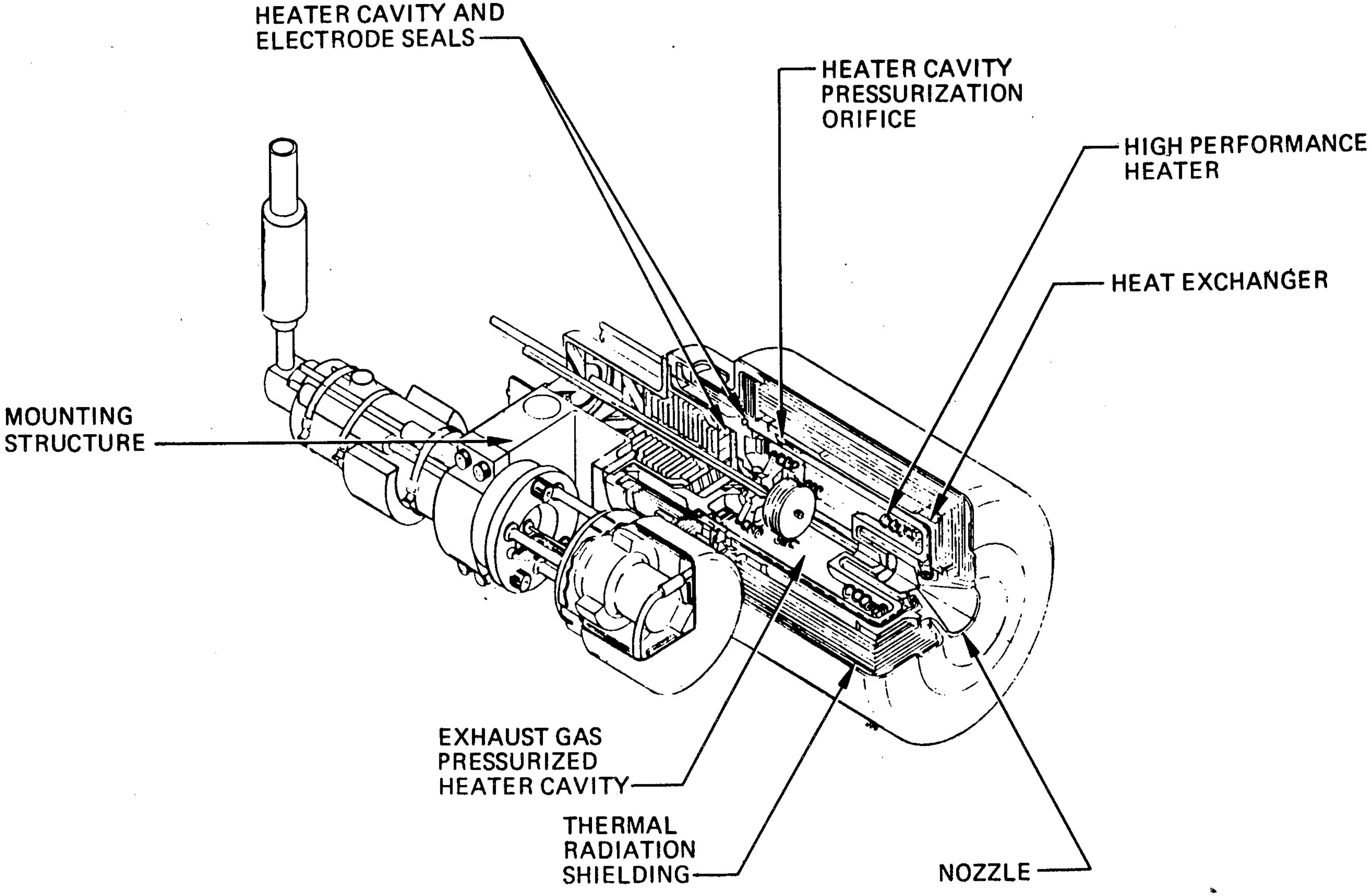
Second, a sealed cavity resulted in exposing the heater wire to N_2H_4 decomposition products at temperatures for which there was an inadequate data base. Previous vented cavity designs (i.e. MR-501) only exposed the filament to vacuum. Sublimation of tungsten into a vacuum was reasonably well characterized by incandescent lamp industry data. The decomposition products of N_2H_4 included H_2, N_2, and NH_3, as well as trace quantities of H_2O, CO_2 (as carbasic acid), and O_2. The effects of these species on the hot filament were totally unknown. In addition, the expected wire temperature of up to 5300°F was higher than previous designs and was close to the thermal failure limit of the stabilized tungsten wire material.

Finally, there was no seal design to implement a sealed cavity. Such a seal must endure the temperature of the thruster, withstand thermal cycling over the multiple year life of the thruster, form an interface between ceramic insulating materials and refractory metals, and seal decomposition gases within the thruster body.

Another objective of this phase was to determine the needs of the user community for low thrust moderate power thrusters. Spacecraft power availability, Isp and thrust requirements, life, and thruster physical characteristics (weight and envelope) were needed to allow thruster optimization. A preliminary performance specification was to be developed using input obtained from spacecraft prime contractors.

Candidate design solutions were identified and evaluated. These and the mission survey results are presented in the following sections.

HIGH PERFORMANCE RESISTOJET
BASELINE DESIGN IMPROVEMENT FEATURES



11165-48B

Figure 2-1

2.1.1 Mission Analysis — Performance Specification

A mission analysis questionnaire was prepared and sent to numerous spacecraft prime contractors. Table 2-1 presents the questions that were included in the mission questionnaire. Table 2-2 presents the responses received from the prime contractors. The responses were reviewed and an attempt was made to summarize a consensus position. This effort resulted in the top level performance specification presented in Table 2-3.

Table 2-1
HIGH PERFORMANCE RESISTOJET
APPLICATION SURVEY QUESTIONNAIRE

- Near-term mission parameter questions:
  1. On-orbit spacecraft dry mass
  2. Stationkeeping maneuver ΔV
  3. Simultaneous stationkeeping and attitude control (Y/N)
  4. Off-pulsing for attitude control (Y/N)
  5. Stationkeeping propellant load
  6. Initial on-orbit feed pressure
  7. Spacecraft positional or pointing accuracy
  8. Desired thrust level or maximum maneuver duration
  9. Electric power availability
  10. Peak battery voltage and bus voltage letdown characteristics
  11. Special thruster weight, size or interface requirements
  12. Nominal mission duration

2.1.2 Thruster Analysis

Using the performance specification and starting with the baseline design a series of analyses were completed to form the basis of the conceptual design of the thruster to be carried into the next phase. The following sections summarize these analyses.

2.1.2.1 Heater Sizing

The determination of heater envelope and operating characteristics were key to achieving the desired level of performance. Sizing the heater involved a large number of variables and assumptions including:

- voltage
- wire diameter and length
- electrical power and resistance
- wire temperature
- major and minor filament diameter
- filament geometry
- filament view factors
- wire and cavity thermal emissivity
- cavity wall temperature
- cavity diameter and length
- heat losses
- life effects
- thermal expansion

Table 2-2

MISSION ANALYSIS SURVEY — QUESTIONNAIRE RESPONSES

	COMPANY	BOEING		LOCKHEED		AERO-SPACE	INTELSAT		R C A	
	CONTACT			DICK GUHSE/ IRV BENARD		GREG HOFFMAN	BOB SCHREIB			
	APPLICATION	SURVEILL. S/C	CLASSI-FIED	CLASSI-FIED	CLASSI-FIED	DSCS III	COMMUNICATIONS S/C		COMM. S/C	DBS
1.	DRY SPACECRAFT MASS (LBM)	12-15,000	5-10,000	3500	8000	1875	2200	5060	3200	2700
2.	DELTA-V (FT/SEC/YR)	TBD	1000 TOTAL	0.26 PER EVENT	5.1 PER EVENT	1373 TOTAL 155	164	164	11.55 Per Manv.	11.55 Per Manv.
3.	STATIONKEEPING & ATT. CONTROL	YES	YES MAYBE SEQ.	YES	YES	YES	YES	YES	YES	YES
4.	OFF PULSING?	YES	NO	YES	YES	NO	YES	YES	YES	YES
5.	PROPELLANT LOAD (LBM)	2-300	1% of Mo	31	100	600	360	860	720	700
6.	INITIAL FEED SYSTEM PRESSURE (PSIA)	3-400	300	125	300	350-400	220	125 Low Bd.	260	220
7.	POSITIONAL & POINTING ACCURACY (DEGREES)	N/A	±1 LONG.	N/A	N/A	0.1	0.06	0.06	.05-.07	.05-.07
8.	TOTAL THRUST LEVEL (LBF)	0.05-0.5	0.1	1 - 3	1	1	N/A	N/A	.4-.6	.4-.6
9.	ELECTRICAL POWER	N/A	1 KW	DEPENDS ON BENEFITS SOLAR ARRAY TRADES		1075-1275 890-980	PEAK 1000-1500 WATT	PEAK 1500-2800 WATT	PEAK 3400 WATT	PEAK 3000 WATT
10.	BATTERY VOLTAGE (VDC)	24-32	DESIGN DEPEND.	28 ± 6		28 3-37A-HR	30 2-30A-HR	30 2-46A-HR	28 4-60A-HR	100 2-27A-HR
11.	SPECIAL INTERFACE?	NOT AT THIS TIME	YES	NO	NO	NO	NO	NO	NO	NO
12.	MISSION DURATION (YRS)	5-10	10	3-7 UP TO 10		8.86 + 1 DRIFT	7-10	7-10	10	10

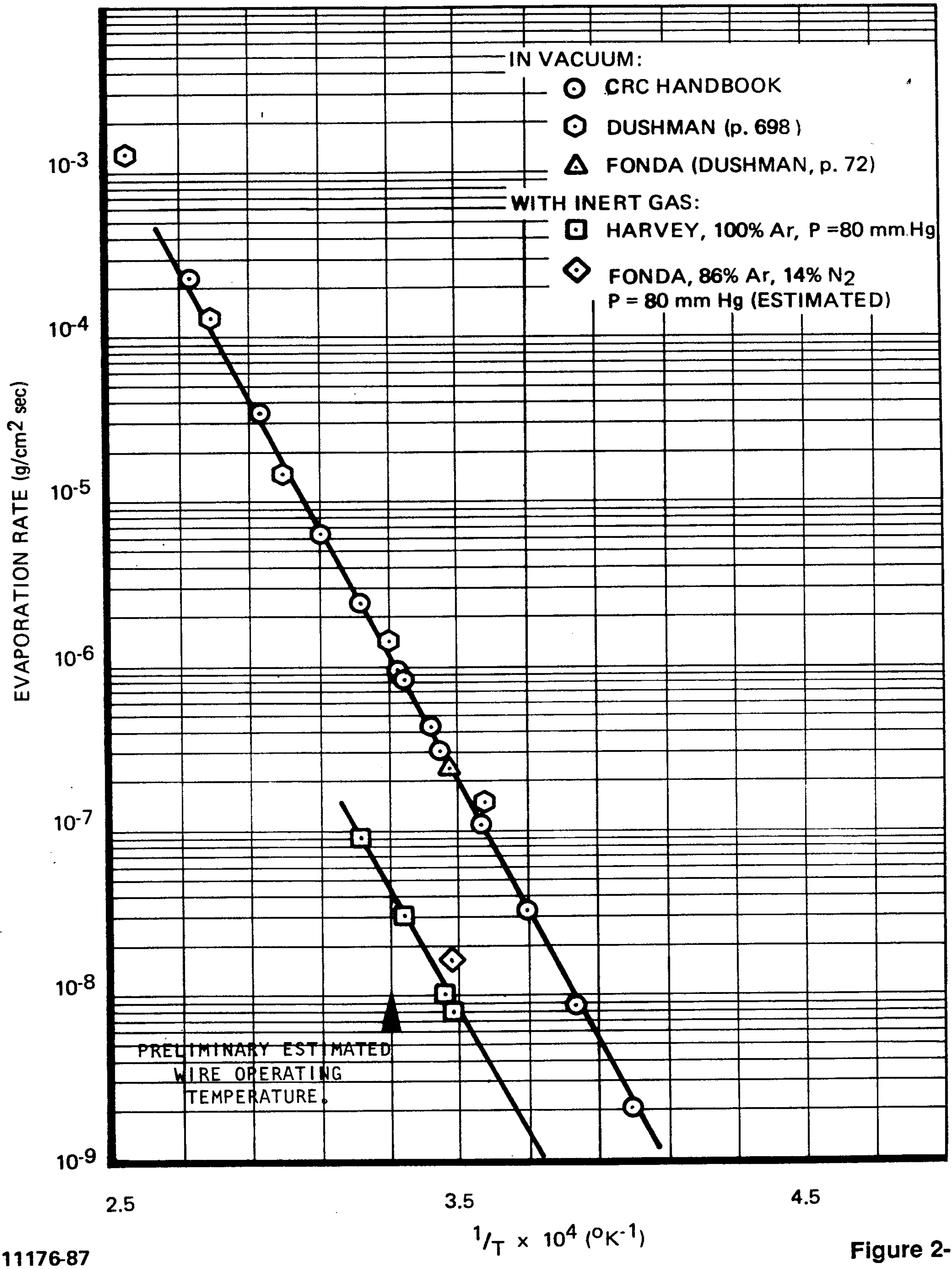
Table 2-3
HIGH PERFORMANCE RESISTOJET PRELIMINARY PERFORMANCE SPECIFICATION

• Mission	• N-S stationkeeping geosynchronous communication satellite
• Life	• 10 years (250-hour total firing time)
• Thrust level	• 0.125-lbf nominal design point
• Total impulse	• 117,000 lbf-sec
• Specific impulse	• 360 lbf-sec/lbm average over feed pressure blowdown range (300 — 100 psia)
• Power requirement	• Direct operation from S/C bus. Simple current surge limiter circuit on start-up desirable but not required
	• Regulated or battery voltage let-down
	• 28 vdc nominal peak. adjustable as required
	• 1600 watt at P_f = 300 psia; 1400 watt at 100 psia
• Propellant pressure	• Blowdown 300 to 100 psia
	• Regulated 150 psia minimum
• Thrust repeatability	• ±5%
• Vibration	• Spectrum 0.2 g^2/Hz, 20 — 20,000 Hz
	• Overall 13.0 g rms
• Spacecraft heat rejection	• TBD

Tungsten filament vaporization studies were initiated as part of the heater sizing effort. The need to reduce filament sublimation rate drives the design requirement to have heater cavity seals. If the vacuum sublimation rates were excessive at the desired element operating temperatures, a protective atmosphere would be required around the heater element to limit loss of tungsten from the wire. Figure 2-2 is a compilation of measured test results of tungsten filament sublimation rates as a function of temperature. The upper curve shows data in a vacuum, and the lower curve shows data obtained with a protective atmosphere of argon at a pressure of 80 torr.

Using a predicted temperature of 5000°F, the vacuum sublimation rate indicated is 1.2×10^{-6} grams/cm^2-sec. With a filament 0.030 inch in diameter, the wire would be consumed in under 100 hours. With argon at 80 torr, the sublimation rate drops to 4.5×10^{-8} grams/cm^2-sec resulting in about a 7% diameter decrease in 300 hours. This indicates that seals and a protective atmosphere are needed to sustain high performance operation for the desired lifetimes.

MEASURED TUNGSTEN FILAMENT EVAPORATION RATES



11176-87

Figure 2-2

Mission analysis results suggested 125 mlbf thrust as a nominal value. Preliminary thermal analyses were conducted to estimate heat exchanger cavity temperature profiles for various performance levels. The performance goals and temperature profiles were incorporated into an analysis to determine packaging configurations and heater wire temperatures for a range of heater surface areas. The results of the heater sizing are shown in Figure 2-3. Curves for three different performance levels are shown. Two curves are shown at each performance level to account for view factor uncertainty (F_{cc}). Specific configurations that were optimized by the heater sizing program are shown as data points. Wire diameter, the number of filaments, and whether the configuration is parallel filament or double helix are noted. As shown, wire temperatures required for 388 seconds Isp are too close to the melting point of tungsten. The wire temperature could be decreased by increasing the heater cavity length and diameter, but thermal losses would increase with size and unreasonable amounts of power would be required. Wire temperatures around 5000°F associated with 359 sec Isp are more reasonable for an initial design point. However, wire creep in a 1-g environment may limit the amount of ground test time the thruster can be subjected to in one position.

The plot in Figure 2-4 was used to size the heater filament by defining the wire surface area required in the rhenium heat exchanger cavity to achieve a range of Isp values. This analysis assumes a wire diameter of 0.025 inch. The drawing in the figure illustrates two heater filament options that contain the desired wire surface area and fit in the envelope.

2.1.2.2 Nozzle Design

To support the selection of a thruster nozzle configuration, a study was performed that included analysis of several configurations validated with cold gas testing.

A trumpet nozzle and a MR-501 nozzle were modelled with the Two Dimensional Kinetics (TDK) code. The TDK code calculates a pressure profile in the chamber and throat using isentropic flow relations. Nozzle pressures are calculated with a numerical integrator. The nozzle pressure profile is subsequently used in a method of characteristics sub-routine that calculates divergence and viscous losses. Preliminary results indicated 6% better performance for the trumpet nozzle than for the MR-501 nozzle. A preliminary throat diameter of 0.035 inch was selected.

Four nozzle configurations were fabricated including two trumpet shaped, a conical, and one bell shaped design. Throat Reynolds numbers from 500 to 9000 were tested with H_2 and N_2 to validate the model predictions. The results of this test were reported separately (Grisnik, 1987). Figure 2-5 illustrates the nozzle configurations tested and Table 2-4 presents dimensions and performance values. Figure 2-6 is a combined analytical and experimental data plot of I_{sp} efficiency as a function of Reynolds number. I_{sp} efficiency is defined as the ratio of measured specific impulsed (thrust/flow) to theoretical maximum specified impulse (300 for H_2 and 78 for N_2 at room temperature). The I_{sp} efficiency increases for increasing Reynolds number for all of the nozzles. All of the nozzles gave the same performance within experimental error. The analytical results proved to be a rather poor predictor of measured performance.

HIGH PERFORMANCE RESISTOJET HEATER SIZING STUDIES

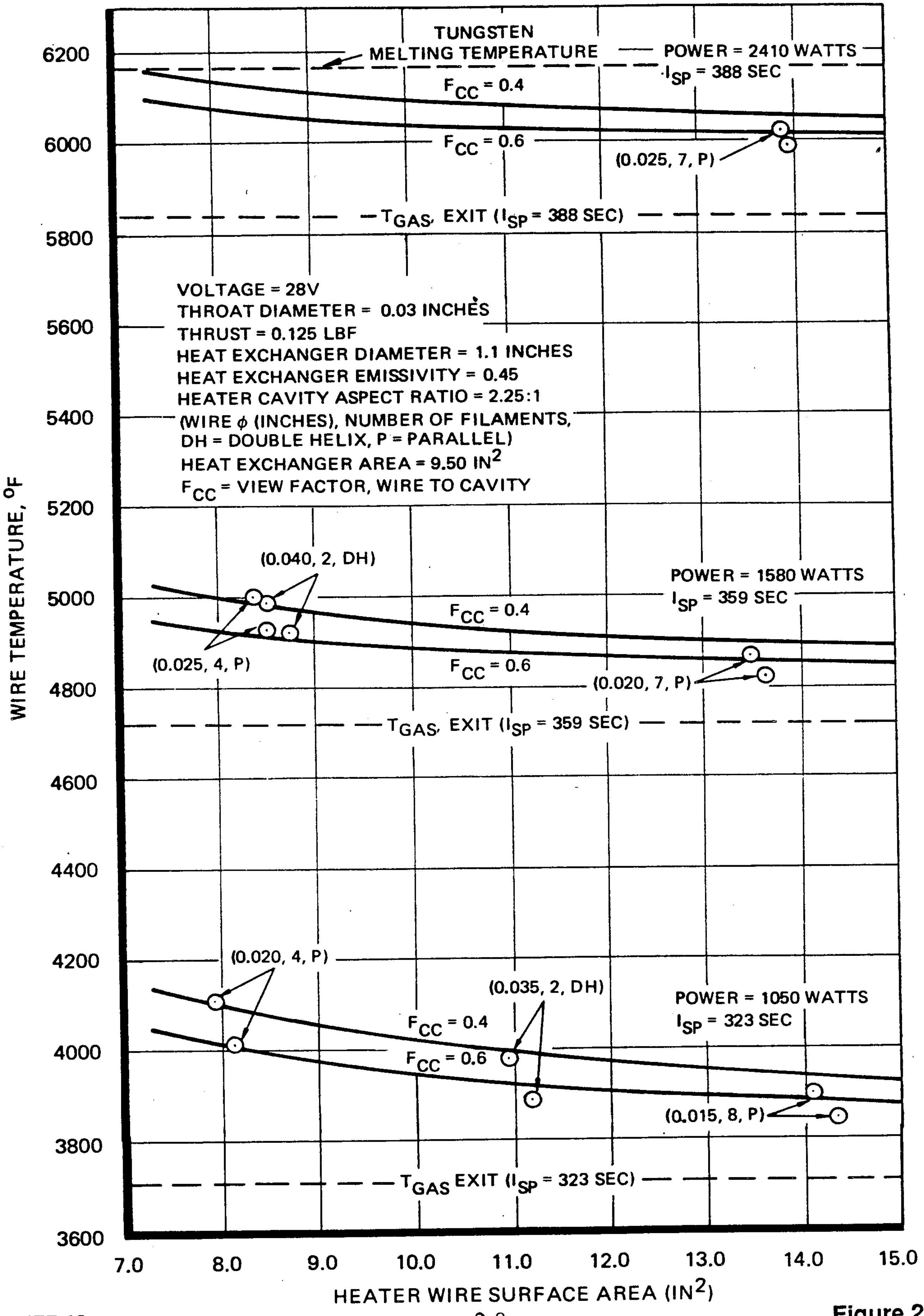


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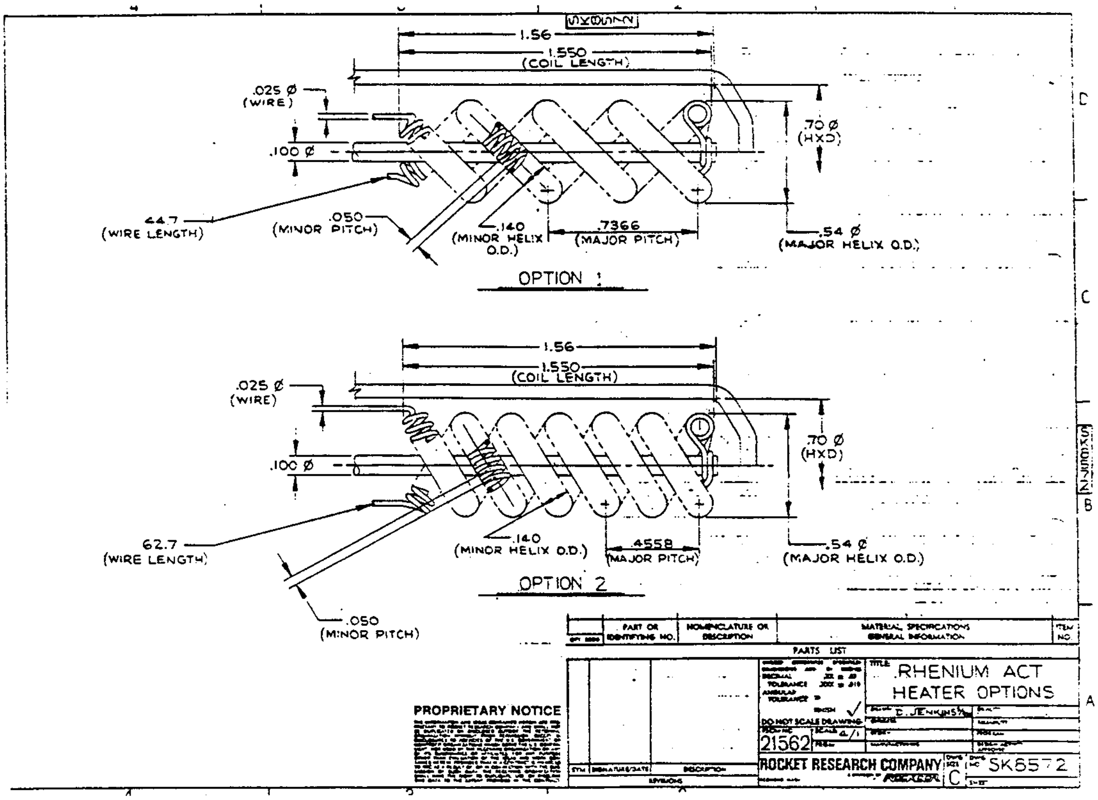
Figure 2-3

RHENIUM ACT HEATER SIZING STUDY AND OPTIONS FOR FABRICATION



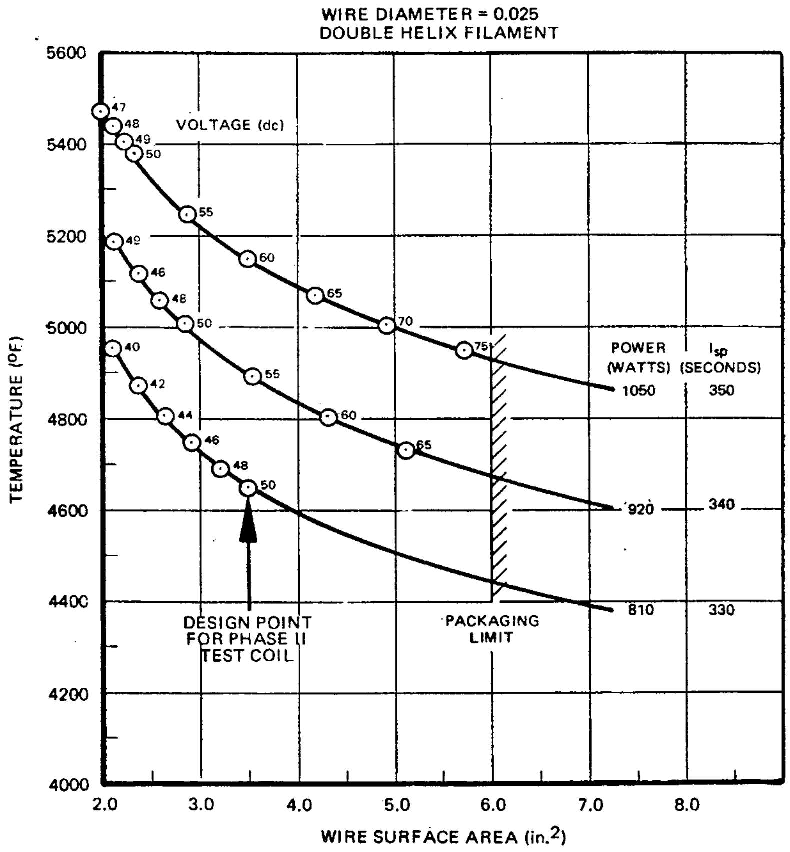


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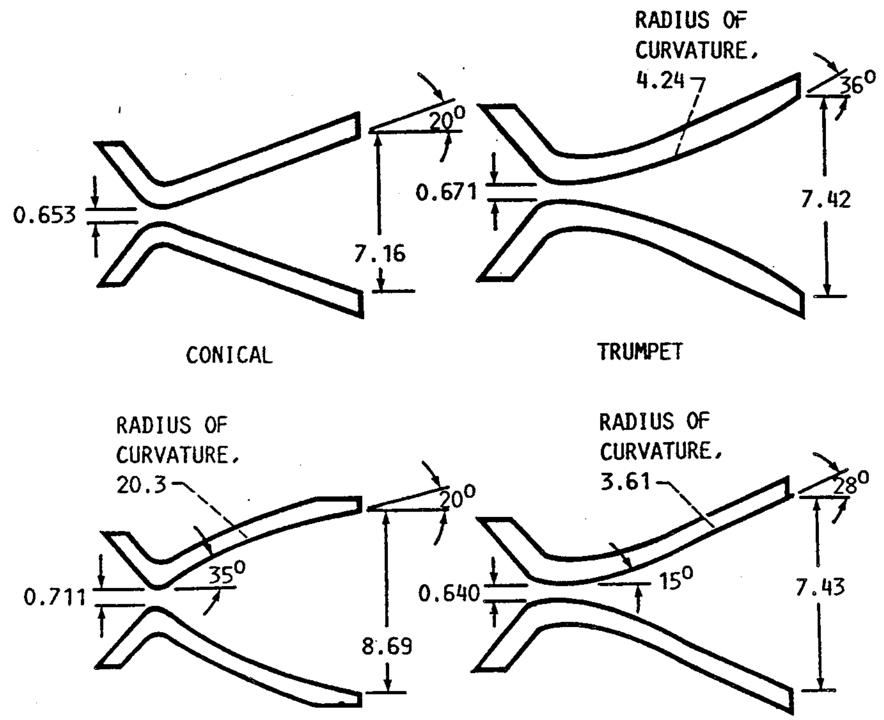
Figure 2-4

NOZZLE GEOMETRIES
All Dimensions are in Millimeters



11232-16 **Figure 2-5**

2.1.2.3 Configuration Trade Study

A structural and performance trade-study was conducted to determine a suitable thruster operating pressure (P_C) range with acceptable heat exchanger creep margins. Figure 2-7 illustrates the effect of throat diameter on other performance parameters over a range of P_C values. The figure shows beginning-of-life (BOL), middle-of-life (MOL), and end-of-life (EOL) conditions for 3:1, 2:1, and 1.5:1 feed pressure blowdown schedules. The MOL design point is 125 mlbf thrust at 365 sec Isp and when 50% of the mission propellant has been consumed.

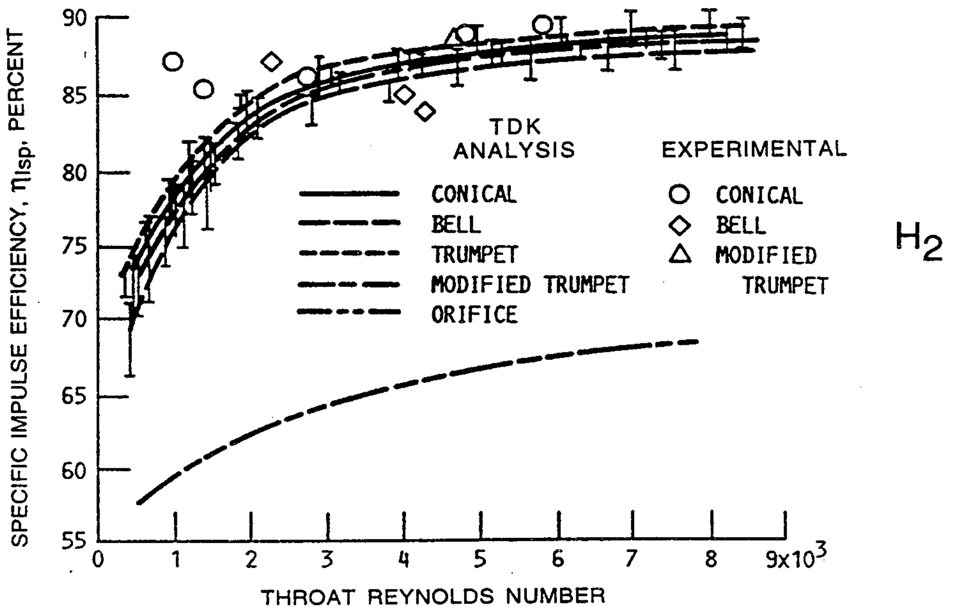
Creep effects drive operating conditions toward large throat sizes and lower pressures. The preliminary results predicted Isp values of up to 372 sec with thrust from 92 to 197 mlbf, gas temperatures from 4100° to 5000°F, and power from 1300 to 1650 W for a 250-hour mission. Creep of the outer heat exchanger body was the primary performance limiting feature. Thermal analysis at an Isp of 369 sec (exhaust gas almost 5000°F) yielded the following predicted temperatures: heater filament, nearly 5300°F; outer body, greater than 4800°F; metal to ceramic seal, about 1600°F; and throat, almost 3500°F. These temperatures were compared to the best available creep data using worst-case pressures. Rhenium appeared acceptable in terms of creep, rupture, and margin on rupture. Lower creep values are obtained

Table 2-4

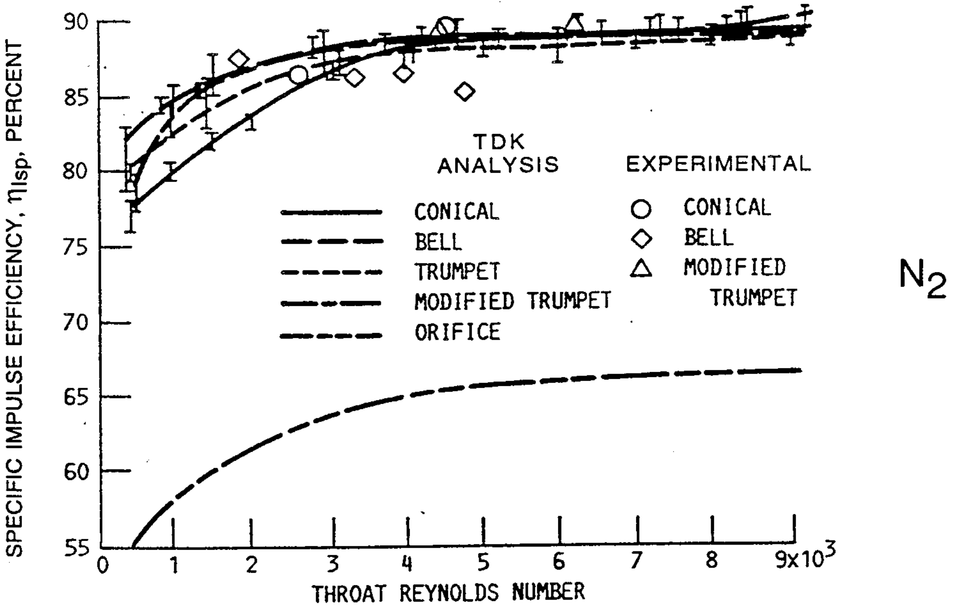
NOZZLE PARAMETERS AND CHARACTERISTICS AT A REYNOLDS NUMBER OF 1000 FOR NITROGEN AND HYDROGEN

Nozzle	Shape	Exit Half-Angle		Throat Diameter (mm)	Area Ratio	Discharge Coefficient (C_D)		Specific Impulse Efficiency (N_{Isp})		Thrust Coefficient (C_F)	
		Throat	Exit Plane			Nitrogen	Hydrogen	Nitrogen	Hydrogen	Nitrogen	Hydrogen
1	Conical	20°	20°	0.653	120:1	0.87	0.88	0.80	0.78	1.18	1.17
2	Bell	35°	20°	0.711	150:1	0.91	0.92	0.85	0.75	1.31	1.17
3	Trumpet	0°	36°	0.671	125:1	0.88	0.86	0.83	0.78	1.24	1.14
4	Modified trumpet	15°	28°	0.640	135:1	0.93	0.93	0.84	0.76	1.33	1.20
—	Orifice plate	—	—	—	—	0.98	0.94	0.58	0.59	0.97	0.94

SPECIFIC IMPULSE EFFICIENCY AS FUNCTION OF THROAT REYNOLDS NUMBER FOR gH_2 & gN_2. EXPERIMENTAL DATA AND TWO-DIMENSIONAL KINETICS (TDK) NOZZLE ANALYSIS



$$= \frac{4\dot{m}}{\pi\mu_o d^*} \text{ or } \frac{\rho^*\mu^*d^*}{\mu_o}$$



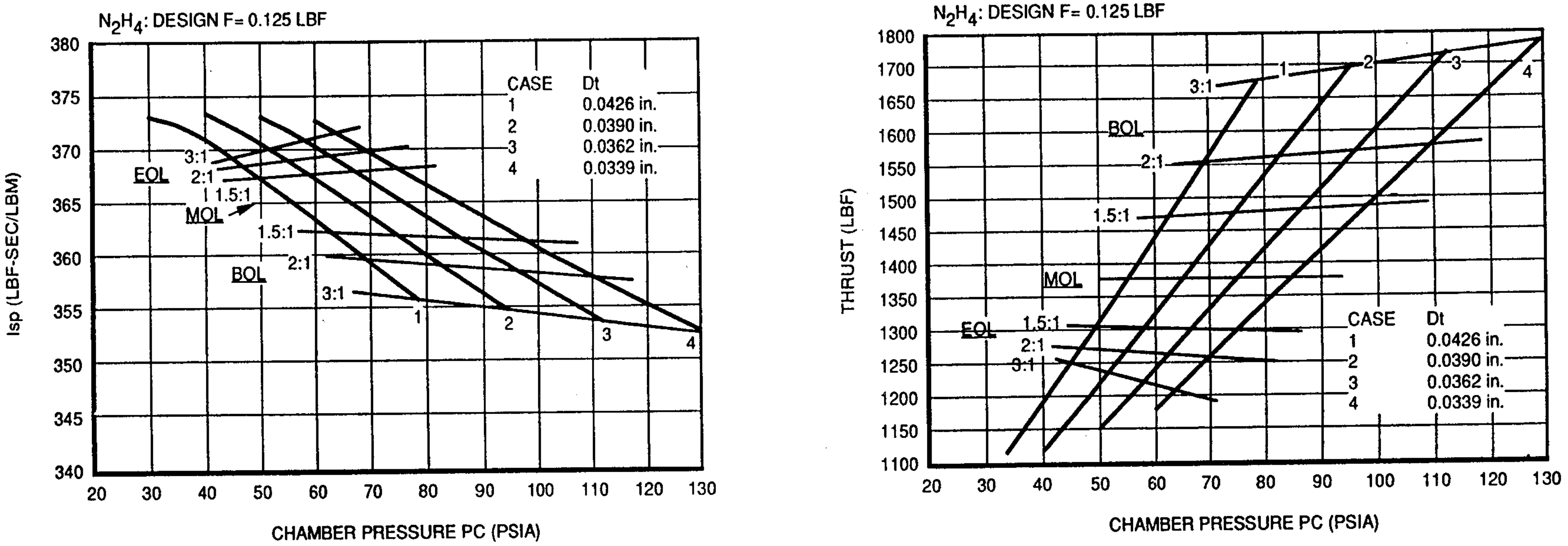
11232-17

Figure 2-6

THRUSTER OPTIMIZATION TRADE STUDY RESULTS

Isp vs CHAMBER PRESSURE

THRUST vs CHAMBER PRESSURE



GAS TEMPERATURE vs CHAMBER PRESSURE

HEATER POWER vs CHAMBER PRESSURE

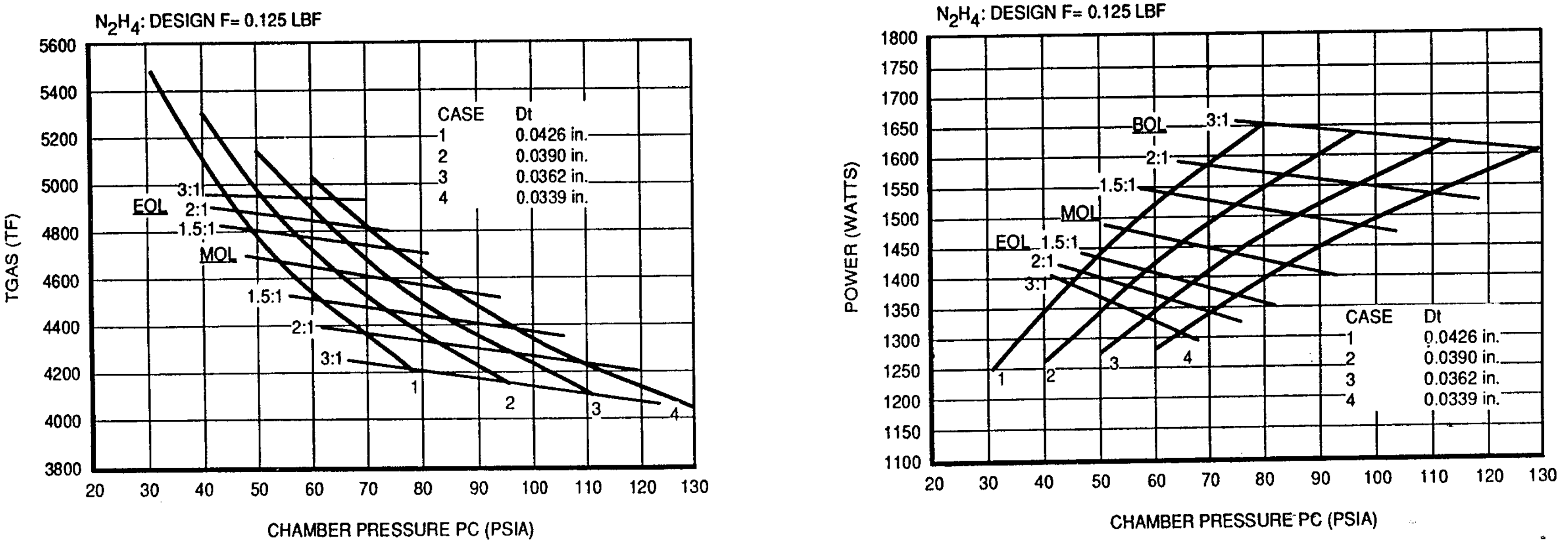


Figure 2-7

for W/25Re, but rupture, and margin on rupture are unacceptable. Tungsten was acceptable for creep, rupture and margin on rupture, but there were concerns regarding manufacturability.,

An option considered was a super-heater which is shown in Figure 2-8 along with a conventional configuration. Thermal results also presented in the figure show no significant advantage for the super-heater. The super-heater requires more power due to increased thermal losses caused by greater HX diameter. Due to higher losses and greater complexity the super-heater concept was rejected.

2.1.3 Material Characterization

Several test series were needed to obtain data to complete the conceptual design. The approaches taken are presented below.

2.1.3.1 Creep

Testing to confirm creep characteristics was planned for samples of hot isostatic pressed (HIP) rhenium, CVD rhenium, and W/25Re. Several laboratories were approached to conduct high temperature material characterization including:

Battelle Laboratories
Westinghouse
Oak Ridge National Laboratory
Lawrence Livermore Laboratory
Los Alamos Laboratory
Olin Materials Research Laboratory
NASA-LeRC

There were few responses to the solicitation to perform this testing. Battelle's maximum temperature capability for material testing was reported to be 4700°F. However, long-term creep testing could only be conducted at 4000°F. The minimum temperature acceptable for testing was 3850°F. Battelle's furnace turned out to only be capable of 3450°F. This eventually led to termination of this test effort.

Without additional creep data, rhenium remained the material of choice for the heat exchanger due to superior joinability as compared to tungsten. The rhenium heat exchanger, fabricated in a previous program, was made available for testing.

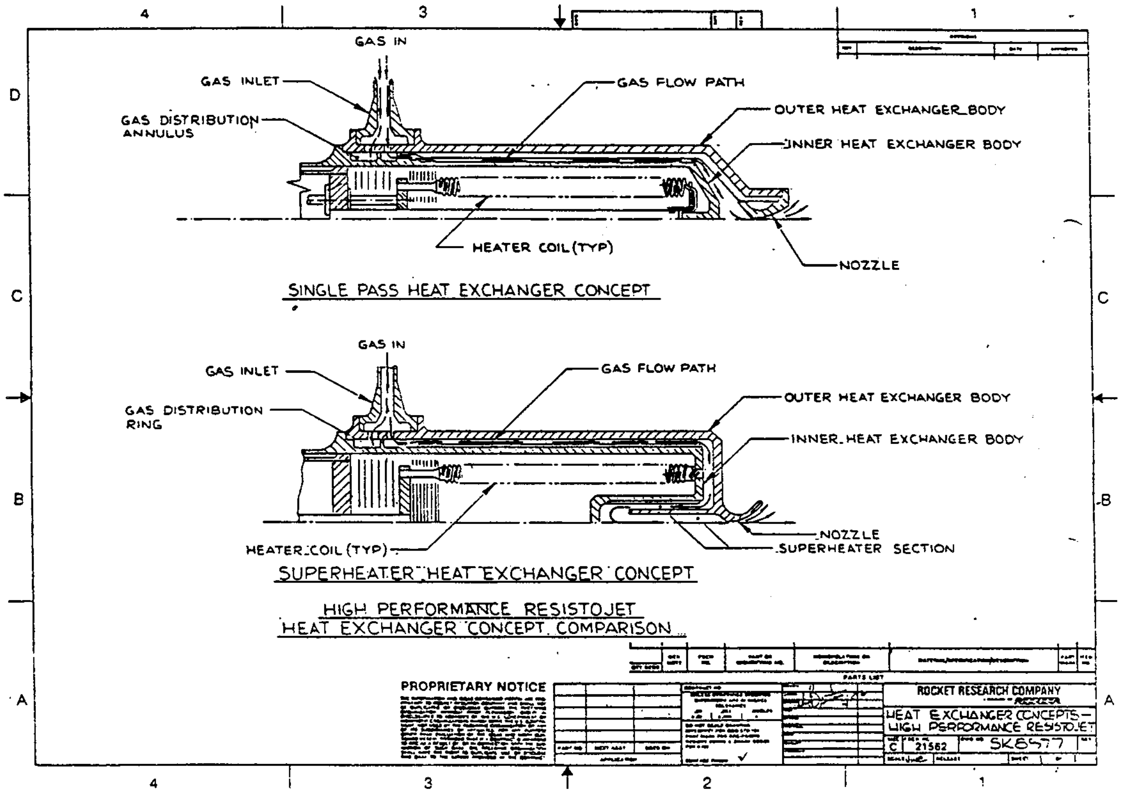
2.1.3.2 High Temperature Filament Wire Exposure

Figure 2-9 illustrates the fixture fabricated to expose filament wire at high temperature to N_2H_4 decomposition gases. The wire was tested using 1 hour on periods with 10 minute cooling periods between cycles. The temperature and pressure conditions in the chamber simulating thruster operation during life are presented in Table 2-5. Fifty cycles were performed at each test condition. Figure 2-10 shows the overall test apparatus.

Table 2-5
HEATER WIRE EXPOSURE TEST CONDITIONS

		ALL FAILURES			
Hours	**1–50**	**51–100**	**101–150**	**151–200**	**201–250**
Wire Temp °F	4640	4815	4990	5135	5280
Chamber Pressure (psia)	80	72	63	54	46

HIGH PERFORMANCE RESISTOJET
COMPARISON OF TEMPERATURE PROFILES FOR SINGLE-PASS AND SUPERHEATER HEAT EXCHANGERS



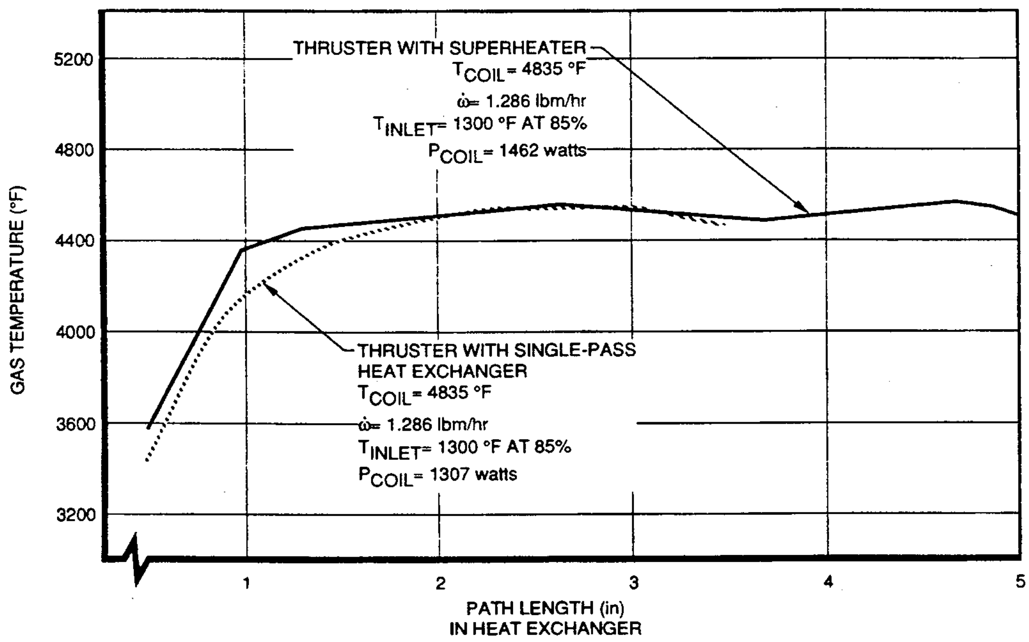
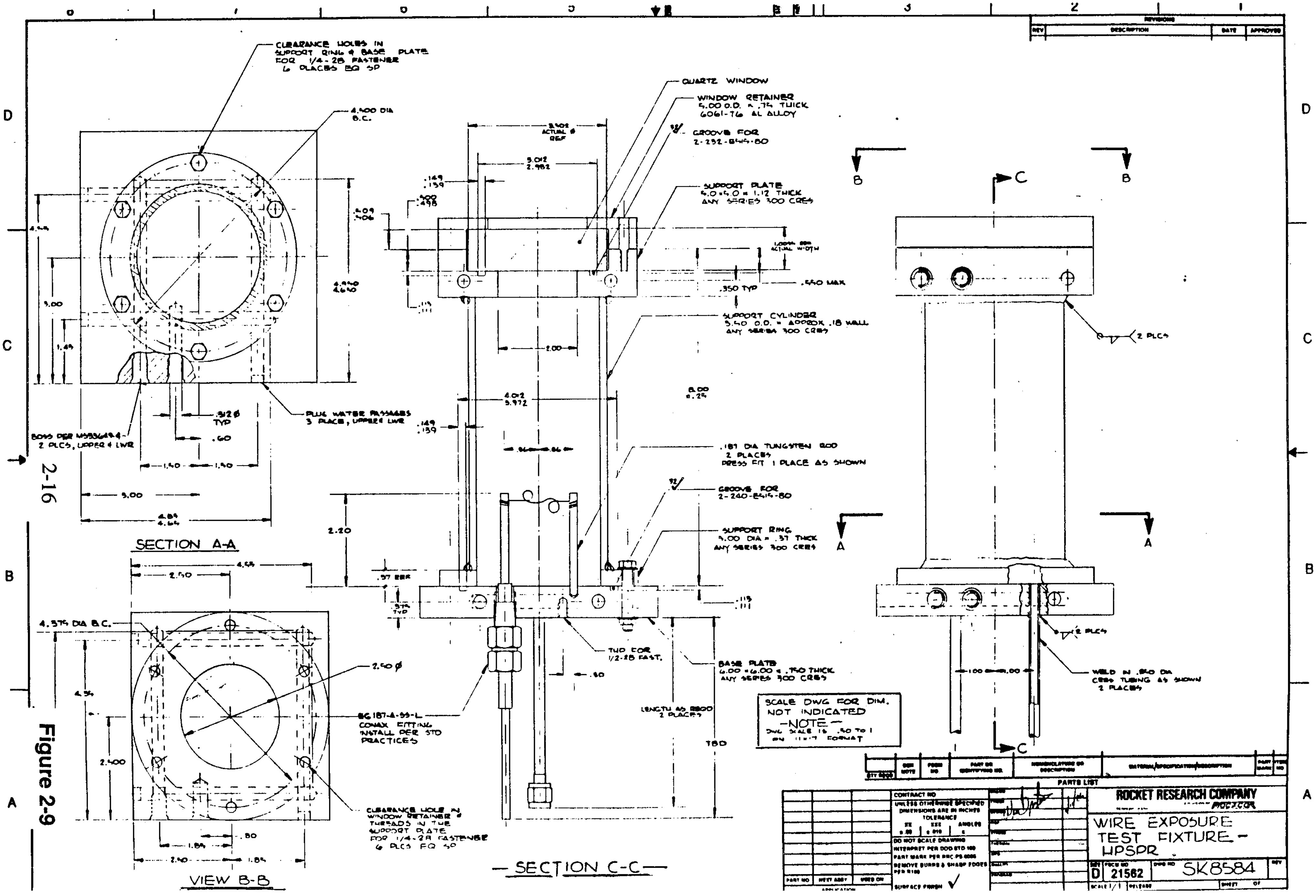


Figure 2-8



CLEARANCE HOLES IN SUPPORT RING & BASE PLATE FOR 1/4-28 FASTENER 6 PLACES EQ SP
4.500 DIA B.C.
QUARTZ WINDOW
WINDOW RETAINER 5.00 O.D. × .75 THICK 6061-T6 AL ALLOY
GROOVE FOR 2-232-E515-80
SUPPORT PLATE 5.0×5.0 × 1.12 THICK ANY SERIES 300 CRES
1.000 REF ACTUAL WIDTH
.550 MAX
.350 TYP
SUPPORT CYLINDER 5.50 O.D. × APPROX .18 WALL ANY SERIES 300 CRES
8.00 ±.25
.187 DIA TUNGSTEN ROD 2 PLACES PRESS FIT 1 PLACE AS SHOWN
GROOVE FOR 2-240-E515-80
SUPPORT RING 5.00 DIA × .37 THICK ANY SERIES 300 CRES
BASE PLATE 6.00 × 6.00 × .750 THICK ANY SERIES 300 CRES
TWD FOR 1/2-28 FAST.
BG187-A-55-L CONAX FITTING INSTALL PER STD PRACTICES
2.50 ⌀
4.375 DIA B.C.
CLEARANCE HOLE IN WINDOW RETAINER & THREADS IN THE SUPPORT PLATE FOR 1/4-28 FASTENER 6 PLCS EQ SP
LENGTH AS REQ 2 PLACES
TBD
PLUG WATER PASSAGES 3 PLACE, UPPER & LWR
BOSS PER MS33649-4 2 PLCS, UPPER & LWR
.312 ⌀ TYP
.60
1.50
1.50
3.00
4.84 4.64
4.44
5.00
1.45
4.640 4.620
3.502 ACTUAL ⌀ REF
3.012 2.982
.149 .139
.500 .498
4.09 4.06
2.00
4.012 3.972
.86 .86
2.20
.37 REF
.375 TYP
.115 .111
.50
1.00
1.00
2 PLCS
2 PLCS
WELD IN .250 DIA CRES TUBING AS SHOWN 2 PLACES
SECTION A-A
SECTION C-C
VIEW B-B
2.50
4.55
4.56
2.400
1.84
1.84
.80
2.50
A
B
C
SCALE DWG FOR DIM. NOT INDICATED
—NOTE—
DWG SCALE IS .50 TO 1 ON 11×17 FORMAT
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
QTY REQD
DSH NOTE
FSCM NO.
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
MATERIAL/SPECIFICATION/DESCRIPTION
PART MARK
ITEM NO
PARTS LIST
PART NO
NEXT ASSY
USED ON
APPLICATION
CONTRACT NO
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
XX ±.00
XXX ±.010
ANGLES ±
DO NOT SCALE DRAWING
INTERPRET PER DOD STD 100
PART MARK PER RRC-PS 4006
REMOVE BURRS & SHARP EDGES PER R100
SURFACE FINISH ✓
ROCKET RESEARCH COMPANY
ROCKCOR
WIRE EXPOSURE TEST FIXTURE - HPSPR
SIZE D
FSCM NO 21562
DWG NO SK8584
REV
SCALE 1/1
RELEASE
SHEET OF
D
C
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A
1
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5
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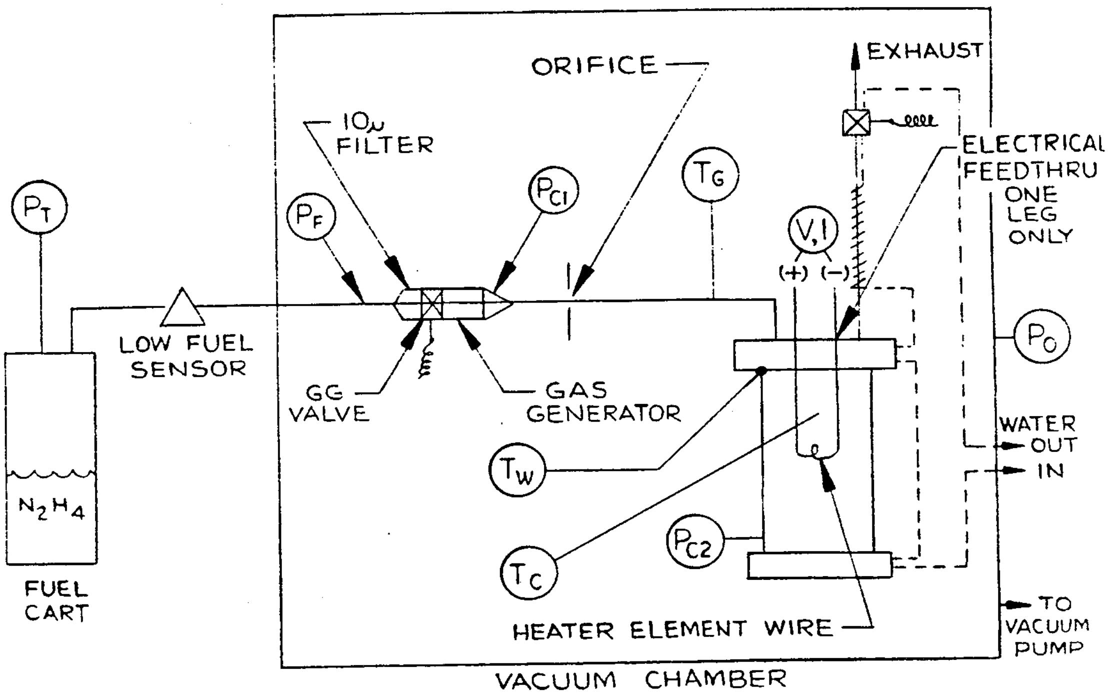
8

Figure 2-9

HEATER WIRE EXPOSURE TEST SCHEMATIC

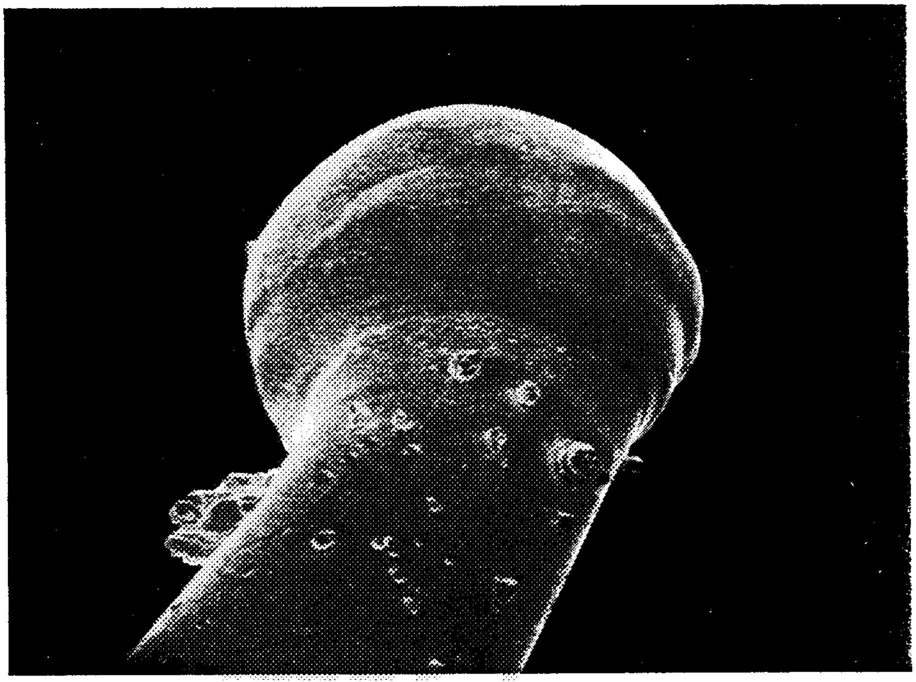


11186-70A **Figure 2-10**

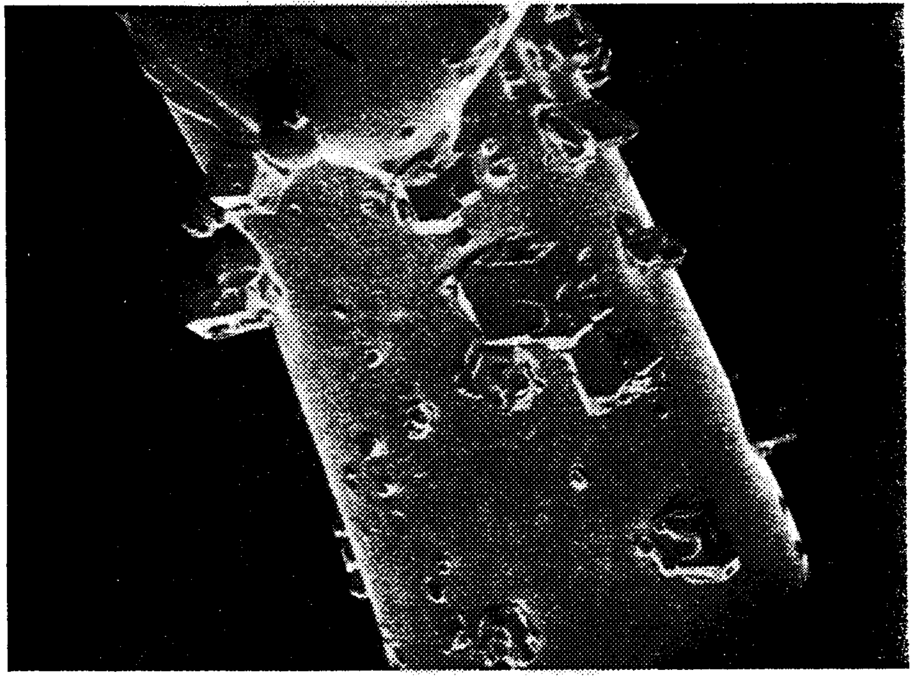
Three separate identical wire samples were tested. All three tests were terminated after approximately 120 cycles, short of the 250 cycle goal. In the first sample a visible kink developed in the wire near one of the two support posts and the test was terminated after 119 cycles. The second sample test was terminated when the wire failed open after 116 cycles. The third sample, which had a thermal expansion loop incorporated, was terminated when the wire failed open after 100 cycles. There was water condensation within the test apparatus in all cases.

Two wires were inspected using a Scanning Electron Microscope (SEM). Figure 2-11 shows one of the failed ends from each of the two samples. No evidence of chemical attack of the wires was detected during SEM examination. The primary failure mode appeared to be related to thermal stresses which severed some of the fibrous tungsten strands locally reducing the cross-sectional area and finally melting the wire. Chemical transport of tungsten atoms may have had a small secondary role as the temperature of the wire reached the melting point. Tungsten crystals renucleated from the vapor phase can be seen deposited on each of the wires in cooler regions away from the melted zone.

The conclusion drawn from this test was that heater filaments with the configuration tested will exhibit lifetimes of approximately 100 hours when operated in N_2H_4 decomposition environments up to temperatures of 5000°F. This was only 40% of the lifetime goal. Figure 2-3 indicates an Isp value of <360 sec associated with this temperature. The water condensate may have also played a role in accelerating these failures.



WIRE EXPOSURE TEST NO. 3
SEM PHOTO OF FAILED TUNGSTEN WIRE AFTER 100 HOURS AT
TEMPERATURES TO 5000°F



WIRE EXPOSURE TEST NO. 2
SEM PHOTO OF FAILED TUNGSTEN WIRE AFTER 116 HOURS AT
TEMPERATURES TO 5000°F

Figure 2-11

2.1.3.3 Heater Filament Design Support Tests

A wire sag test at 5300°F was performed. Figure 2-12 illustrates the configuration of the test fixture and one result. Test filaments were briefly flashed to 5400°F to recrystallize the microstructure. A theodolite was used from outside the test chamber to measure the amount of wire sag. The pointed tungsten spike in the middle of the test assembly serves as a spatial reference. Tests were conducted horizontally and vertically. Tests of 25 minutes at 5300°F resulted in a maximum deflection at the center of the filament of 0.060 inch. This amount of heater filament distortion was acceptable for the heater and heat exchanger configuration chosen.

Another critical design feature was the heater element wire transition joint. A sketch of the transition between the wire and the tungsten support post is shown in Figure 2-13. The transition joint was mounted to a hot swaged joint fixture illustrated in Figure 2-14. This assembly was fabricated, heated in a furnace simulating an acceptance test firing to cause diffusion bonding, vibrated to simulate launch, and checked for electrical continuity. The simulated joint was sectioned and the microstructure examined. No problem areas were observed.

2.1.3.4 Heat Exchanger Emissivity Samples

A trade study indicated performance benefits could be derived by increasing the efficiency of the heat exchanger. One approach considered was to increase the inner surface emissivity to enhance radiative heat transfer from the heater filament. Fabrication and evaluation of emissivity samples was performed.

Flat wafer refractory metal samples were machined with grooves 0.009 inch deep, 0.006 wide at the top and 0.012 inch apart to increase surface area. Other samples were machined and etched or coated with CVD tungsten. Based on NASA-LeRC reflectivity measurements for wavelengths from 0.2 to 2.5 microns the CVD tungsten surface performed best, the V-groove surface next, and the machined and etched surface performed worst. SEM analysis of a grooved and CVD coated heat exchanger indicated the coating process produced acceptable results with an even distribution of fine tungsten grains.

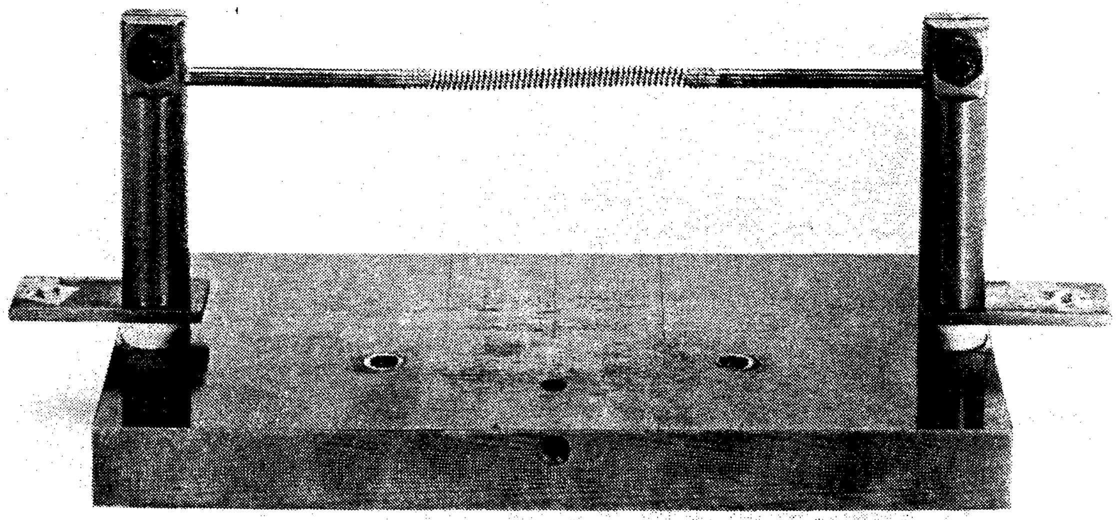
This activity was completed at the end of Phase I. Figure 2-15 presents the results of this effort.

2.1.3.5 Cavity Seal Tests

The primary cavity seal approach was compression of boron nitride (BN) powder. The BN powder was compressed between two ceramic pistons around the electrode post. The seal is to contain heater cavity pressurant gases while maintaining an electrical potential difference between the electrode and support structure. A fixture was designed to test the concept prior to committing to thruster hardware, as illustrated in Figure 2-16. The fixture was designed to operate at 1600°F. The fixture was pressurized with gH_2 or gN_2, heated for 1 hour, then depressurized and cooled for 10 minutes. Seal helium leak rates were measured before and after 250 cycles. Testing was not completed in Phase I, but this activity was carried forward into Phase II. Results are presented in subsequent sections.

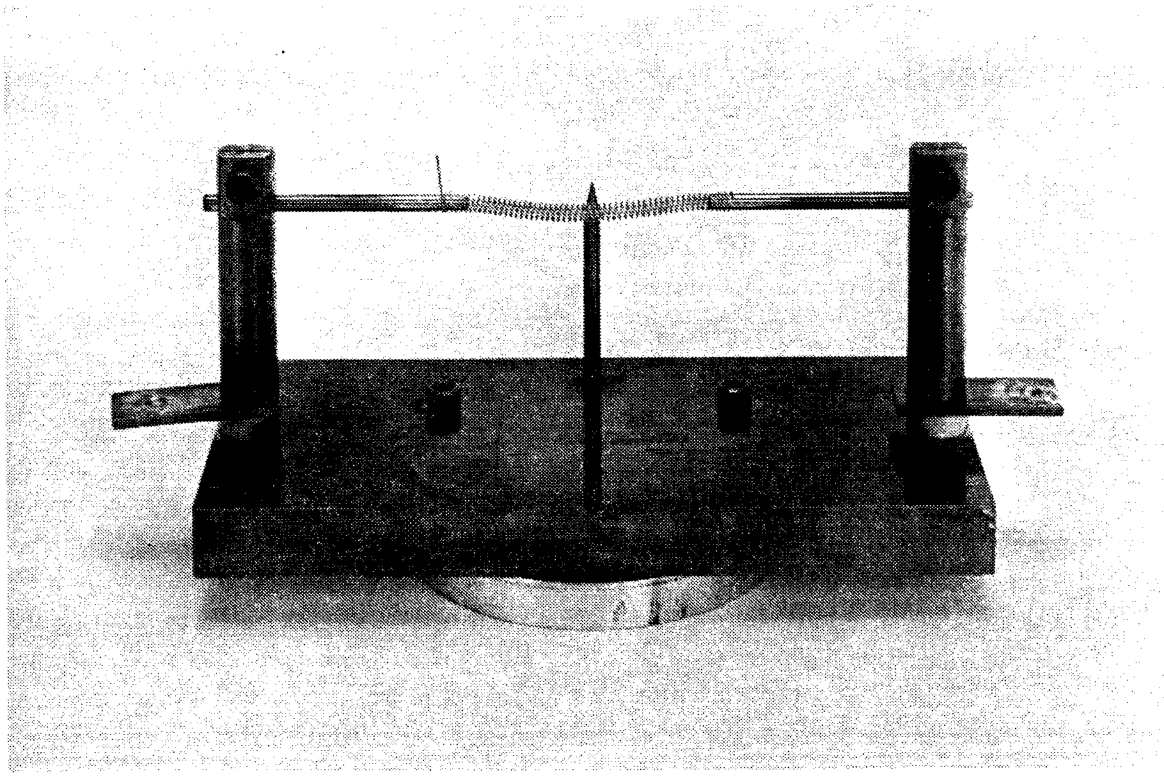
5300°F WIRE SAG TEST FIXTURE AND RESULTS

BEFORE



3037-3

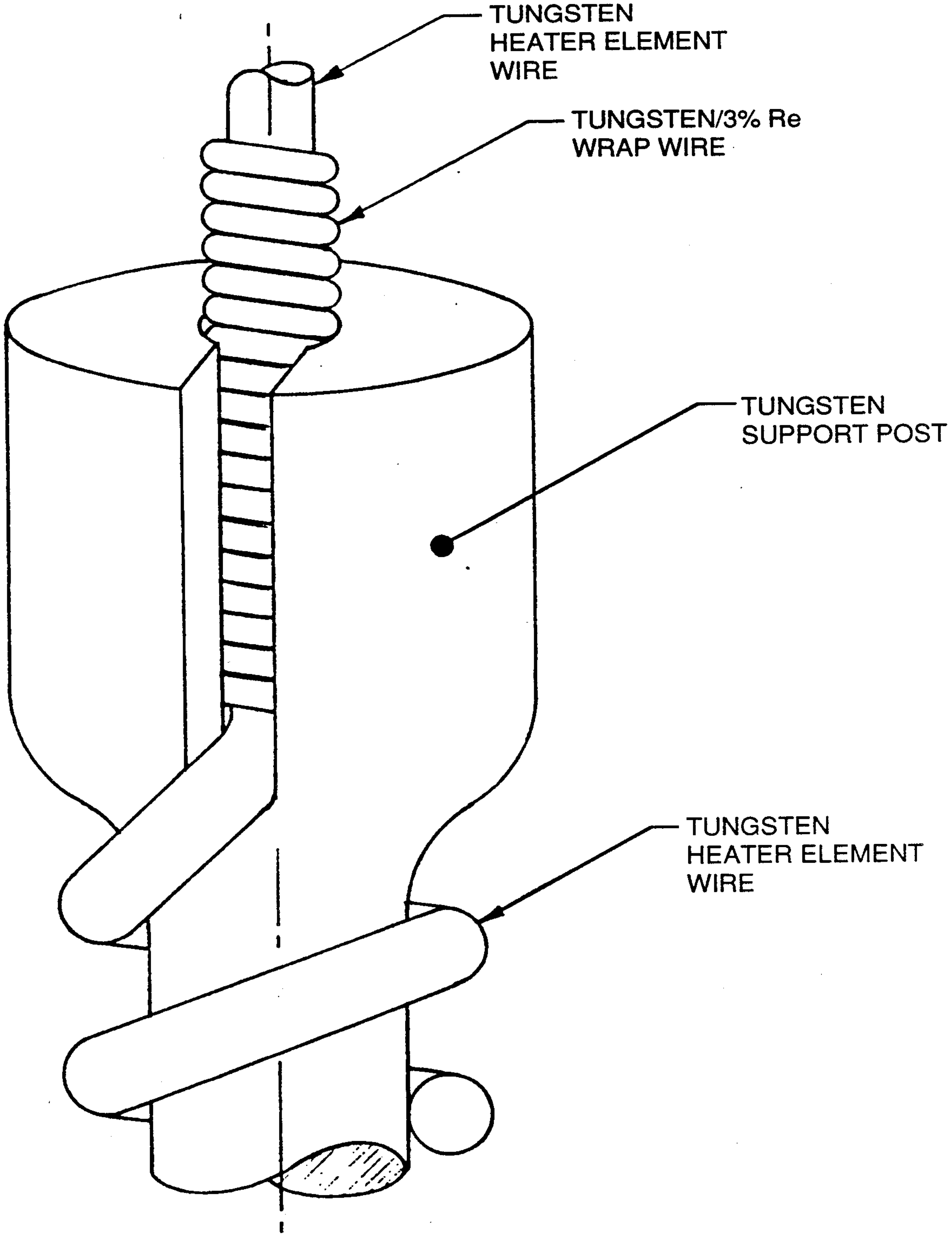
AFTER



3037-4

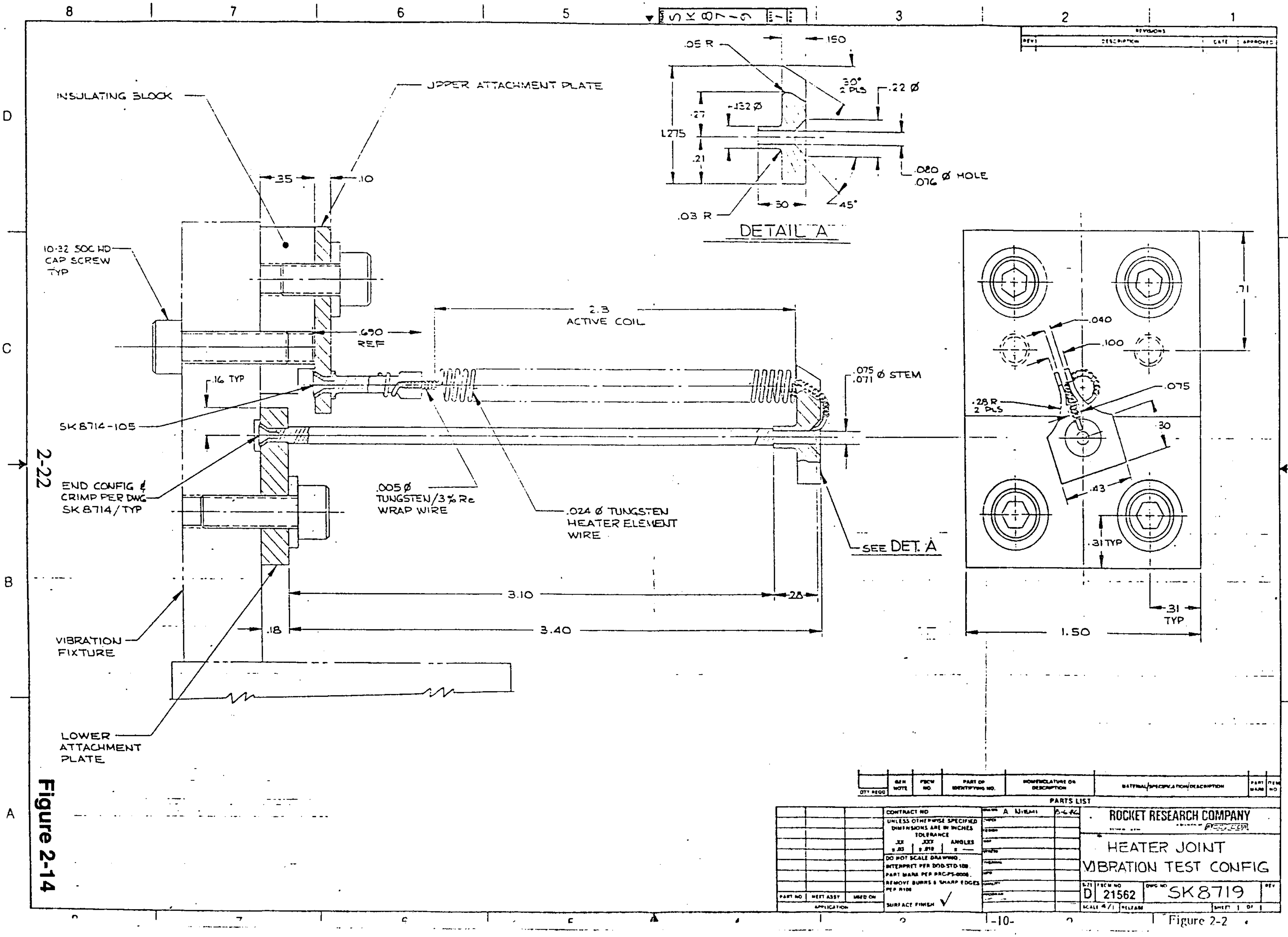
Figure 2-12

HEATER ELEMENT WIRE/SUPPORT POST HOT SQUEEZE JOINT



C11232-34

Figure 2-13


INSULATING BLOCK
UPPER ATTACHMENT PLATE
.35
.10
10-32 SOC HD CAP SCREW TYP
.690 REF
.16 TYP
SK 8714-105
END CONFIG & CRIMP PER DWG SK 8714/TYP
VIBRATION FIXTURE
LOWER ATTACHMENT PLATE
.18
3.40
3.10
.28
2.3 ACTIVE COIL
.005 Ø TUNGSTEN/3% Re WRAP WIRE
.024 Ø TUNGSTEN HEATER ELEMENT WIRE
.075 .071 Ø STEM
SEE DET. A
.05 R
.150
30° 2 PLS
.22 Ø
.27
.132 Ø
1.275
.21
.080 .076 Ø HOLE
.30
45°
.03 R
DETAIL A
.71
.040
.100
.075
.28 R 2 PLS
.30
.43
.31 TYP
.31 TYP
1.50
SK 8719
PARTS LIST
QTY REQD
GEN NOTE
FSCM NO.
PART OR IDENTIFYING NO.
NOMENCLATURE OR DESCRIPTION
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CONTRACT NO
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TOLERANCE
.XX ±.03
.XXX ±.010
ANGLES ± —
DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RRC-PS-0008.
REMOVE BURRS & SHARP EDGES PER R100
SURFACE FINISH √
PART NO
NEXT ASSY
USED ON
APPLICATION
A. Nieami
5-6-86
ROCKET RESEARCH COMPANY
HEATER JOINT
VIBRATION TEST CONFIG
D
FSCM NO 21562
DWG NO SK8719
REV
SCALE 4/1
SHEET 1 OF 1
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
-10-
Figure 2-2
A
B
C
D
1
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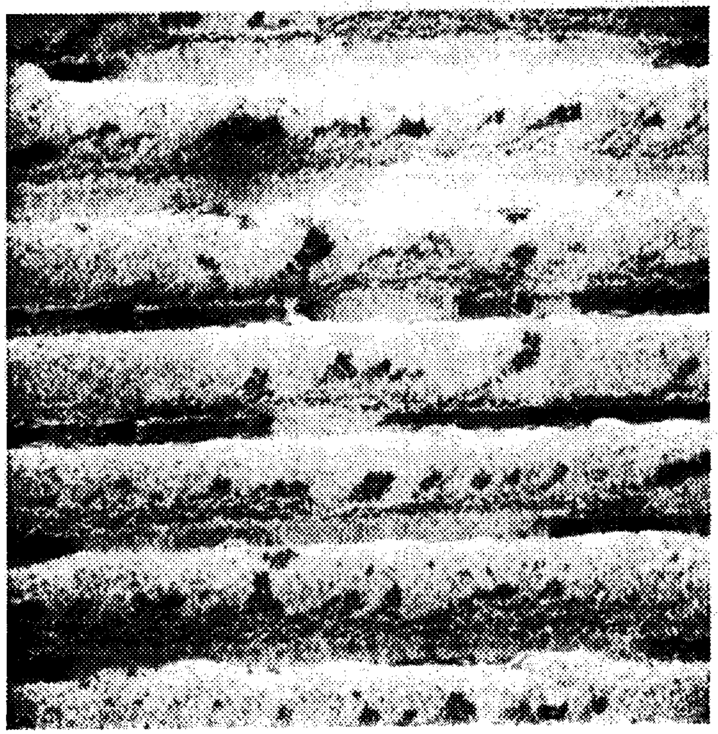
5
6
7
8

Figure 2-14

HEATER CAVITY SURFACE ENHANCEMENT SAMPLE EMISSIVITY MEASUREMENT RESULTS

Sample No.	Surface Preparation	Emissivity
1	AS-MACHINED LIGHT GROOVES ETCHED	0.32
2	AS-MACHINED SMOOTH ETCHED	0.34
3	GROOVED TCHED	0.34
4	ETCHED CVD TUNGSTEN	0.49

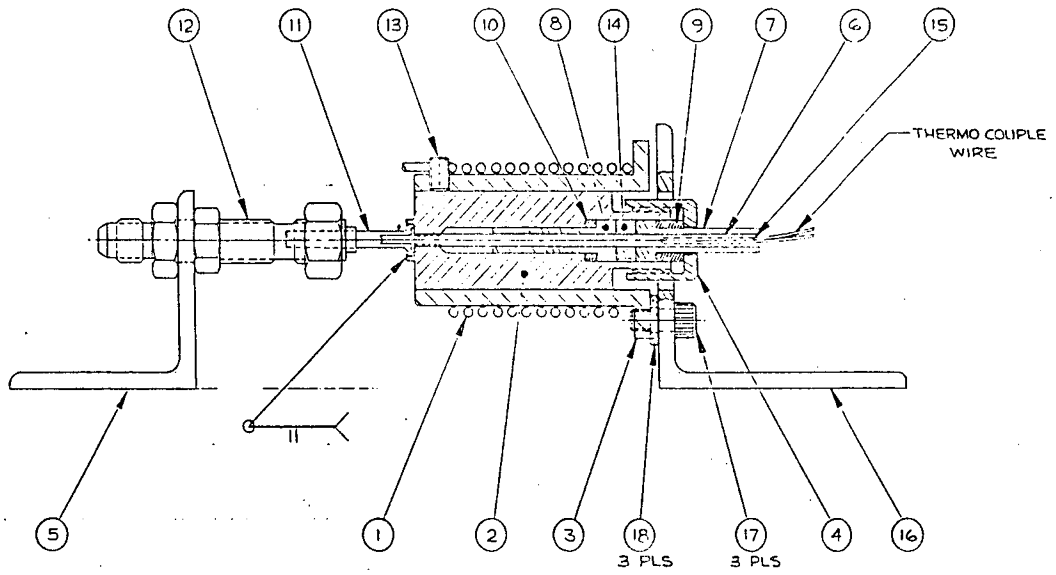
SEM PHOTOMICROGRAPH OF GROOVED AND CVD TUNGSTEN COATED CYLINDER INTERIOR SURFACE



48X

Figure 2-15

11181-84A



3			——	FLAT WASHER NO. 8	1/16 THICK
3			——	8-32 SOC HD CAP SCREW	
1			SK8716	SUPPORT	
1			——	THERMO COUPLE	
1			——	SEALANT	BORON NITRIDE POWDER
1			MS51963-35 OR EQUIV	SET SCREW	8-32
1			2-1BUANF-2	BLKD FITTING	TYLOC (STAINLESS STL)
1			28436-101	GAS DELIVERY TUBE	
1			SK8706-102	SPACER	.100 THICK
1			SK8706-101		.220 THICK
1	1.016		-102	CERAMIC INSULATOR	MAKE FROM CONAX No. EG-187-A
1	406		-101		
1			SK8704	ROD	*TUNGSTEN*
1			——	SUPPORT	1½ × 1½ × ⅛ ALUM ANGLE
1			SK8709	ENCAPSULATING NUT	(CONAX ½-20 UNF-2B THD) REF
1			SK8705	HEATER SLEEVE	
1			SK8703	HEATER SUPPORT, TUBE SIMULATOR	
1			——	HEATER	TAYCO CERAMIC FILLED COILED TUBE 1" I.D. × 12 WRAPS
——			-301-11	——	
-301-11 QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION

PARTS LIST

REV	DESCRIPTION	DATE	APPROVED

REVISIONS

PART NO	NEXT ASSY	USED ON

APPLICATION

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± —

DO NOT SCALE DRAWING.
INTERPRET PER DOD STD 100.
PART MARK PER RRC PS-6008.
REMOVE BURRS & SHARP EDGES PER 8100.
SURFACE FINISH √

DRAWN A. NIEMI 7-31-84

ROCKET RESEARCH COMPANY
ROCKCOR

COMPRESSION SEAL
TEST FIXTURE ASSY

SIZE D FSCM NO. 21562 DWG NO SK8710
SCALE 2/1 RELEASE SHEET 1 OF 1

DWG SK8710 SHT 1 REV

Figure 2-1

-8-

Figure 2-16

2.1.3.6 Results and Conclusions from Phase I

At the end of Phase I an update to the baseline thruster design was completed. The overall configuration is illustrated in Figure 2-17. The heater design is illustrated in Figure 2-18. The heat exchanger design is illustrated in Figure 2-19. This configuration represented the best compromise of the design parameters developed in the configuration study. It was a sealed cavity design with a 1000 W nominal heater power and a rhenium heat exchanger. In most important respects it was very similar to the MR-501 configuration.

The gas generator and mount structure configuration, shown in Figure 2-17, was identical to the production design. The electrical passthrough area was different to assure that the cavity surrounding the heater was sealed. The details of these seals are discussed in subsequent sections. The nozzle shown is a trumpet configuration. A conical nozzle was actually built.

The heater configuration, shown in detail in Figure 2-18, was different than production designs. The heater filament design was the result of an optimization of wire surface area, wire-to-cavity view factor, and heat exchanger cavity size. Four parallel filaments with a grain-stabilized tungsten wire diameter of 0.025 inch was determined to be optimum. The support posts are shown hot swaged into place. More details of the post attachment will be discussed in subsequent sections. Ceramic insulators were included to allow the positive heater lead to pass through the support assembly which was at ground potential.

The sealed cavity heat exchanger, shown in Figure 2-19, was similar to production designs. The material was rhenium. The insulation system was improved to accommodate the higher temperature operation. The insulation is multi-layer molybdenum foil.

Two major areas of risk were left unresolved at this point in the program. First, the high temperature filament wire exposure tests suggested that an Isp of 360 seconds would be difficult to obtain with lifetimes greater than 100 hours. The test results had possible alternate explanations, such as water in the test fixture. However, the SEM analysis suggested that a thermal failure mechanism was most likely. Second, the inability to obtain creep data introduced risk that the heat exchanger would deform sufficiently to short out the wire.

2.2 PHASE II — RADIATIVE HEATER THRUSTER EXPERIMENTS

The original objective of Phase II was to design and conduct critical component level tests to assure reliable performance of the thrusters fabricated and tested subsequently during Phases III and IV.

Due to the limitations in material data following Phase I, Phase II was restructured to proceed immediately to thruster testing. Direct measurement of actual thruster performance promised to provide creep data on heat exchanger materials, wire compatibility data, nozzle performance data, and verification of thermal and structural models. In addition, thruster testing provided direct verification of performance estimates for component improvements identified in Phase 1.

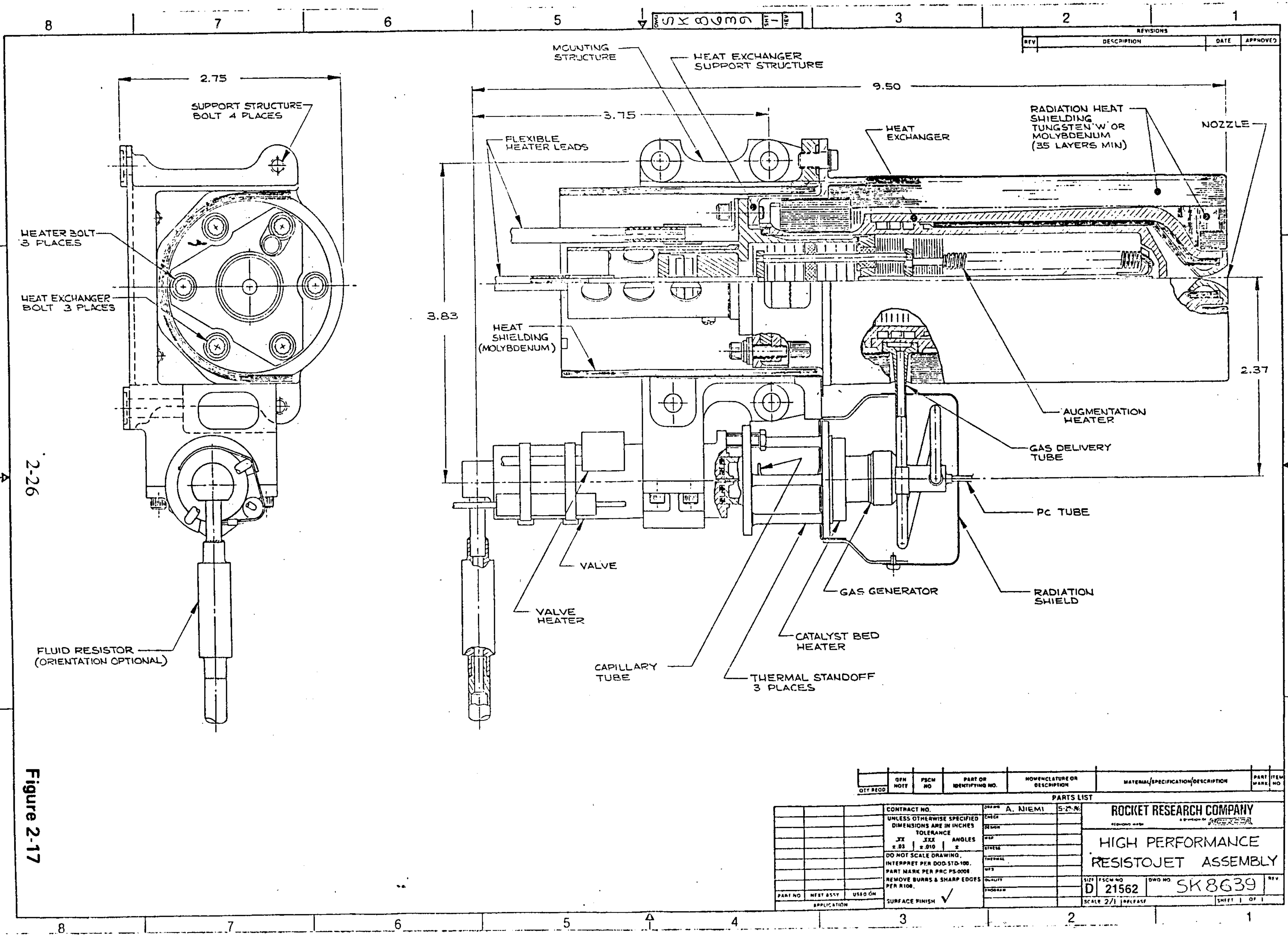

MOUNTING STRUCTURE
HEAT EXCHANGER SUPPORT STRUCTURE
9.50
3.75
2.75
SUPPORT STRUCTURE BOLT 4 PLACES
HEATER BOLT 3 PLACES
HEAT EXCHANGER BOLT 3 PLACES
FLEXIBLE HEATER LEADS
HEAT EXCHANGER
RADIATION HEAT SHIELDING TUNGSTEN 'W' OR MOLYBDENUM (35 LAYERS MIN)
NOZZLE
3.83
HEAT SHIELDING (MOLYBDENUM)
2.37
AUGMENTATION HEATER
GAS DELIVERY TUBE
Pc TUBE
VALVE
VALVE HEATER
GAS GENERATOR
RADIATION SHIELD
CATALYST BED HEATER
CAPILLARY TUBE
THERMAL STANDOFF 3 PLACES
FLUID RESISTOR (ORIENTATION OPTIONAL)
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
PARTS LIST
ROCKET RESEARCH COMPANY
HIGH PERFORMANCE RESISTOJET ASSEMBLY
A. NIEMI
D
21562
SK8639
SCALE 2/1
SHEET 1 OF 1
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE .XX ±.03 .XXX ±.010 ANGLES ±
DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER PRC PS-0008
REMOVE BURRS & SHARP EDGES PER R108.
SURFACE FINISH √

Figure 2-17

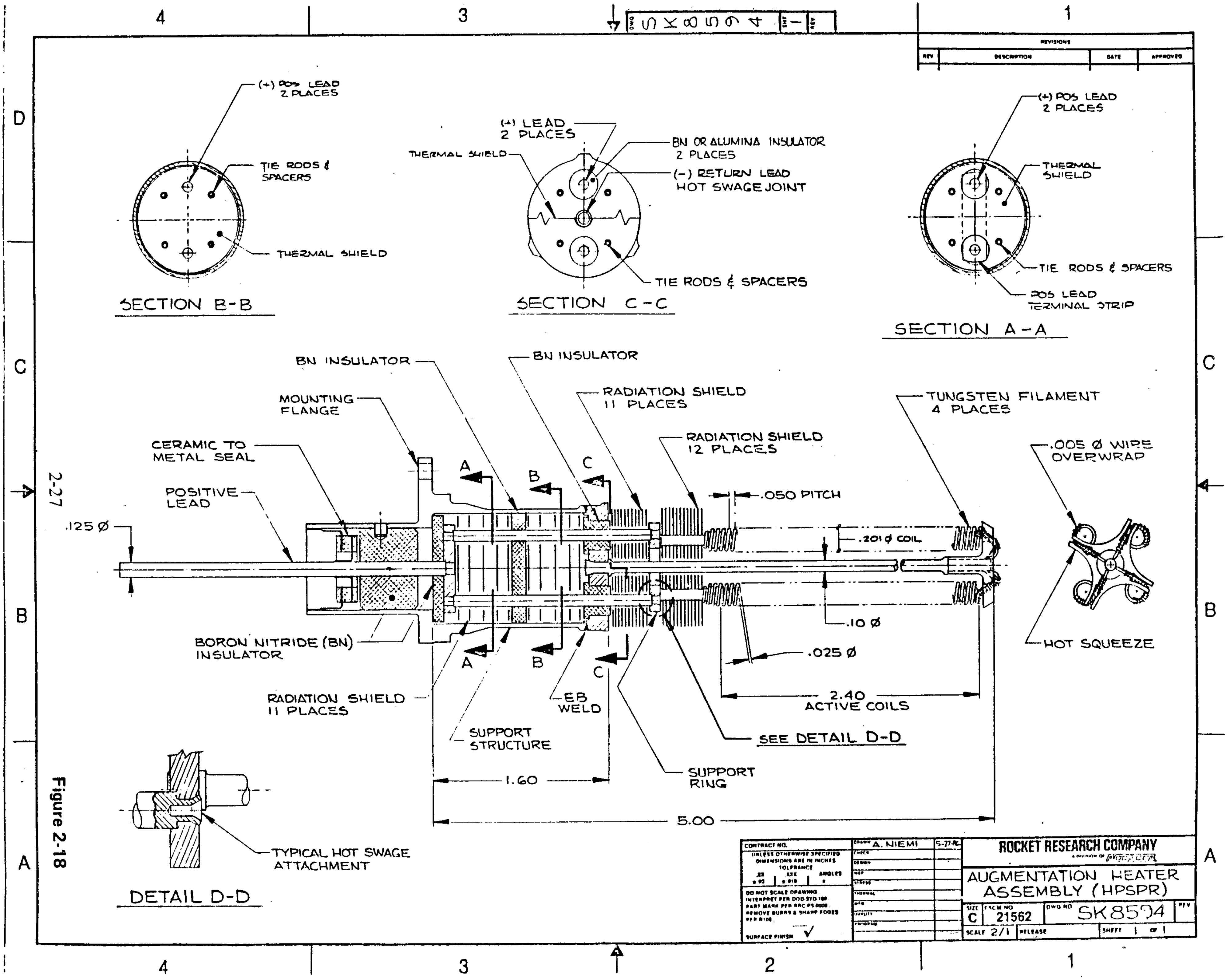

SECTION B-B
(+) POS LEAD 2 PLACES
TIE RODS & SPACERS
THERMAL SHIELD
SECTION C-C
(+) LEAD 2 PLACES
THERMAL SHIELD
BN OR ALUMINA INSULATOR 2 PLACES
(-) RETURN LEAD HOT SWAGE JOINT
TIE RODS & SPACERS
SECTION A-A
(+) POS LEAD 2 PLACES
THERMAL SHIELD
TIE RODS & SPACERS
POS LEAD TERMINAL STRIP
BN INSULATOR
BN INSULATOR
MOUNTING FLANGE
RADIATION SHIELD 11 PLACES
RADIATION SHIELD 12 PLACES
TUNGSTEN FILAMENT 4 PLACES
.005 Ø WIRE OVERWRAP
CERAMIC TO METAL SEAL
POSITIVE LEAD
.125 Ø
A
B
C
.050 PITCH
.201 Ø COIL
.10 Ø
.025 Ø
HOT SQUEEZE
BORON NITRIDE (BN) INSULATOR
RADIATION SHIELD 11 PLACES
EB WELD
SUPPORT STRUCTURE
2.40 ACTIVE COILS
SEE DETAIL D-D
SUPPORT RING
1.60
5.00
TYPICAL HOT SWAGE ATTACHMENT
DETAIL D-D
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
CONTRACT NO.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX
.XXX
ANGLES
DO NOT SCALE DRAWING
SURFACE FINISH
DRAWN A. NIEMI 5-77
ROCKET RESEARCH COMPANY
AUGMENTATION HEATER ASSEMBLY (HPSPR)
SIZE C
FSCM NO 21562
DWG NO SK8594
SCALE 2/1
RELEASE
SHEET 1 OF 1
DWG SK8594
4
3
2
1
A
B
C
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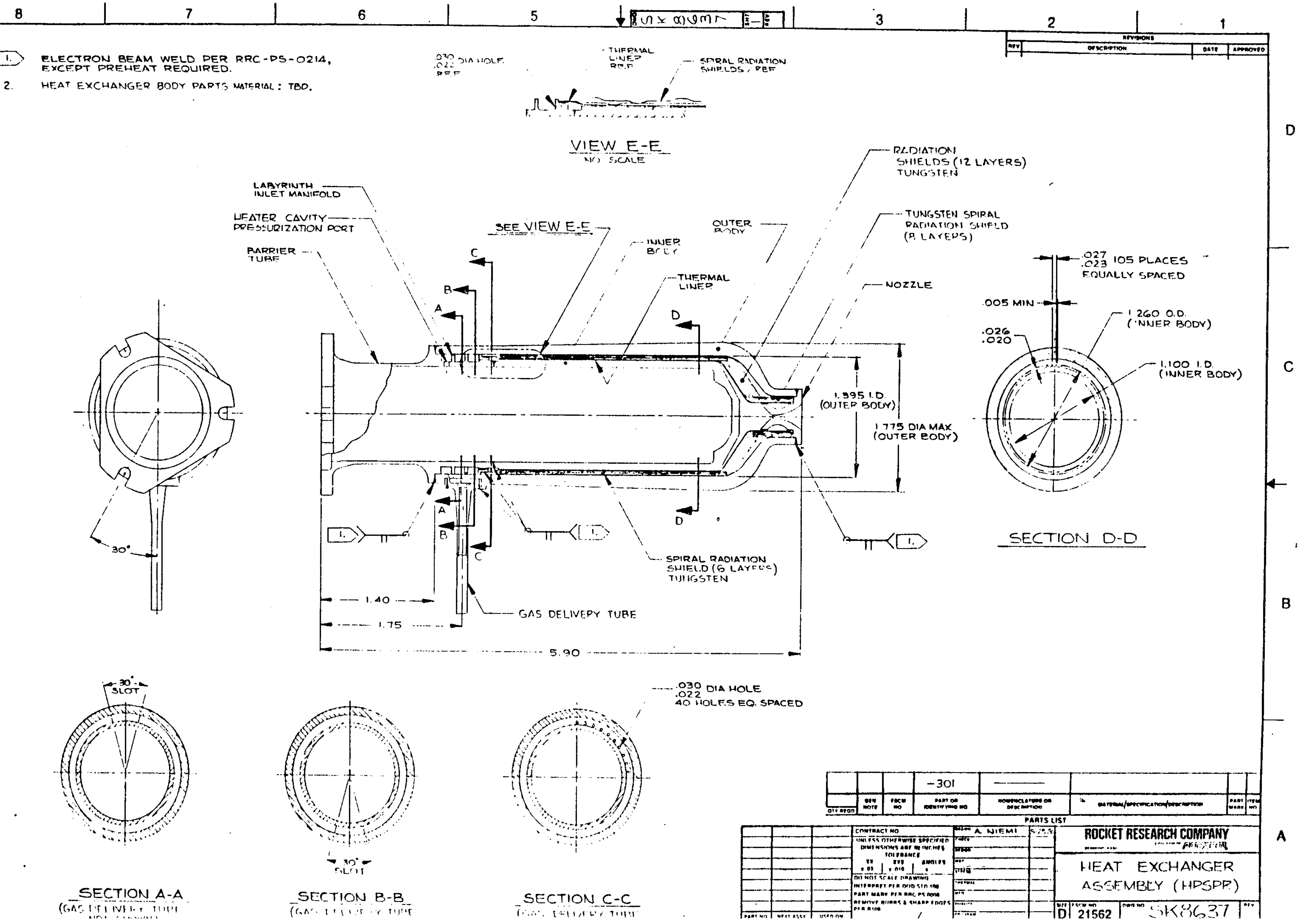
Figure 2-18


8
7
6
5
3
2
1
D
C
B
A
REVISIONS
REV
DESCRIPTION
DATE
APPROVED
1. ELECTRON BEAM WELD PER RRC-PS-0214, EXCEPT PREHEAT REQUIRED.
2. HEAT EXCHANGER BODY PARTS MATERIAL: TBD.
.030 .022 DIA HOLE REF
THERMAL LINER REF
SPIRAL RADIATION SHIELDS / REF
VIEW E-E
NO SCALE
LABYRINTH INLET MANIFOLD
HEATER CAVITY PRESSURIZATION PORT
BARRIER TUBE
SEE VIEW E-E
OUTER BODY
INNER BODY
THERMAL LINER
RADIATION SHIELDS (12 LAYERS) TUNGSTEN
TUNGSTEN SPIRAL RADIATION SHIELD (8 LAYERS)
NOZZLE
.027 .023 105 PLACES EQUALLY SPACED
.005 MIN
1.260 O.D. (INNER BODY)
.026 .020
1.100 I.D. (INNER BODY)
1.395 I.D. (OUTER BODY)
1.775 DIA MAX (OUTER BODY)
A
B
C
D
1.
30°
SPIRAL RADIATION SHIELD (6 LAYERS) TUNGSTEN
GAS DELIVERY TUBE
1.40
1.75
5.90
SECTION D-D
30° SLOT
.030 .022 DIA HOLE 40 HOLES EQ. SPACED
SECTION A-A
(GAS DELIVERY TUBE
SECTION B-B
(GAS DELIVERY TUBE
SECTION C-C
(GAS DELIVERY TUBE
-301
QTY REQD
GEN NOTE
FSCM NO
PART OR IDENTIFYING NO
NOMENCLATURE OR DESCRIPTION
MATERIAL/SPECIFICATION/DESCRIPTION
PART MARK
ITEM NO
PARTS LIST
CONTRACT NO
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TOLERANCE
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ANGLES ±
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REMOVE BURRS & SHARP EDGES PER R100
PART NO
NEXT ASSY
USED ON
A. NIEMI
ROCKET RESEARCH COMPANY
HEAT EXCHANGER ASSEMBLY (HPSPR)
SIZE D
FSCM NO 21562
DWG NO SK8637
REV

Figure 2-19

Several considerations went into making this choice:

1. The lack of material creep data at temperatures of interest introduced considerable uncertainty into the structural analyses. Since gathering the necessary data by conventional means proved to be unworkable (i.e., direct measurement from heated, stressed samples), it was decided to measure the deformation of an actual heat exchanger under representative conditions. From the measured deformation estimates could be made of the creep rate for use in further analysis.
2. Uncertainty in the actual nozzle efficiency made all performance estimates based on thermal analyses highly suspect. Actual performance measurements at conditions of interest were necessary.
3. The results of the heater wire exposure tests were inconclusive. An actual test of a filament of the appropriate configuration in a representative environment was the best available option.
4. A rhenium heat exchanger of the MR-501 design was available for use. Adaptation of this hardware to function with a sealed cavity seemed logical, even if the designs were not thermally optimal in order to learn more about the items above.

Two radiative heat exchanger thruster configurations were tested. The first was a vented cavity heat exchanger operating at a higher temperature than existing designs. The second was a sealed cavity thruster using the same heat exchanger design but modified to allow heater pressurization with decomposition gases.

2.2.1 Phase II — Hardware Support Activities

2.2.1.1 Seal Test

The heater cavity seal test is the only test from the original Phase II plan that was continued into the restructured program. Under this task seal designs developed for the sealed cavity heater were tested in the laboratory at the component level.

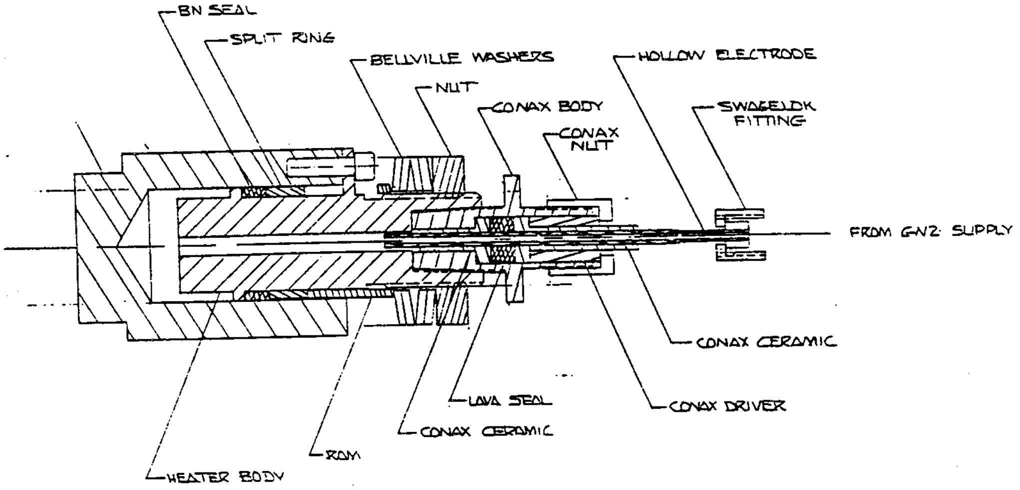
Three seals were required in the heater design:

1. Forward cavity seal
2. Conax-type electrode seal — denoted "Lava Seal"
3. Swagelok seal, connecting the hollow electrode to the pressurant gas feed system.

Of these, the most challenging was the forward cavity seal due to the severe thermal environment predicted by the thermal model. The electrode seal was located in a less severe thermal environment. Moreover, essentially identical seals had been used successfully at RRC on a number of low and high power arcjet programs, so that their viability is much less in doubt. Finally, the Swagelok-type seal was located in a still less severe thermal environment.

For these reasons, the design of the initial cavity seal tests and test fixtures concentrated on evaluation of the forward cavity seal. The seal test fixture is depicted in Figure 2-20.

SEAL TEST RIG



11232-73 **Figure 2-20**

The seal tests were conducted in a tube furnace. The following steps were performed:

1. Pressurize test cavity to 60 psig at ambient temperature
2. Close valve and monitor pressure decay for 10 minutes
3. Raise test fixture temperature to 1800°F with valve open
4. Close valve and monitor pressure decay for 10 minutes
5. Cool fixture below 200°F with valve open
6. Close valve and monitor pressure decay for 10 minutes
7. Repeat 3—6 for 10 cycles.

The baseline seal material was powdered boron nitride (BN). Other seal materials were also evaluated:

1. *Boron Nitride (BN) Split Ring*: A split ring was machined from solid HP grade BN. It was hoped that the ring could be crushed as the axial sealing force was applied to form essentially a powder seal. Formation of the powder after assembly of the seal piece parts is attractive because it will minimize contamination by BN powder of other parts of the heater. Several unsuccessful tries resulted in the conclusion that is is not possible to crush the solid BN to a fine enough powder within allowable axial force limits. Solid BN was, therefore, rejected as a potential seal material.
2. *Al_2O_3 Powder*: All seals produced with Al_2O_3 powder exhibited unacceptably high leak rates, probably due to the large initial particle size, and the failure of the axial sealing force to produce smaller particle sizes by attrition. In addition, Al_2O_3 is chemically less stable than BN at temperatures expected in the heater. For these reasons Al_2O_3 was rejected as a seal material.
3. *MgO Powder*: Unacceptable leakage occurred in all tests with this material, although this material performed better than Al_2O_3.

4. *Iron Powder*: Finely divided iron powder was tried in one test. Gross leakage occurred and testing with this material was discontinued. Also, the seal material needed to be electrically insulating.
5. *Grafoil*: A Grafoil split ring cut to the size of the test fixture cavity was tested. Leak rates were unacceptable. The problem with this approach was apparently due to the split ring, which is necessary because a complete Grafoil ring would not fit over larger diameter features at either end of the barrier tube. The majority of the leakage apparently occurred at the interface between the two ring halves. Intimate, gas-tight contact between the halves was not achievable.
6. *BN Pellets*: In order to reduce the likelihood of contamination of other parts of the heater, BN pellets were tried as an alternative to BN powder, which is rather difficult to insert into the seal cavity.

Sealing Procedure

Preliminary testing indicated that an ultimate axial seal thickness of 0.1-inch was optimal for this application, and that a 10/1 linear compression of free BN powder was required for adequate sealing. Use of the BN pellets described above allowed adequate sealing to be achieved with a manageable linear compression ratio.

After insertion of the BN pellets into the seal activity, a flat washer was installed in place of the Belleville washers, and approximately 2000 lb of axial force was applied to the pellets by tightening of the nut. It was found that this high axial force was necessary to properly crush the BN and form a tight seal. The flat washer was used because the Belleville washers are not strong enough to transmit such a high force. After seal formation the flat washer was replaced by the Belleville washers, and an ambient temperature leak test performed.

Initial testing at 1800°F was discontinued due to excessive leakage. Disassembly and inspection of the test fixture revealed that the Belleville washers, fabrication from Inconel 600, had relaxed at the test temperature. The resulting decrease in axial force had allowed the seal to leak. A second set of Belleville washers was then fabricated from TZM alloy and used in all subsequent testing. These TZM washers exhibited little or no tendency to creep in testing, so that a constant axial force of approximately 360 lbs (calibrated using a Carver press) was maintained on the BN seal. Acceptable seal performance was obtained.

Test results for the 16 cycles carried out using the TZM Belleville washers are summarized in Table 2-6. The first 11 cycles were carried out with an axial sealing force of approximately 360 lbs. The leak rate at ambient temperature and 1800°F was less than 0.01% of the expected thruster mass flow rate for all cycles.

While this leak rate was acceptable for sealing the cavity, results of thermal analyses ongoing during the early cycles of the seal test showed that the 360 lb sealing force may cause unacceptable creep deformation of the barrier tube, which forms the seal outer boundary. The axial sealing force was, therefore, incrementally reduced during the remaining 5 thermal cycles of the test, with encouraging results. Even at the final value of 50 lb the seal was effective. The leak rate was less than 0.01% of the nominal thruster mass flow rate.

Preliminary creep analysis indicated that this final sealing force, even if transmitted "hydrostatically" in the radial direction, would result in an acceptable creep deformation over a 250-hour life test of less than 3%.

Table 2-6
RESULTS OF CAVITY SEAL TEST

Cycle. No.	Sealing Force (lbf)	Ambient (scc/hr)	Leakage Rate —1800°F	
			scc/hr gN_2	%*
1	360	78	19	0.005
2	360	106	20	0.005
3	360	132	22	0.006
4	360	121	22	0.006
5	360	115	23	0.006
6	360	115	24	0.006
7	360	115	22	0.006
8	360	121	23	0.006
9	360	127	23	0.006
10	360	144	28	0.007
11	360	150	22	0.006
12	200	115	23	0.006
13	200	115	21	0.005
14	100	141	27	0.007
15	50	144	26	0.007
16	50	130	30	0.008

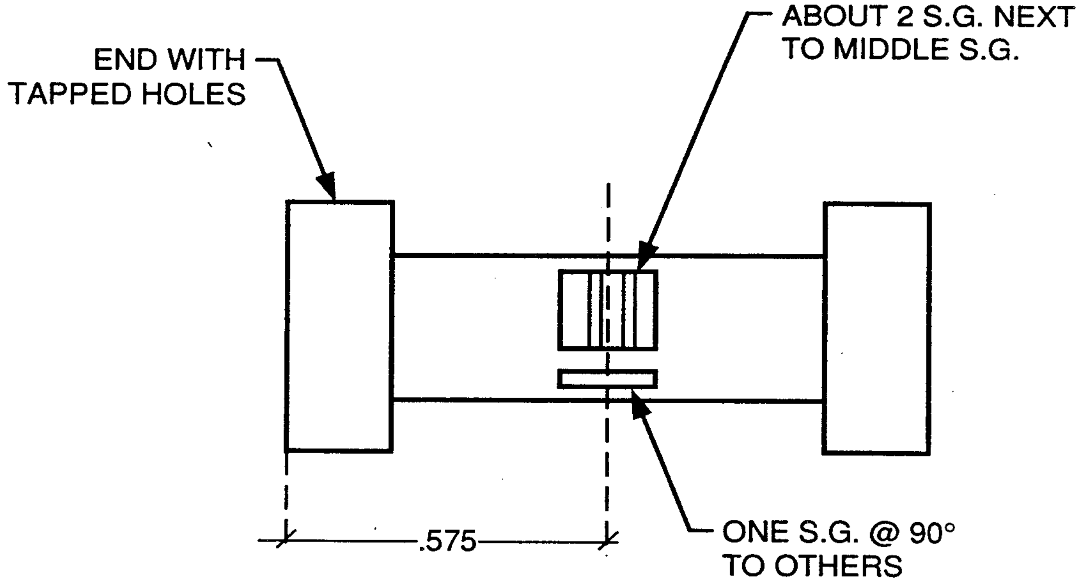
*Defined as wt% of nominal thruster flow rate of 0.45 lbm/hr.

After the seal test was completed, an attempt was made to determine whether the transfer of the sealing force through the BN seal is "hydrostatic", i.e., whether the axial pressure in the seal is equal to the radial pressure. With regard to the creep problem, "hydrostatic" force transfer was an extreme worst-case.

The seal test rig was modified slightly to measure directly the hoop stress resulting from the BN seal force on the barrier tube. The wall of the outer body of the fixture was machined to a thickness of 0.022 inch to approximate the Re barrier tube. Five strain gages were installed as shown in Figure 2-21. A BN seal was formed from BN pellets with the strain gage output monitored during and after seal formation. The maximum hoop stress during seal formation was found to be approximately 30,000 psi, substantially less than the 200,000 psi predicted for "hydrostatic" transmission of the 2000 lb axial force estimated.

The heritage of boron nitride usage at RRC suggests that the BN should remain chemically stable as well as electrically insulative during the 250-hour life test. BN insulators used in the MR-501 resistojet typically see 2300°F during continuous operation, with no apparent degradation in dielectric strength or physical integrity. Moreover, testing at RRC has taken BN samples over 3000°F for extended periods of time. A BN plug was used as a support for a tungsten heater filament during extended testing of the filament at temperatures above 3000°F. During these tests, the BN plug was in direct contact with the resistively heated tungsten filament. No apparent degradation was observed after 100 hours at 3200°F, while

STRAIN GAGE PLACEMENT ON CAVITY SEAL TEST FIXTURE



C11232-37 **Figure 2-21**

significant degradation apparently occurred after an additional 40 hours at 3400°F. All of the thermal analyses carried out to date indicate that the temperature of the key BN parts in the sealed cavity heater will not exceed 3000°F.

2.2.1.2 Sealed Cavity Heater Design and Fabrication.

The redirected phase included tasks to design and fabricate a sealed cavity heater, install the heater into the existing rhenium heat exchange, and complete the assembly of a thruster for performance and life testing.

The new heater design was based on the following assumptions:

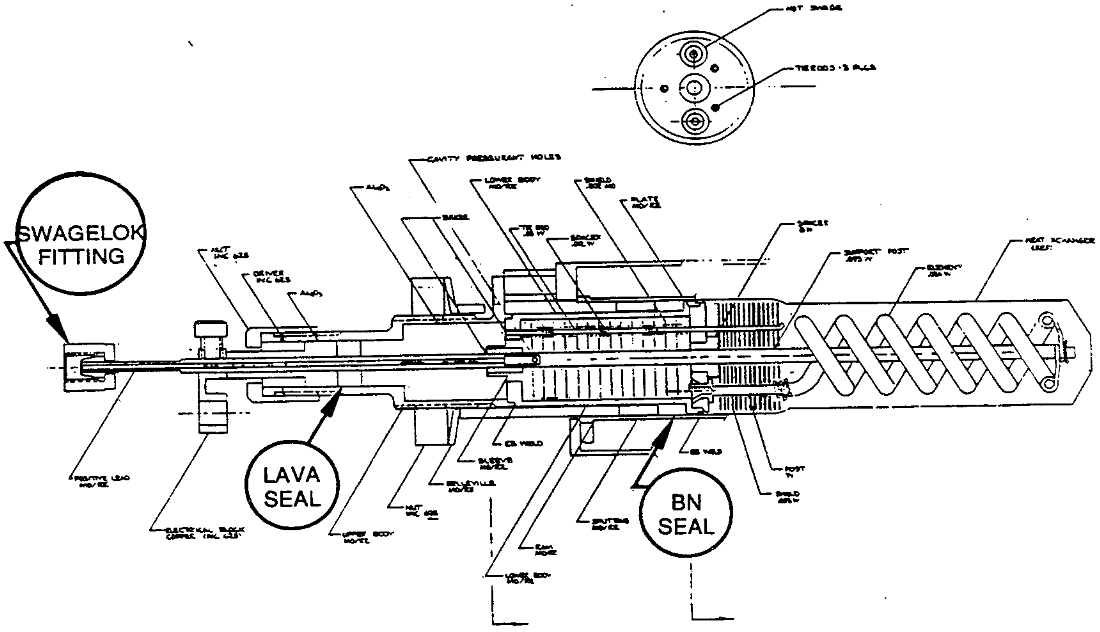
- A recrystallized heater filament fabricated in Phase I would be used. It was dimensionally inspected and the room temperature resistance was measured.
- The heater design would allow cavity pressurization with a variety of gases.

Performance and thermal analyses were conducted to determine Isp and thrust levels as a function of propellant mass flow and power. Critical component temperatures (e.g. heater braze joints) were determined over the operating range. Component level testing of designs for electrical isolation of the cavity pressurization tube as well as testing of hot swage heater support post joint techniques were also completed.

Prototype piece-parts were used to establish hot swage joint parameters prior to swaging the central rod to the heater support structure closure.

The original conceptual design for the sealed cavity heater is presented in Figure 2-22. Several notable features of this design are discussed below:

CONCEPTUAL DESIGN OF SEALED CAVITY HEATER



C11232-37

Figure 2-22

1. *Hollow Electrode Cavity Pressurization* — The cavity was to be pressurized during operation through a hollow tube, fabricated from Mo/41Re, which also serves as the positive electrode. The return electrical path is through the heater body and mounting structure. This approach has the advantage that only one pass-through at the rear of the heater is required, rather than two. Originally, it was intended to pressurize the cavity through a small hole in the inner body of the heat exchanger. The approach used had the advantage that it made no irreversible changes to the rhenium heat exchanger. An additional advantage to the approach was that it allowed pressurization of the cavity by various gases, including:

   a. Hydrazine decomposition products from the thruster gas generator.
   b. Inert gases (e.g. argon, krypton) from a separate pressurization system.
   c. Hydrazine decomposition products from a second gas generator (for test only).

   Moreover, vented cavity operation was possible simply by allowing the cavity to vent to the vacuum chamber through the hollow electrode.

   The option of pressurization with inert gases as well as hydrazine decomposition products was attractive for two reasons:

   a. Evaluation of the effect of a pressurized cavity on heater wire sublimation rates was possible, exclusive of any potential chemical interaction between the heater wire and hydrazine decomposition products.

   b. Flight designs of sealed cavity thrusters will be hermetically sealed by welding or brazing, so that seal failure will not be pertinent. The cavity seals discussed here were required for the Phase II life test only.

2. *Electrode Seal* — The electrode seal was designed as a Conax-type seal using a Conax BN pellet as the packing material.

3. *Cavity Seal* — Heater cavity seal testing was retained as part of the restructured Phase II program. The proposed design used Belleville washers to compress boron nitride powder firmly against the heater wall and the barrier tube with a split ring to effect a seal. Temperatures in the vicinity of the seal approached 3000°F.

4. *Belleville Washer* — The BN cavity seal was pressurized axially by one or more Belleville washers, fabricated from a refractory such as Mo/41Re or TZM. The axial force was necessary to allow for the effects of differential thermal expansion over multiple thermal cycles. The integrity of the washers was tested in a more severe environment than expected in the life test, since they will be brought to the same temperature as the seal itself.

5. *Connection of the Hollow Electrode to The Coil Support Post* — The electrode and support post were brazed together using a Mo/Re sleeve. A number of vent holes were incorporated into the connection to allow rapid evacuation of the cavity when the gas generator was turned on or off, so that pressure gradients across the heat exchanger inner body wall could be minimized when the heat exchanger was at high temperature.

6. *Use of* Al_2O_3 — The spacers on either side of the BN electrode seal were fabricated from Al_2O_3. This material was chosen because solid BN was thought to be too soft, and therefore not suitable to withstand the sealing pressure applied by the Inconel nut. Al_2O_3 was the next logical choice for an insulating material.

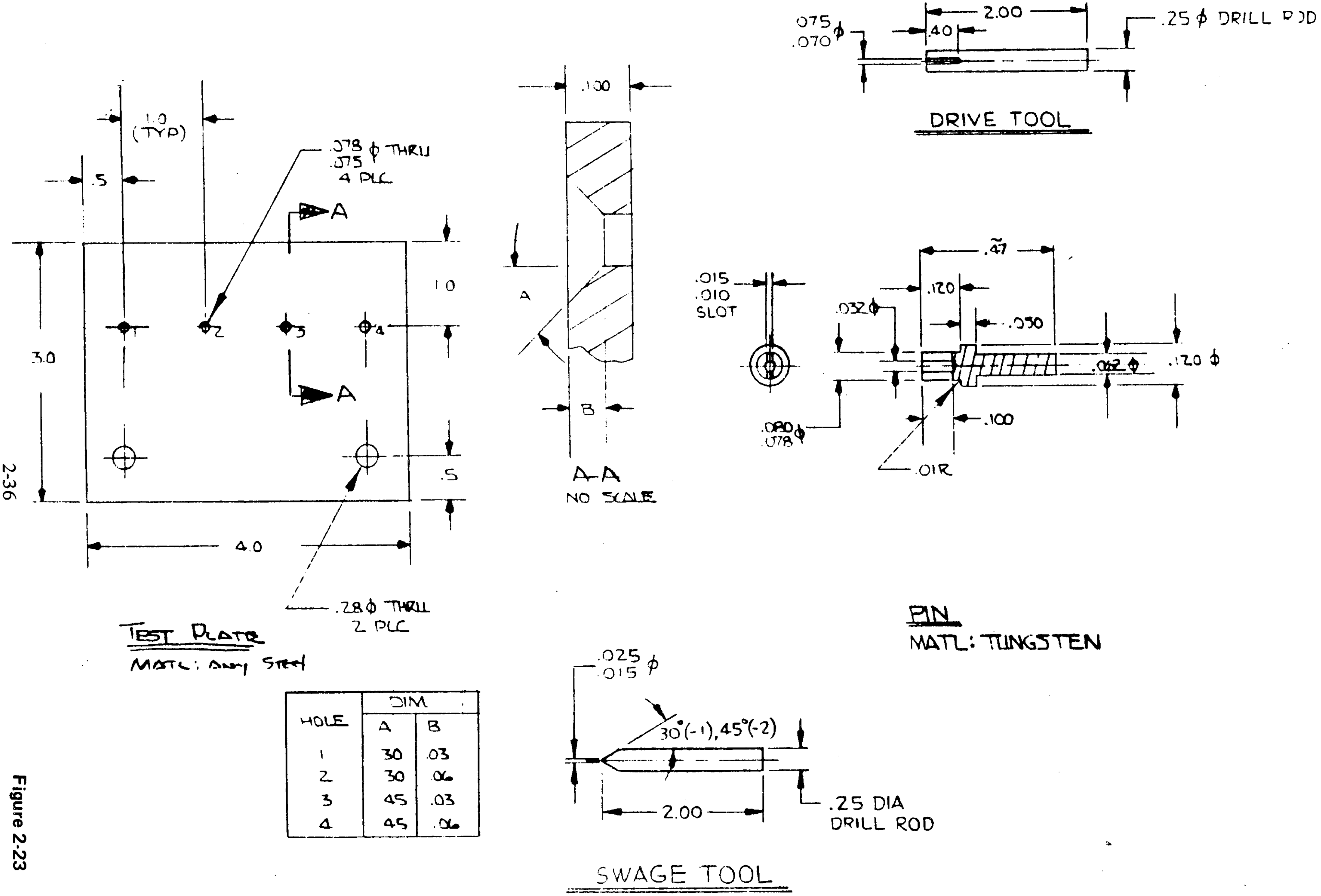
7. *Electrical Isolation of Hollow Electrode From Gas Generator* — Since the heater body acted as the return electrode, and was in electrical contact with the gas generator, the hollow electrode was isolated electrically from the gas generator (GG). This isolation was accomplished by a nonconductive fitting about two inches downstream from the GG.

Hot Swage Test (Heater Support Post)

The hot swage test fixture and test samples shown in Figure 2-23 were fabricated and hot swage testing completed. The test procedure included the following steps:

1. Tungsten pin was inserted into one of the four holes in the test plate. The drive tool was used because the pins and plate holes were designed for an interference fit.
2. The plate/pin assembly was heated to the swaging temperature with an air heat gun.
3. Swaging was attempted with an impact load using the swaging tool.

The swage tests were conducted at ambient temperature (1 pin), 350°F (2 pins), 750°F (1 pin). The results of the swage tests were disappointing at all temperatures. In all cases, severe cracking or splitting of the tungsten pins occurred at impact forces high enough to



HOLE	DIM	
	A	B
1	30	.03
2	30	.06
3	45	.03
4	45	.06

Figure 2-23

cause any bending of the "ears". The problem is the particular alloy used (tungsten/2% thoria). An alternate alloy with a specialized grain structure would be required for the swage joints to work as designed. Moreover, a specific swaging procedure would have to be developed by trial and error once the proper alloy was obtained.

Choosing the proper tungsten alloy and developing the proper swaging procedure would involve a significant effort. Therefore, design alternatives for attaching the tungsten filament support posts to the support plate were examined. Threading the posts and plate was identified as an attractive alternative and incorporated into the baseline design.

Coil Attachment Test

To evaluate methods for attaching the heater filament to the support posts, and for attaching the support posts to the support plate, a filament attachment test was conducted. The test apparatus, depicted in Figure 2-24 incorporates the threaded filament support posts as well as the filament attachment scheme depicted in Figure 2-25. The straight sections of filamented wire were to be made from 0.024-inch, sag-resistant, W/3% Re heater wire developed by RRC under an IRAD program. These sections were connected electrically in parallel, so that a poor electrical connection between a filament and post caused a readily observable difference in temperature between the two filaments.

COIL ATTACHMENT TEST – 3/10/87

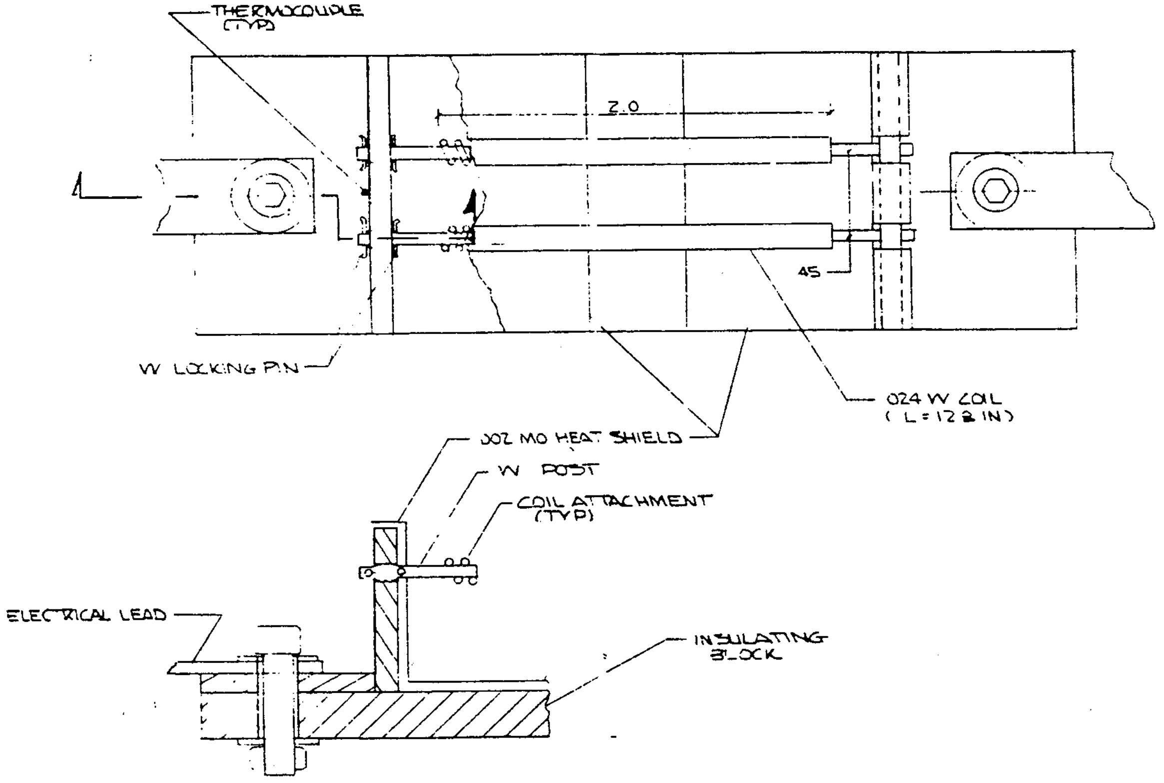


Figure 2-24

This test fixture was primarily designed to test the interference fit between the filament and support post at high temperature. Different thermal expansion rates could cause the fit to loosen at temperature, increasing the electrical and thermal resistance at the interface. With a tight fit, it was expected that diffusion bonding of the filament to the post would occur.

The fabrication and assembly of the test apparatus was accomplished without problems. Single-point machining of the threads in the tungsten support posts proved feasible, and the tight diametrical tolerances were maintained. After assembly, the test fixture was installed in a vacuum chamber such that the unit was visible through a quartz window. After the appropriate vacuum level was achieved, power was applied to the filaments at a low voltage and gradually increased while the filament temperature was monitored with an optical pyrometer. The applied voltage was stabilized when the observed filament temperature reached 4600°F, and the filaments allowed to remain at the temperature for 2 hours.

The apparatus operated as expected, with no discernable difference in brightness temperature between the support posts, indicating good electrical and thermal contact between the two filament spans. Those filaments through which support posts passed were considerably cooler than those between the filaments and posts. This contact was apparent throughout the duration of the test, indicating that little or no squirm occurred. Upon disassembly, the filaments were found to be tightly attached to the support posts. Specific examination for diffusion bonding was not undertaken due to the short test duration.

The conclusion of the filament attachment test was that the proposed filament attachment design was less complex than previous methods with no performance loss.

Heater Design Update

The heater design was updated to the design concept depicted in Figure 2-25. This update was performed to incorporate design improvement resulting from hot swage and filament attachment tests.

1. *Attachment of the Heater Coil to Support Posts*: The conical feature shown previously at the end of the support posts was removed in the updated design. The filament support posts were smooth cylinders at the filament end, with the attachment of the filament to the post occurring by interference fit. Test samples of the filament and post indicated that secure attachment could be achieved by this method at 70°F, and the assembly procedure is quite simple.
2. *Attachment of Coil Support Posts to Support Plate*: Due to the failure of the hot swage tests described above, the attachment problem was revisited, with the result that a superior attachment method was identified. The new design incorporates male and female threads on the post and support plate, respectively. Once in place, the posts were be be held securely by a short tungsten wire which passes through a hole in the post. Preliminary machining of samples at RRC indicated that the threads could be single-point machined into the tungsten posts. Tapping of the holes in Mo/41Re support plate was not expected to present any fabrication problems.

Thermal Model

A thermal model of the sealed cavity heater was completed. This model used the RRC TMG thermal analysis program, and was based on the baseline heater design shown in Figure 2-25. Preliminary runs using boundary conditions typical of test data and results of thermal models of similar engines indicated that the model predicts accurate temperature profiles at lower power levels (450 to 550 W). Runs at higher power levels were difficult to evaluate due to lack of test data. These runs did predict steady-state temperatures in excess of 3000°F at the BN cavity seal and the BN spacer at the 750 W power level.

It became evident that the sealed cavity heater model which had been developed was not accurate as a stand-alone model with arbitrary assignment of thermal boundary conditions. A model of the heat exchanger and mounting bracket surrounding the heater was required so that temperature profiles within the heater could be more accurately assessed.

It was possible to adapt an existing MR-501 thermal model for use in the thermal model of the proposed life test thruster. The previously developed thermal model of the sealed-cavity heater was inserted into an existing model of the MR-501 thruster in place of the MR-501 heater. A few minor modifications were made to the MR-501 model to more closely represent the life test thruster. For example, the heat exchanger and barrier tube thermal properties were changed to those of rhenium, the throat diameter was changed to that of the existing rhenium heat exchanger, and the radiation shield configuration was changed slightly. The model was checked against test data at 500 watts input heater power, and agreement was acceptable.

The inputs to the thermal model were flow rate and heater power. The outputs of the model included temperatures and estimates of Isp and thrust. Table 2-7 presents results of the thermal model for three cases taken as first approximations of BOL, MOL, and EOL thruster operation for a typical feed pressure blowdown cycle. Heater input power was assumed to be a nominal 750 watts. The values of feed pressure (P_f) and chamber pressure (P_c) are not used explicitly by the thermal model, but are the values necessary to give the specified flow rate.

The results presented in Table 2-7 illustrate the central performance problem encountered in the design effort. The Reynold's numbers for the flow conditions of interest were so low that lower predicted Isp efficiencies offset potential Isp gains expected for lower flow rates. In lower power resistojet designs, as flow rate decreases with decreasing feed pressure, Isp, and the internal thruster temperatures increase. These thrusters operate at Reynold's number regimes in which Isp efficiency remains essentially constant. In the present case, however, as feed pressure, and thus flow rate, decrease, the resulting chamber temperature increase did not produce the expected increase in actual Isp. The thermal model predicts that Isp values above approximately 335 sec are not attainable with the existing heat exchanger, as shown in Figure 2-26.

The performance predictions in Figure 2-26 illustrate for several power levels the decrease in performance with decreasing flow rate caused by the reduction in Isp with decreasing

PREDICTION OF SEALED CAVITY THRUSTER SPECIFIC IMPULSE AS A FUNCTION OF PROPELLANT MASS FLOW RATE FOR SEVERAL POWER LEVELS

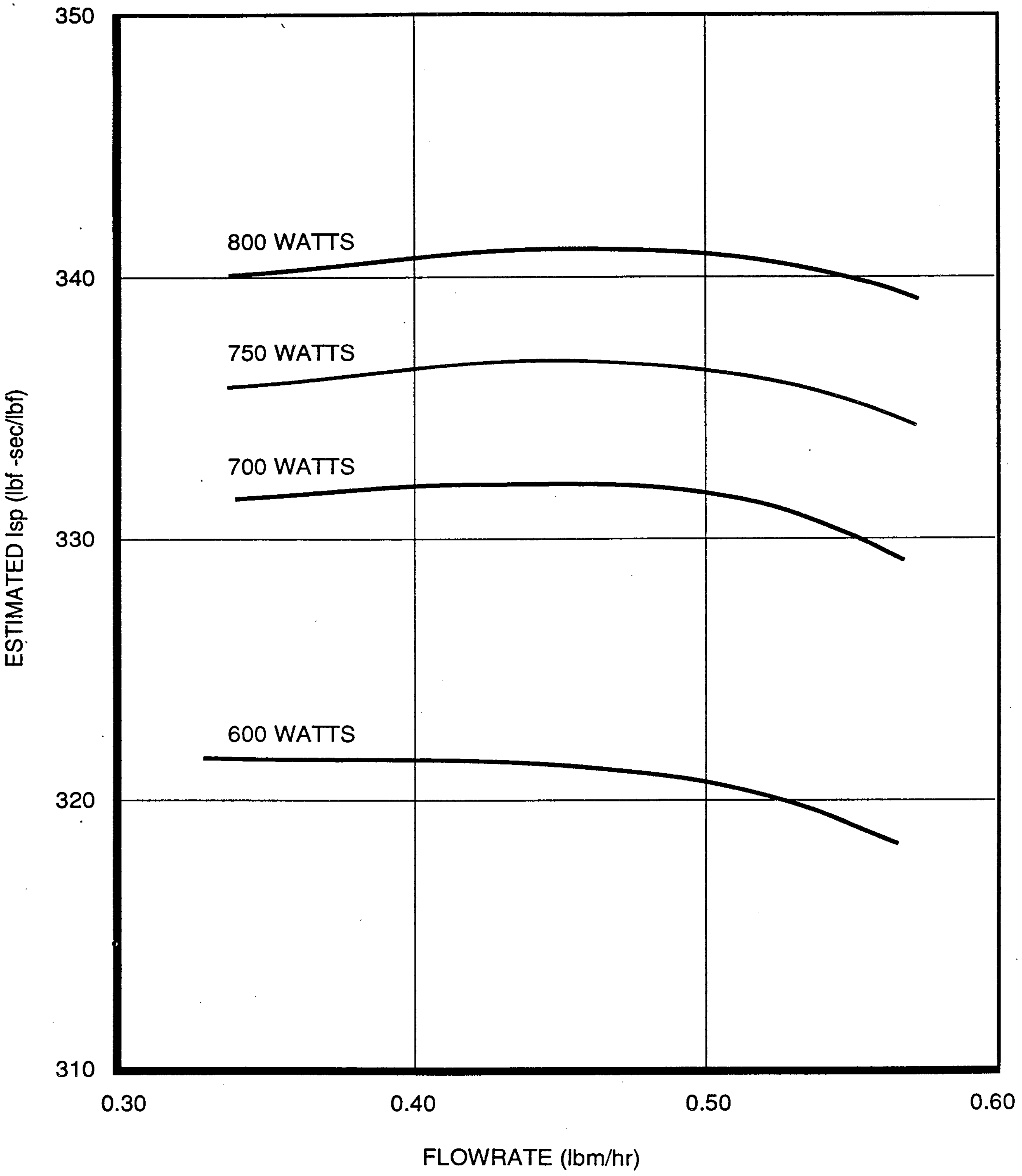


Figure 2-26

Table 2-7
PREDICTED NOMINAL THRUSTER OPERATING CONDITIONS
Typical Blowdown Cycle

Parameter	BOL	MOL	EOL
Power (watts)	763	739	724
Flow rate (lbm/hr)	0.68	0.45	0.35
Isp (lbf-sec/lbm)	337	336	335
Thrust (lbf)	0.064	0.042	0.032
Feed pressure (psia)	300	150	100
P_C (psia)	78	54	43
T_C (°F)	4250	4475	4635

Reynold's number. As the flow rate is increased above approximately 0.45 lbm/hr (at 750 watts), the predicted Isp also decreases slightly. This is due to the decrease in chamber temperature which is not overcome by an increase in efficiency.

Figures 2-27, 2-28 and 2-29 present temperature profiles within the sealed cavity heater for the three cases characterized in Table 2-7. The node number column is denoted by a "#", and the temperature column by an °F. Of particular interest in these profiles are the temperatures of the BN parts, the heater filament, and the heat exchanger outer body.

As with all parts of the heater, the BN spacer temperature (node 7031) increases with feed pressure blowdown. The spacer temperature starts at approximately 2850°F, and increases to approximately 3150°F at the end of life. The spacer average temperature was predicted to be approximately 3050°F. Thus during the entire life test, the spacer temperature was predicted to be below the temperature at which the successful operation of BN in contact with tungsten was demonstrated for 100 hours. The predicted temperatures of the BN cavity seal near node 7044 range from 2500° to 2760°F, well within the range of apparent material stability.

Predicted heater filament temperatures at the nozzle end (node 1100) range from 4560° to 5050°F, with an average of approximately 4920°F. These temperatures are well into the range at which tungsten sublimation retardation would be required to prevent premature heater failure.

Heat exchanger outer body temperatures (nodes 2222 and 2224) ranged from approximately 4100° to 4600°F. Combined with the chamber pressures necessary to achieve the required flow rates, these temperatures could cause unacceptable creep during the 250-hour life test.

In cases that matched performance predictions to previous data, the thermal analyses discussed above show that the sealed-cavity heater design is less efficient that a flight-type design would be, primarily due to the more massive components necessary to effect an

CASE 38

Heater Power	(watts)	72.4
Flowrate	(lbm/hr)	0.346
Exit gas temp.	(°F)	4647
Heat Loss	(watts)	466
Estimated Isp	(sec)	333.8

"P_F = 100 psia"

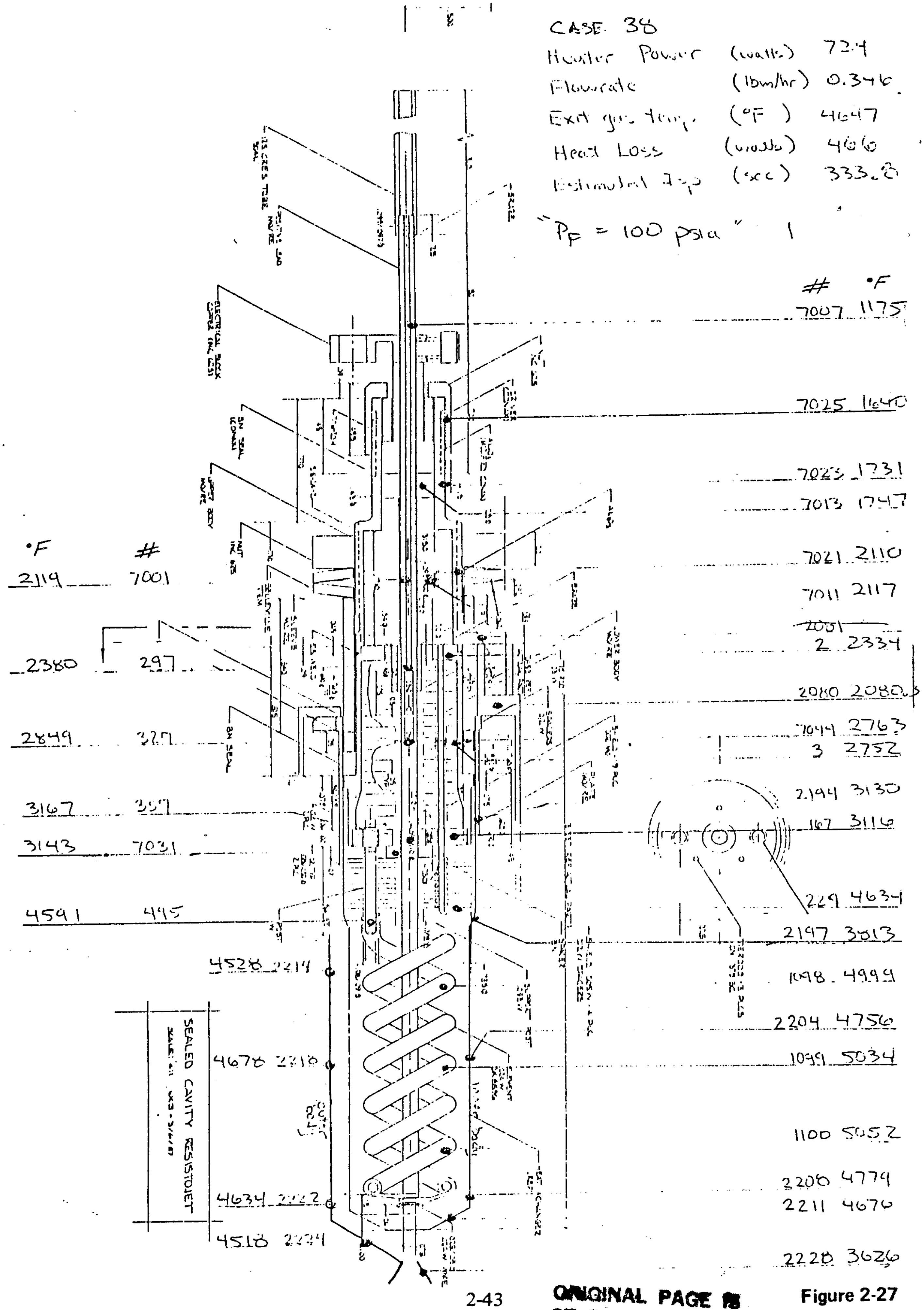


Figure 2-27

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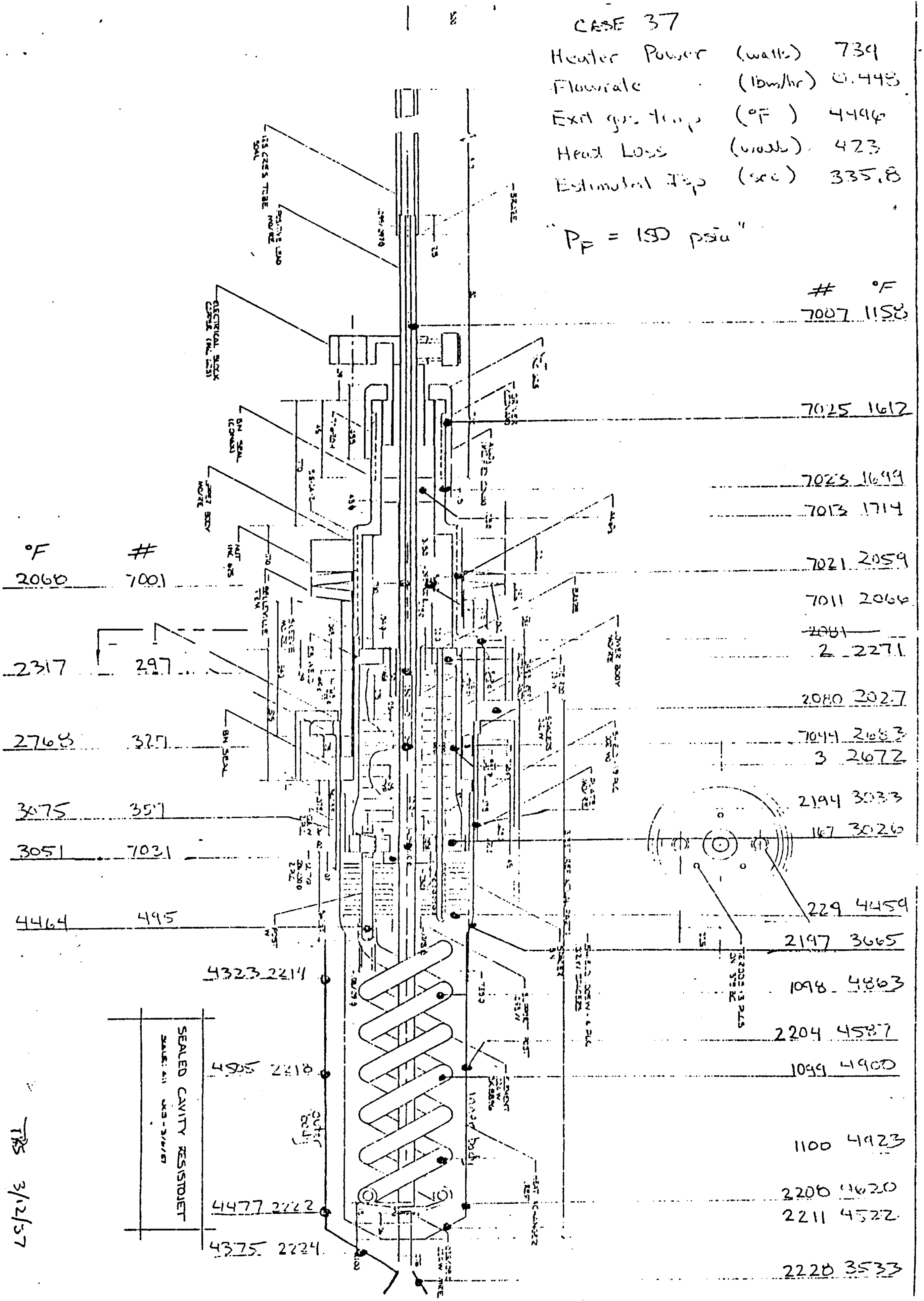
CASE 37

Heater Power	(watts)	739
Flowrate	(lbm/hr)	0.448
Exit gas temp	(°F)	4496
Heat Loss	(watts)	423
Estimated Isp	(sec)	335.8

"P_F = 150 psia"



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2-44

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Figure 2-28

CASE 36

Heater Power	(watts)	763
Flowrate	(lbm/hr)	0.679
Exit gas temp	(°F)	4166
Heat Loss	(watts)	339
Estimated Isp	(sec)	333.2

" P_F = 300 psia "

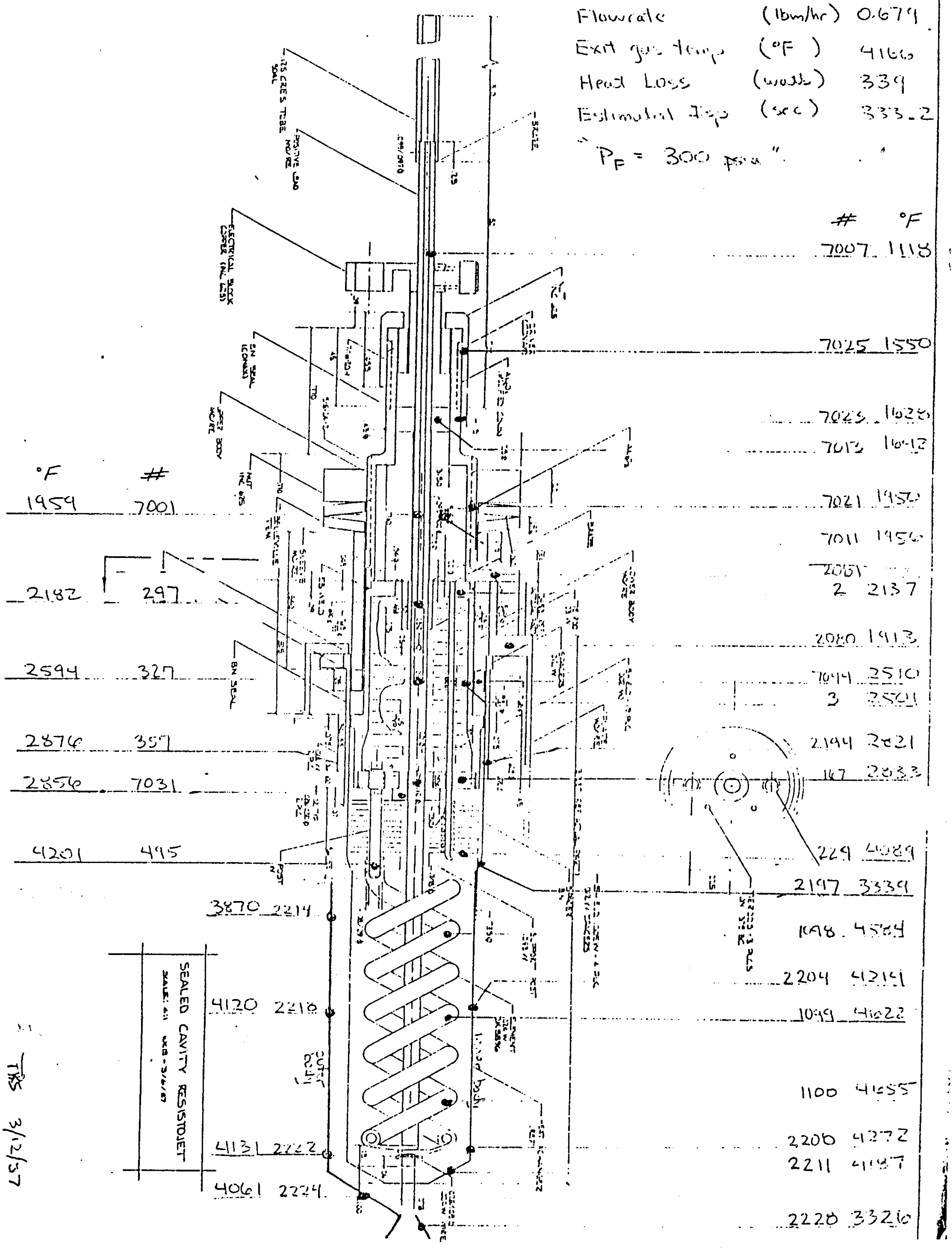

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Figure 2-29

adequate seal to the existing heat exchanger. More heat would be conducted to the rear of the heater than in a flight thruster for which the cavity seal would most likely be welded or brazed.

Structural Analysis

In the absence of a vibration requirements for the life test thruster, the most pressing structural concern was creep life of the heat exchanger outer body. Since the cavity was to be pressurized, the pressure differential across the heat exchanger inner body would be negligible during steady-state operation, and creep was not a concern for this component. The outer body of the rhenium heat exchanger, however, was not designed to withstand the combination of temperature and pressure predicted by the analyses described above.

The empirically derived algorithm used at RRC to predict creep rates in rhenium may be written, for constant stress and temperature, as:

$$\varepsilon = 177.8\,[e^{-4.96\,E4/T}]\,[\tau^{1.727}] \text{ x } t$$

where:

ε = strain, in./in.
T = temperature, °F
τ = stress, ksi
t = time, hr

The outer body creep predicted for the 250-hour life test using the above algorithm is given in Table 2-8. Typical margins for flight-qualified resistojets are less than 5% creep over the component life. The predicted 250-hour total creep for the heat exchanger outer body far exceeds this guideline.

Table 2-8
PREDICTED 250-HOUR CREEP
HEAT EXCHANGER OUTER BODY

Pressure (psi)	Temperature (°F)	Strain Rate (%/hr)	Total Strain (250 hrs) (%)
78	4200	0.09	22
54	4500	0.10	25
43	4650	0.10	24

Even considering the uncertainty in the creep algoritm, these creep predictions were cause for concern. A further examination of this problem was conducted. An estimate was made of the performance degradation necessary to remain within creep margins during the life test. Further evaluation of the Isp efficiency correlation used in the thermal model was conducted. Small changes in the predicted outer body temperatures can result in substantial changes in the predicted outer body temperatures which are driving the predicted creep rates to unacceptable levels. The test of this design is described in paragraph 2.2.3, but the duration of the test was not sufficient to validate creep performance.

2.2.2 "Fast Track" Test

The so-called "fast track" test was added to the program to provide testing of important design elements in a vented cavity design, as well as to provide vented cavity heater performance data as a benchmark for comparison with sealed cavity heater performance data.

The fast-track test was undertaken to supplement the performance predictions of the thermal model. Questions regarding the use of the Isp predictions in the thermal model remained. These preidctions were based on cold-gas experiments, and their applicability at high temperatures was uncertain.

The configuration on which the rhenium heat exchanger was based had been tested at RRC at power levels up to 600 watts but not at the low flow rates, and thus low Reynold's numbers anticipated for the life test unit. RRC therefore proposed to NASA LeRC that vented cavity testing at power levels and flow rates typical of the life test unit be undertaken.

The rhenium heat exchanger assembly, including the mounting bracket, valve, and viscojet, were used in the fast-track test, along with a standard design EHT heater borrowed from an in-house program. This heater had been recently rebuilt, and the filament had not had power applied except for initial checkout during assembly. After assembly, the thruster was mounted on RRC's pendulum balance thrust stand in a vacuum test chamber.

Each test at power levels >500 W typically lasted only 15 minutes in order to minimize filament sag and to avoid unnecessary stress on the rhenium heat exchanger. After an initial thrust stand calibration, the thruster was run for approximately 15 minutes at a power setting of 500 watts for warm-up to minimize the operating time at high power. The thruster was run at high power only until the measured performance stabilized, at which time a 2-minute data acquisition sequence was initiated. After data acquisition was complete, the heater was shut down. The gas generator was run for an addition 2 minutes to avoid damage to the valve due to thermal soakback. After the gas generator was shut down, the thrust stand was recalibrated and automatic data reduction of the HP controller commenced.

A total of 33 runs were carried out during the fast-track test program. The results of these runs are summarized in Table 2-9. Figure 2-30 presents a plot of measured Isp as a function of heater power. Included in this figure for comparison are the results of previous testing of the same heat exchanger at lower power levels.

Much performance data were obtained in these tests at power levels higher than any previously performed with resistojets. Specific impulse levels near 350 seconds were demonstrated.

2.2.3 Sealed Cavity Test

The most important technology demonstration planned for the restructured Phase II effort was a 250-hour life test of a sealed cavity resistojet. This test was planned to utilize the existing rhenium heat exchanger and the sealed cavity heater designed and fabricated during Phase II.

Table 2-9
FAST-TRACK TEST RESULTS

Run No.	Power (watts)	Flow Rate (lbm/hr)	Thrust (mlbf)	T-Heater (°F)	Isp (lbf-s/lbm)
7	500	0.475	40	4265	303
2	500	0.477	41	4287	307
12	500	0.477	40	4223	304
15	500	0.467	39	4252	301
17	500	0.468	40	4241	313
20	500	0.651	58	4099	319
21	500	0.474	40	4262	305
29	500	0.465	39	4225	302
3	600	0.470	41	4551	317
4	650	0.460	41	4668	323
5	656	0.531	47	4532	322
6	750	0.445	40	4836	324
8	750	0.445	50	4787	336
11	751	0.431	39	4862	330
14	751	0.449	41	4850	328
18	751	0.547	49	4789	328
22	750	0.636	58	4711	328
24	750	0.633	60	4697	342*
26	751	0.632	57	4701	328
30	750	0.541	50	4724	330
33	747	0.569	53	4768	337
9	800	0.542	50	4881	333
10	801	0.431	40	4895	336
13	800	0.456	42	4906	334
19	800	0.537	50	4555	336
23	800	0.650	61	4792	338
25	800	0.641	60	4796	340
27	855	0.660	62	4751	339
28	850	0.652	61	4799	338
32	848	0.542	52	4975	348

*Probably spurious

SPECIFIC IMPULSE AS A FUNCTION OF POWER

RHENIUM RESISTOJET
BASELINE PERFORMANCE

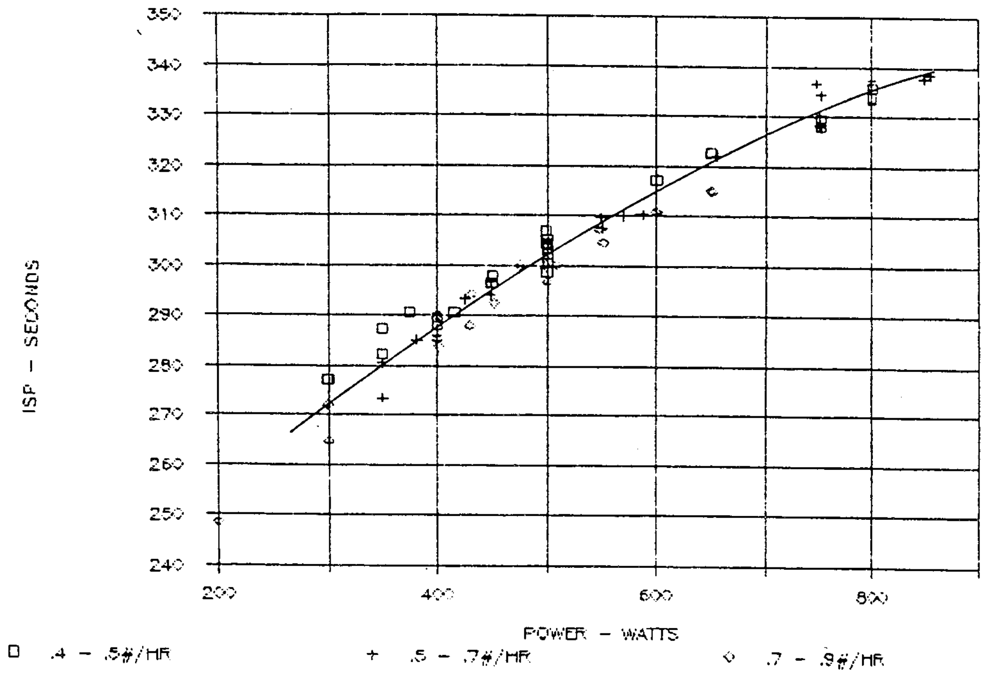


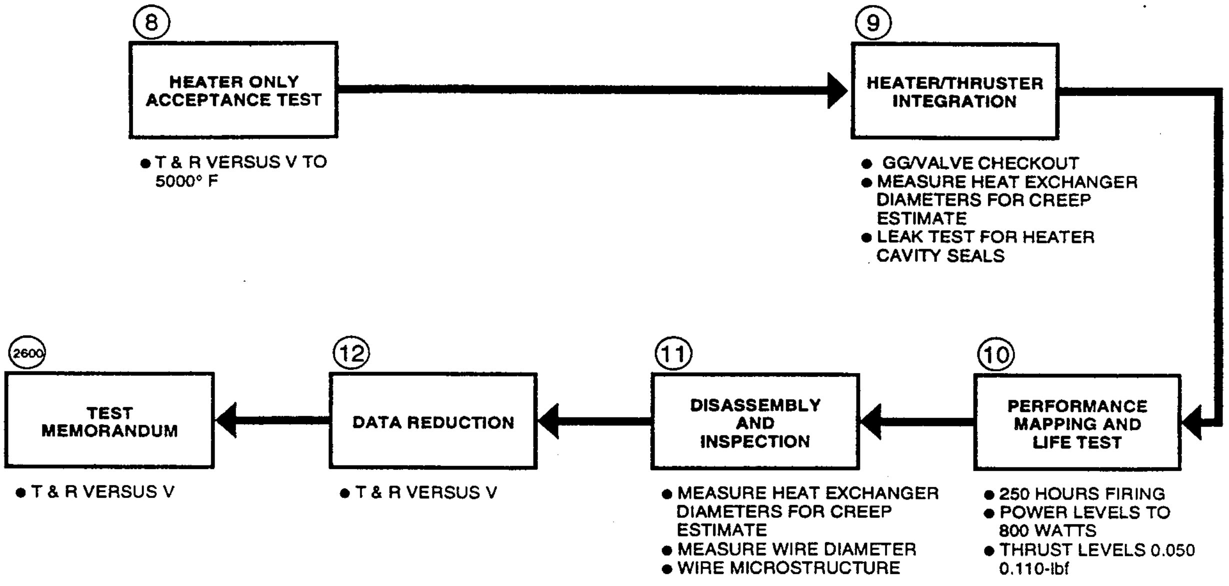
Figure 2-30

The objective was to test the sealed cavity heater in the rhenium heat exchanger for 250 hours at flow and power levels typical of spacecraft operation. High-purity hydrazine propellant was utilized. Wire temperatures necessary to achieve 330 to 340 seconds Isp were expected to cause significant sag, even with sag-resistant wire. An electric motor was used to rotate the test bed 180 degrees after each run was used during life testing to counteract the effects of sag. The test flow plan is given in Figure 2-31. The thruster was to be tested on a thrust stand during pretest and post-test performance mapping as well as during health checks after 100 and 200 hours. During the remainder of the life test, the thruster was to be attached to the rotator and not the thrust stand. Chamber pressure and flow rate were measured to calculate characteristic velocity for performance assessment during the periods the thruster was not on the thrust stand.

A check-out test of the heater was performed prior to installation into the rhenium heat exchanger. An existing fixture with cooled walls and a view port to measure the wire temperature was used. Power, resistance, voltage and wire temperature measured over the operating range were within acceptable limits.

**PHASE II SEALED CAVITY HEATER,
RHENIUM HEAT EXCHANGER TEST FLOW PLAN**

TASK 2900



C11232-30 **Figure 2-31**

2.2.3.1 Thruster Assembly

The sealed cavity heater fabrication and assembly was completed, and the heater was installed in the rhenium heat exchanger to complete the life test thruster assembly. Key areas of activity included the following:

1. The modified designs of the lower body housing parts were fabricated along with suitable weld samples. After successful testing of the weld sample, the lower body subassembly was successfully EB welded to the upper body subassembly. The resulting subassembly is shown in Figure 2-32 and 2-33, after installation of the inlet tube subassembly, Conax seal, and nut.
2. The decision was made to use 0.002-in. radiation shields instead of 0.005 in. shields that proved to be difficult to fabricate. These parts were on hand. The filament ends slipped readily over the tungsten support posts and the center post. The completed assembly is shown in Figures 2-34 and 2-35. Two minor flaws are apparent from the views in these figures: misalignment of the tungsten radiation shields due to a hand operation, and a slightly misshapen configuration of the installed heater filament.
3. The heater filament was recrystallized in situ by resistance heating. The heater, as shown in Figures 2-34 and 2-35, was mounted vertically in the vacuum chamber, and the recrystallization process carried out with the filament restrained only by the support posts and the center post. Minimal squirm was observed. A flexible filament was required for mounting on the support posts.

LOWER BODY SUBASSEMBLY

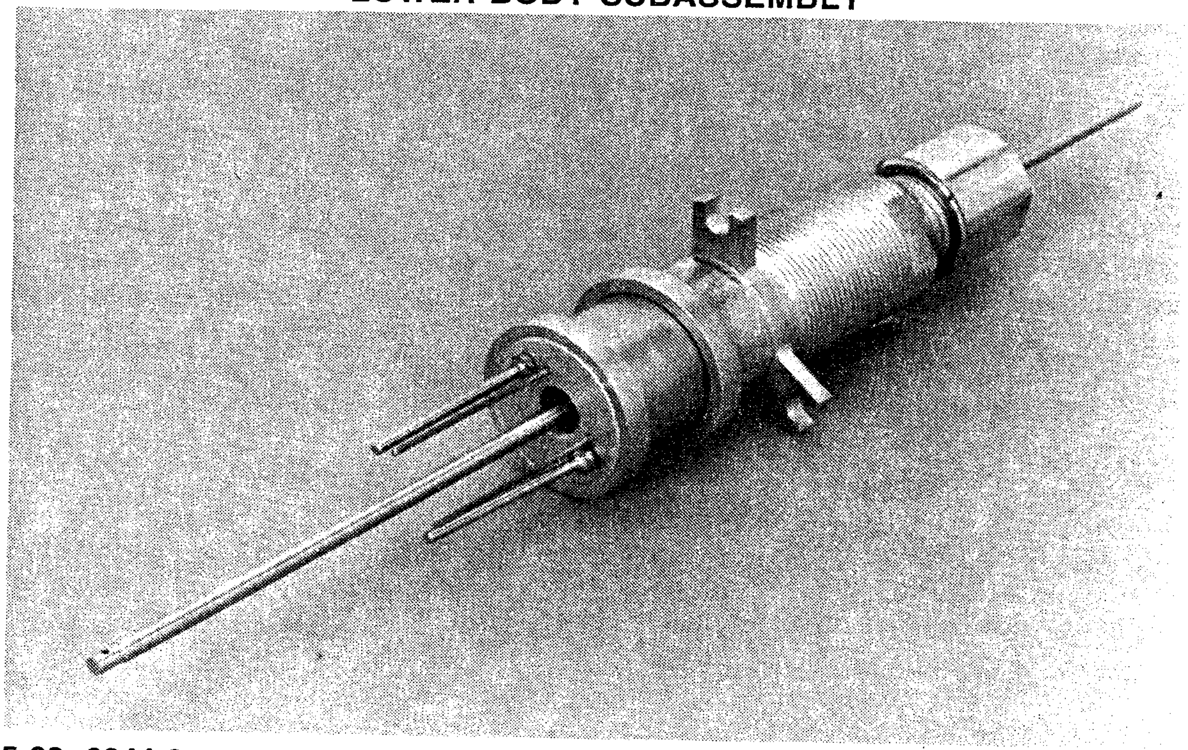


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Figure 2-32

LOWER BODY SUBASSEMBLY

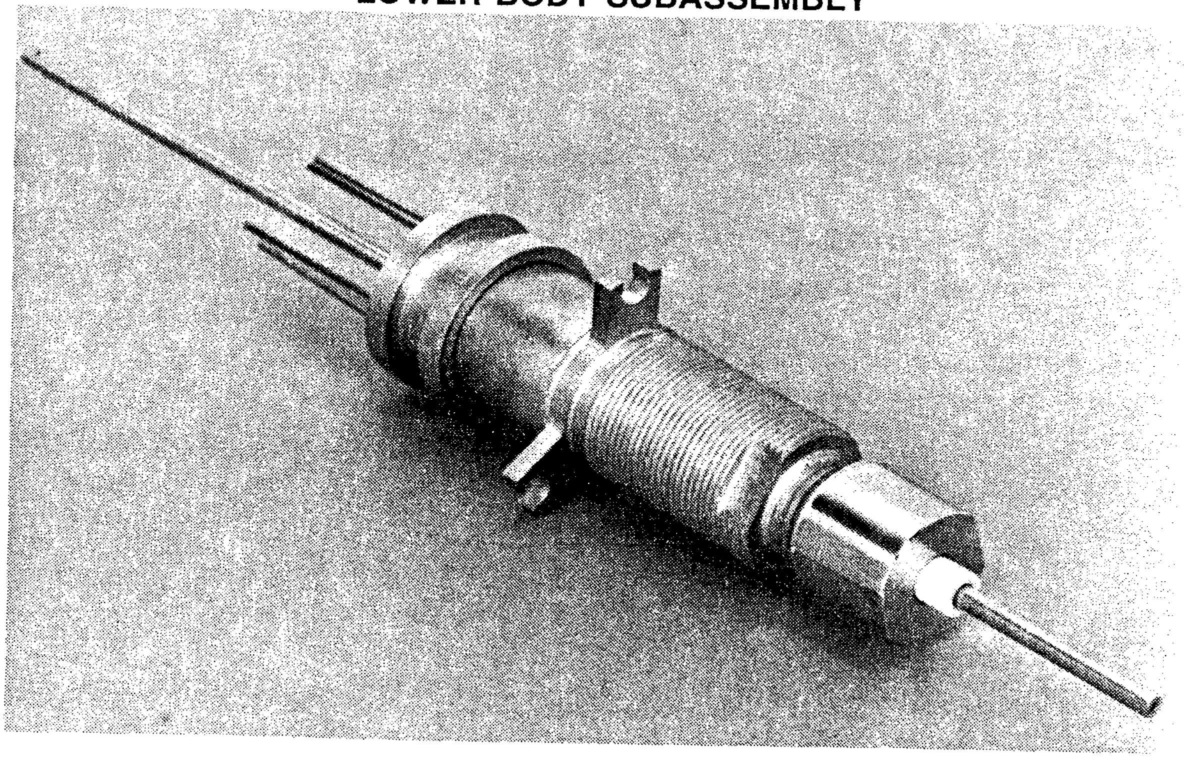

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Figure 2-33

HEATER SUBASSEMBLY

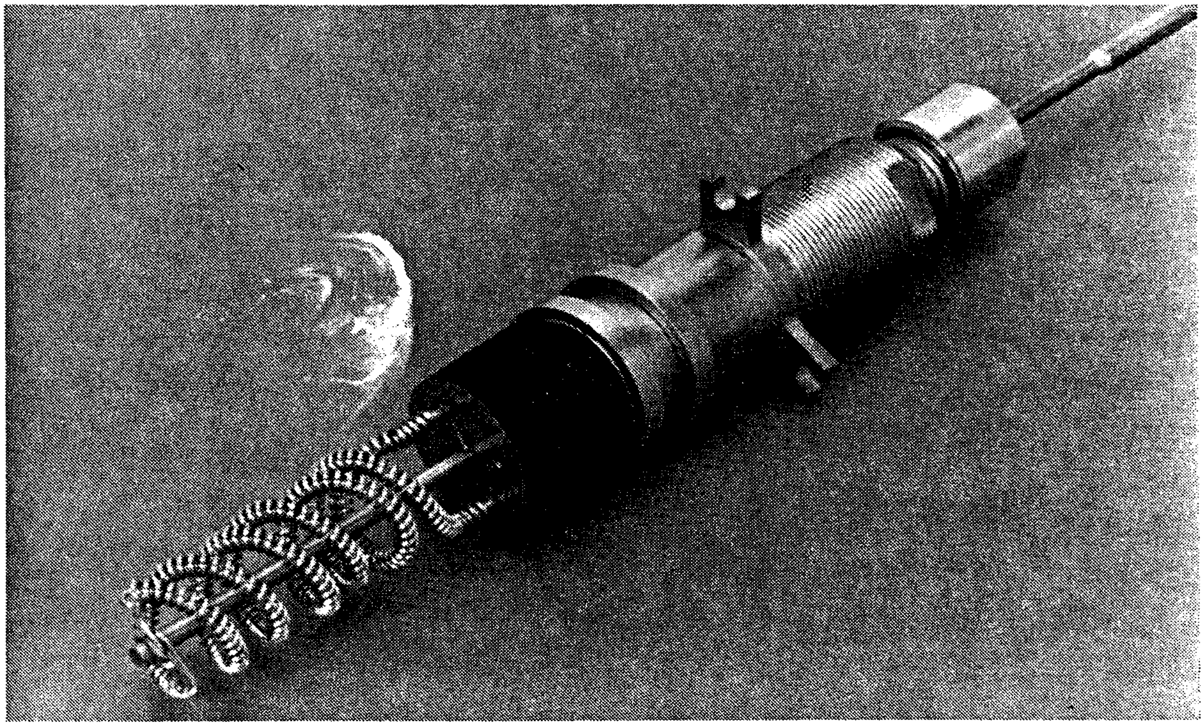

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Figure 2-34

HEATER SUBASSEMBLY

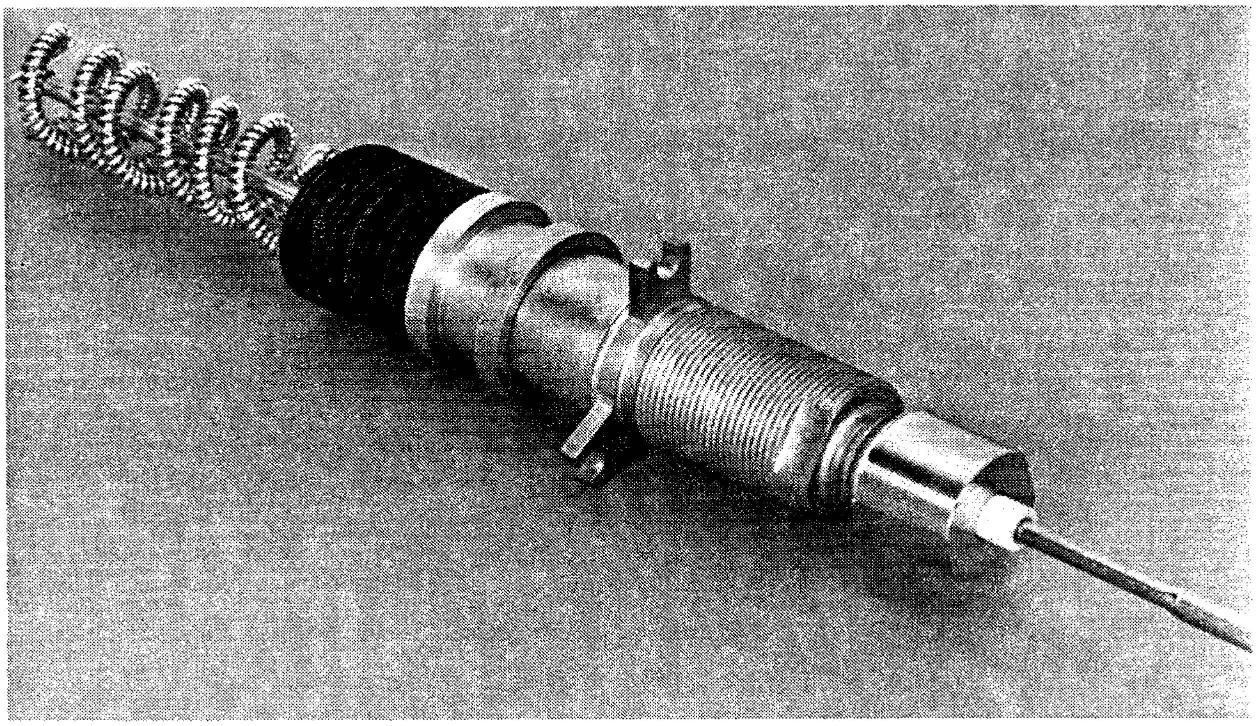

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Figure 2-35

4. The heater was installed into the rhenium heat exchanger to complete the thruster assembly. The formation of the seal was completed without incident using the procedure developed during seal testing. After connection of the P_c tap to the hollow electrode, a leak check of the sealed cavity indicated a leak rate similar to those measured during the seal testing. Use of BN pellets allowed the seal to be formed with only trace amounts of BN contamination on other parts of the heater. This completed thruster assembly is shown in Figures 2-36 and 2-37.

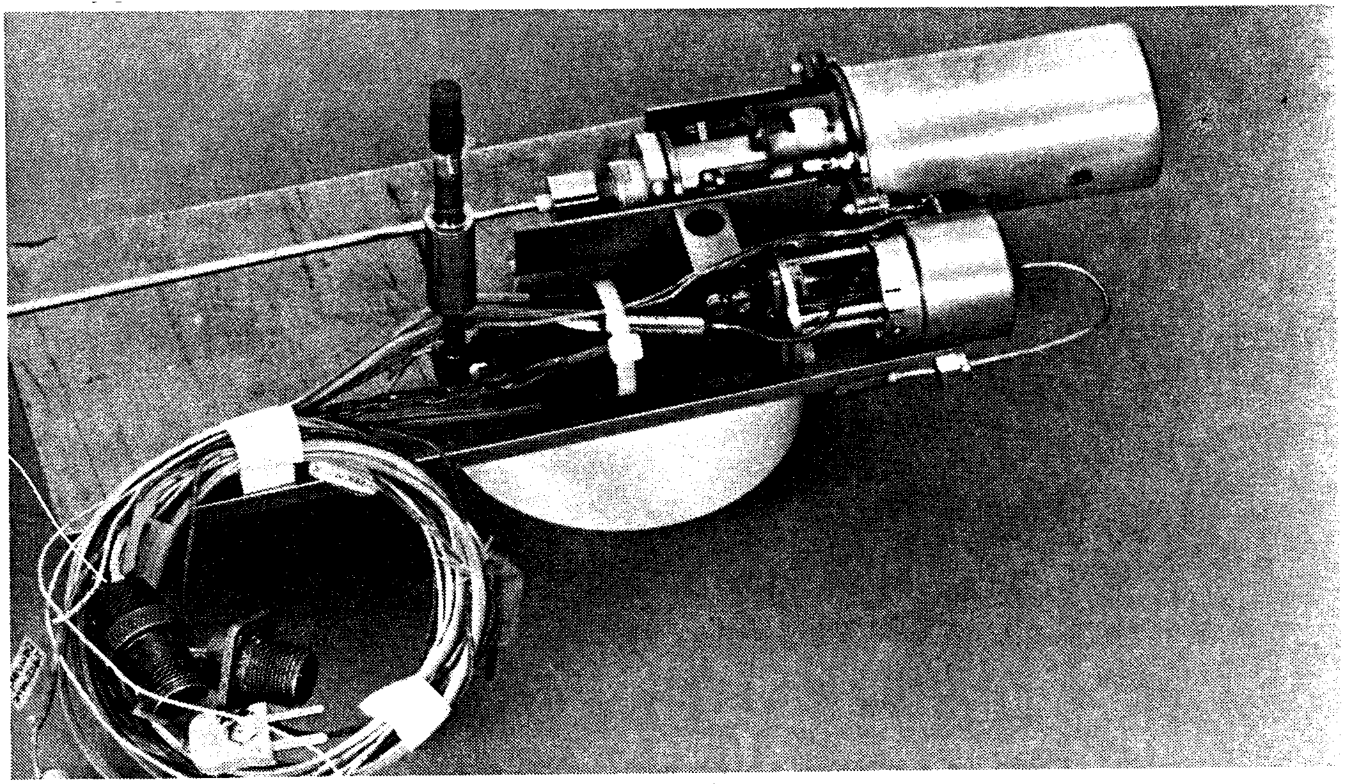
2.2.3.2 Sealed Cavity Thruster Life Test

Preparation of Cell 10 was completed and operation of the thruster at low power was begun. Activities under this task included the following:

1. Fabrication, assembly, and testing of the rotator was completed, and the rotator was installed on the thrust stand.
2. A water-cooled thruster mounting bracket was fabricated and installed on the rotator.
3. The thruster was mounted on the bracket, and the propellant and water lines routed onto the thrust stand as required.
4. Modifications to the controller software were completed and tested.
5. Thermocouples were installed on the thruster assembly.
6. Support brackets for the W3Re/W25Re thermocouple probes were designed, fabricated, and installed. The thermocouples were then mounted in place so that their tips made firm contact with the heat exchanger outer body wall.
7. A tool for measurement of heat exchanger OD was designed and fabricated. This tool was a "C" shaped frame which supports diametrically opposed bolts. When positioned properly around the nozzle end of the heat exchanger, the bolts could be screwed through the frame and through the thermocouple access holes until each seats firmly on the heat exchanger outer body in "micrometer-like" fashion. Figure 2-38 shows one of the thermocouple access holes.
8. An unaugmented firing was conducted successfully, followed by a powered firing at 550 W for approximately 30 minutes. This powered run was aborted due to a short from a power cable to the thrust stand. Preliminary results obtained prior to shutdown indicated thruster performance was lower than was expected from thermal analysis.

The sealed thruster was operated for approximately 10 hours total, during which performance mapping in both the sealed cavity and vented-cavity modes was carried out. Operation in both modes was successful, although heat exchanger and gas temperatures, and thus thruster performance, were lower than that expected based on thermal model predictions. In an attempt to raise heat exchanger and temperatures, radiation shielding was installed around the rear end of the heater after the performance mapping was complete. During the first run after the radiation shields were installed, the thruster failed due to the melting of three bolts and a nut plate which attached the heater to the heater support structure.

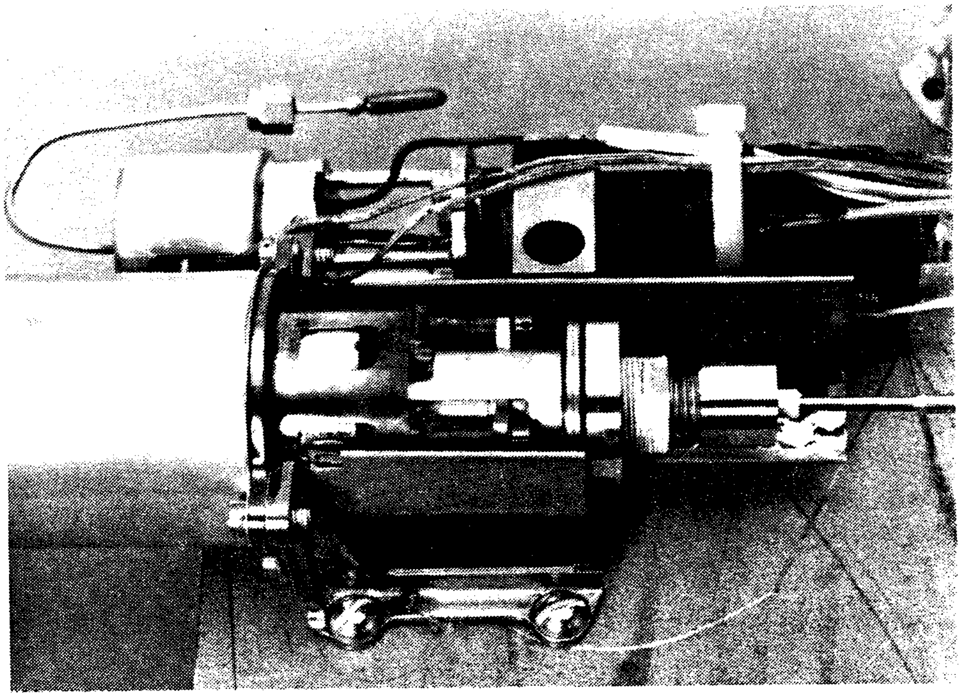
THRUSTER ASSEMBLY



11195-85 3150-2

Figure 2-36

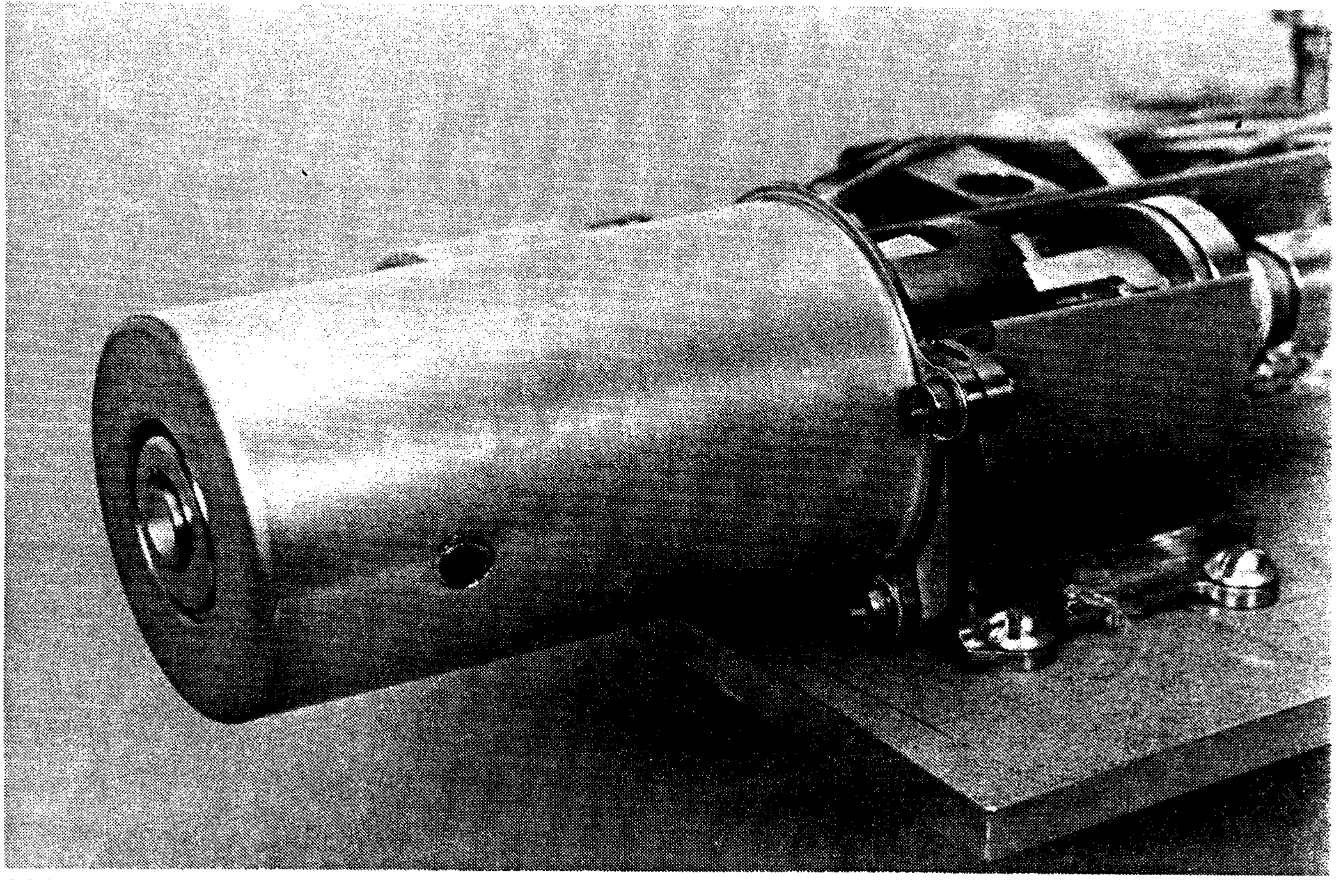
THRUSTER ASSEMBLY



11195-87 3250-5

Figure 2-37

DETAIL OF OPENING ON THRUSTER FOR THERMOCOUPLES



11195-86 3250-4 **Figure 2-38**

2.2.3.3 Sealed-Cavity Thruster Test Results

A total of 18 sealed-cavity runs were made after the heater lead short was fixed. The tests were run at various power levels up to 850 W, and flow rates at or near 0.45, 0.55, or 0.65 lbm/hr. These flow rates were used in most of the thermal modelling carried out prior to the testing.

The thruster operated for 30 minutes before performance data were recorded. This time period was sufficient to allow the thruster to reach thermal equilibrium, but short enough to avoid heater shorting due to filament sag.

Results of the sealed-cavity tests and subsequent vented cavity tests are summarized in Table 2-10. Performance at 750 W was lower than expected, based on thermal model runs which assumed a hard vacuum. This result was attributed to heat losses from the rear (of the thruster which were higher than thermal model predictions. This additional heat loss was attributed to:

1. Greater than expected heat conduction to the rear of the heater.
2. Greater than expected convection losses from the thruster due to chamber back pressure.

Table 2-10
SEALED CAVITY THRUSTER PERFORMANCE MAPPING TEST RESULTS

Run No.	Cavity Status	Power (W)	Flow Rate (lbm/hr)	Thrust (mlbf)	T-Heater* (°F)	Isp (lbf-sec/lbm)
2	Sealed	0	0.512	25.9	—	182
3	"	295	0.468	34.6	3200	267
5	"	500	0.547	44.0	3675	290
6	"	500	0.645	51.6	3625	288
7	"	500	0.554	44.5	3675	290
8	"	650	0.542	45.7	4000	304
9	"	650	0.445	37.1	4075	300
10	"	649	0.641	53.8	3960	303
11	"	0	0.611	31.3	—	186
12	"	650	0.643	54.2	3975	304
13	"	750	0.532	46.1	4190	312
14	"	750	0.444	38.0	4275	309
15	"	751	0.629	54.5	4220	312
16	"	751	0.530	46.0	4180	313
17	"	850	0.625	55.9	4300	322
18	"	850	0.526	46.4	4340	318
19	Vented	500	0.553	44.5	3625	290
20	"	500	0.457	36.8	3650	290
21	"	500	0.647	52.0	3540	289
22	"	750	0.529	45.9	3875	312
23	"	750	0.435	37.4	3840	310
24	"	750	0.628	54.5	3850	312
25	Sealed	751	0.528	46.1	4340	315

*Based on pyrometric temperature calibration conducted after test completion (Fig. 2-31).

The filament temperatures inferred from measured filament resistances were also lower than expected. Filament temperatures and, by inference, heat exchanger temperatures, were not high enough for filament evaporation evaluation or heat exchanger creep evaluation planned for the life test.

The cavity seal appeared to work flawlessly during the sealed-cavity testing. Upon completion of run 18, the test cell was opened and the thruster was inspected. A pressure test on the heater cavity indicated no change in the seal leak rate compared to the leak rate at the start of testing. Heat exchanger measurements also indicated no change in OD as measured through the thermocouple access holes. Creep in the rhenium heat exchanger was negligible.

Upon completion of the thruster inspection described above, the cavity pressurization line was disconnected and the test cell closed in preparation for the vented-cavity tests.

2.2.3.4 Vented-Cavity Thruster Test Results

A total of 6 test runs were carried out with the thruster in the vented-cavity configuration. Results of these runs are summarized in Table 2-10 (Runs 19—24). Performance measurements were made at 500 and 750 W and at flow rates 0.45, 0.55, and 0.65 lbm/hr. No change in performance between the sealed and vented-cavity configurations was observed. The only difference between the two sets of runs was the apparently lower vented-cavity filament temperatures at 750 W and at all flow rates. In contrast, the filament temperatures at 500 W were nearly identical for the two configurations.

Upon completion of Run 24, the test cell was opened and the thruster was inspected. Measurement of the heat exchanger OD through the thermocouple access holes indicated no measurable creep. Throughout the preceding 24 runs, the tantalum shielded, Re/W25Re thermocouple probes had given obviously spurious readings. For this reason, and because the access holes were needed for pyrometric temperature readings, these thermocouple probes were not reinstalled after the heat exchanger OD measurements. Observation of previous runs had also indicated that the probes constituted significant heat conduction paths. It was, therefore, expected that removal of the probes would result in a slight performance improvement.

Data sheets for all valid test runs have been included in Appendix B. Note that flow rates based on sightglass readings have been handwritten on the data sheets. These values were used to calculate the handwritten Isp values on the sheets.

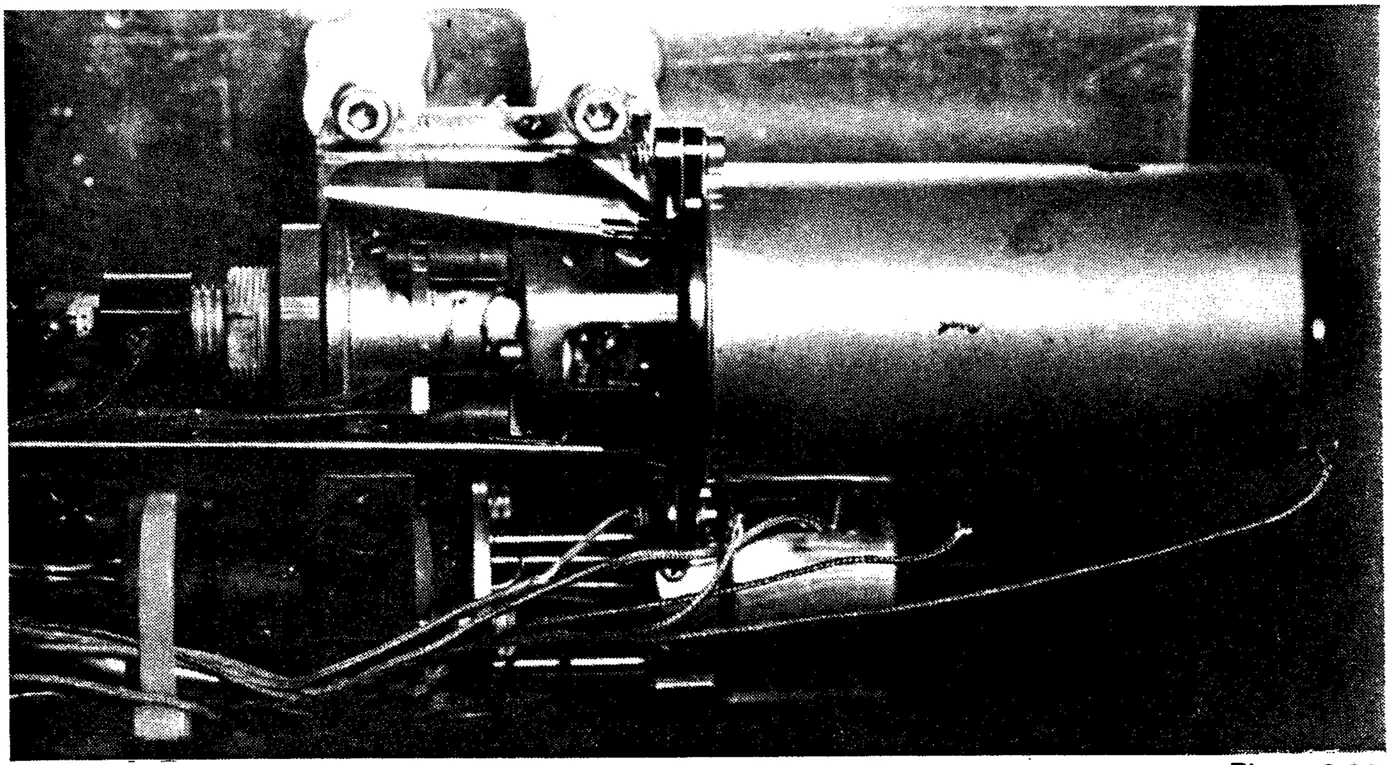
2.2.3.5 Further Pressurized-Cavity Runs

After the heat exchanger inspection, the cavity pressurization line was reconnected. A cavity leak check indicated that the cavity seal was still performing as in the first 19 runs. One sealed-cavity test (Run 25) was then carried out at 750 W and 0.528 lbm/hr. Results were consistent with previous sealed-cavity runs (Runs 13 and 16), with Isp and filament temperatures slightly higher. These slightly higher values may have been due to the removal of the thermocouple probes.

The low thruster efficiency observed in all tests was attributed to high heat conduction to the rear of the heater, and to high heat losses from the hot rear heater surfaces due to thermal conduction by test cell gases. In an attempt to reduce the heat loss from the rear of the heater, and thus increase the overall thruster efficiency, 13 wraps of moly foil radiation shielding were installed around the rear of the heater and the heater support structure. The thruster failed 1172 seconds into the next run, which was conducted at 700 W and approximately 0.52 lbm/hr. The computer which controlled the experiment had not yet recorded performance data when the failure occurred.

Complete disassembly revealed failures in the three nuts and the nut plate by which the heater was attached to the heater support structure (Figures 2-39, 2-40 and 2-41). When the nuts had failed, the pressure inside the heater cavity had momentarily driven the heat exchanger forward causing misalignment of the heat exchanger with the gas generator, thereby bending the rhenium gas delivery tube.

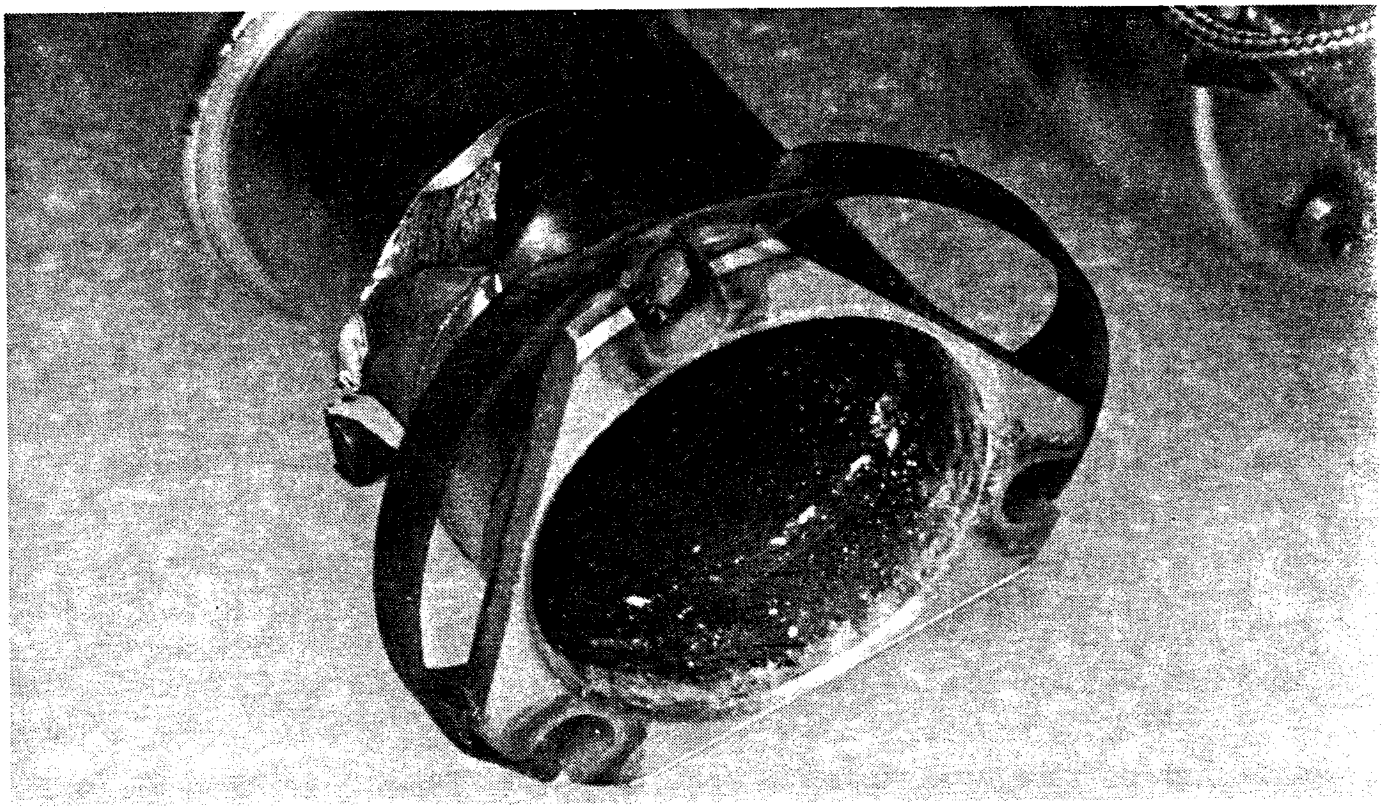
THRUSTER ASSEMBLY FOLLOWING BOLT FAILURE



11197-51 3253-15

Figure 2-39

INTERIOR OF HX FOLLOWING BOLT FAILURE



11197-50 3253-5

Figure 2-40

The bolts and nut plate were fabricated from Waspalloy, a nickel based alloy containing chromium (19%), cobalt (13.5%), and molybdenum (4%). The presence of the radiation shields caused the temperature in the region of the heater/support bracket attachment point to approach the melting point of Waspalloy. After the nut failed, a portion of the nut plate came in contact with the barrier tube and melted, spreading out in the process to cover approximately 1/5 of that part.

The most critical damage was done to the rhenium heat exchanger in three areas:

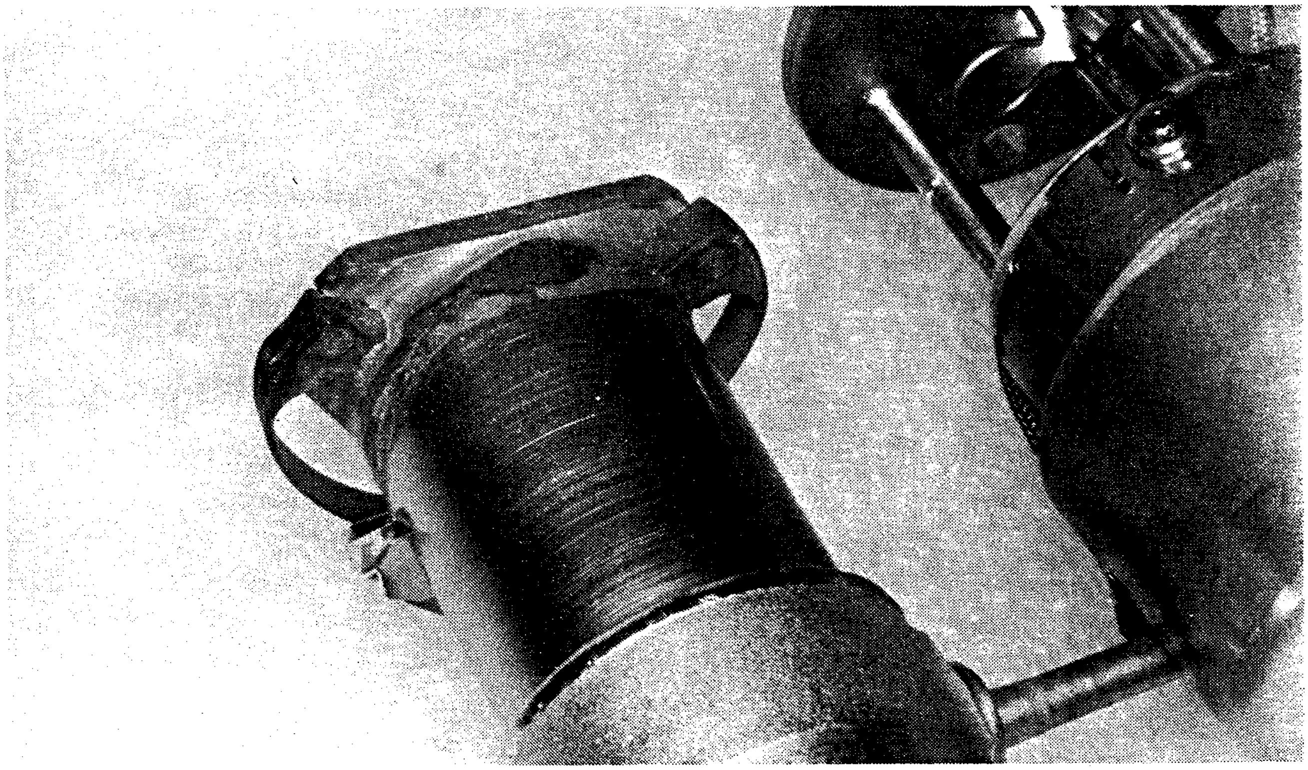
1. A thin layer of molten Waspalloy had spread over the rear end of the barrier tube OD (Figure 2-42). Inspection of the damaged part suggested it was salvageable. The nickel in the Waspalloy can irreparably damage pure rhenium by quickly diffusing into the rhenium metal structure and weakening it such that its high temperature strength would be substantially reduced. The contaminant Waspalloy was completely removed. After the Waspalloy had been completely removed, the barrier tube was inspected. The results of this inspection were encouraging. All dimensions were within specification.
2. A small crack was found in the rhenium gas delivery tube. This crack was probably caused by the movement of the heat exchanger when it was driven forward after the failure. The crack was repaired with an electron beam weld. Subsequent pressure testing revealed no leakage.
3. The same event which caused the crack in the gas delivery tube also caused the tube to be bent at the point where it is welded to the heat exchanger (Figure 2-43). Since rhenium work hardens readily, straightening of the bent tube was deemed too risky and it was left as it was.
4. The molybdenum foil radiation shields which surrounded the heat exchanger were damaged beyond repair during disassembly. Such damage is normal for resistojet disassembly. No abnormal degradation of the shields was noted.
5. The sealed cavity heater itself was undamaged except for possible diffusion bonding of the ram to the seal ring. Figure 2-44 shows the heater, with the BN seal intact, after removal from the thruster.

2.2.3.6 Heater Resistance — Temperature Correlation

For Runs 24—26, a two-color pyrometer was loaned to RRC by NASA LeRC. After the thruster failure and subsequent disassembly, a correlation of the heater filament resistance and temperature was established using the NASA pyrometer. The correlation was established in the same test cell as the thruster testing, and approximately 20 data points were taken.

The correlation is shown in Figure 2-45 along with the original correlation and corresponding values from the Handbook of Chemistry and Physics. The agreement between the slope of this correlation and that of the literature values is acceptable, with the shift to the left being attributable to uncertainty in the length of wire in the heater filament.

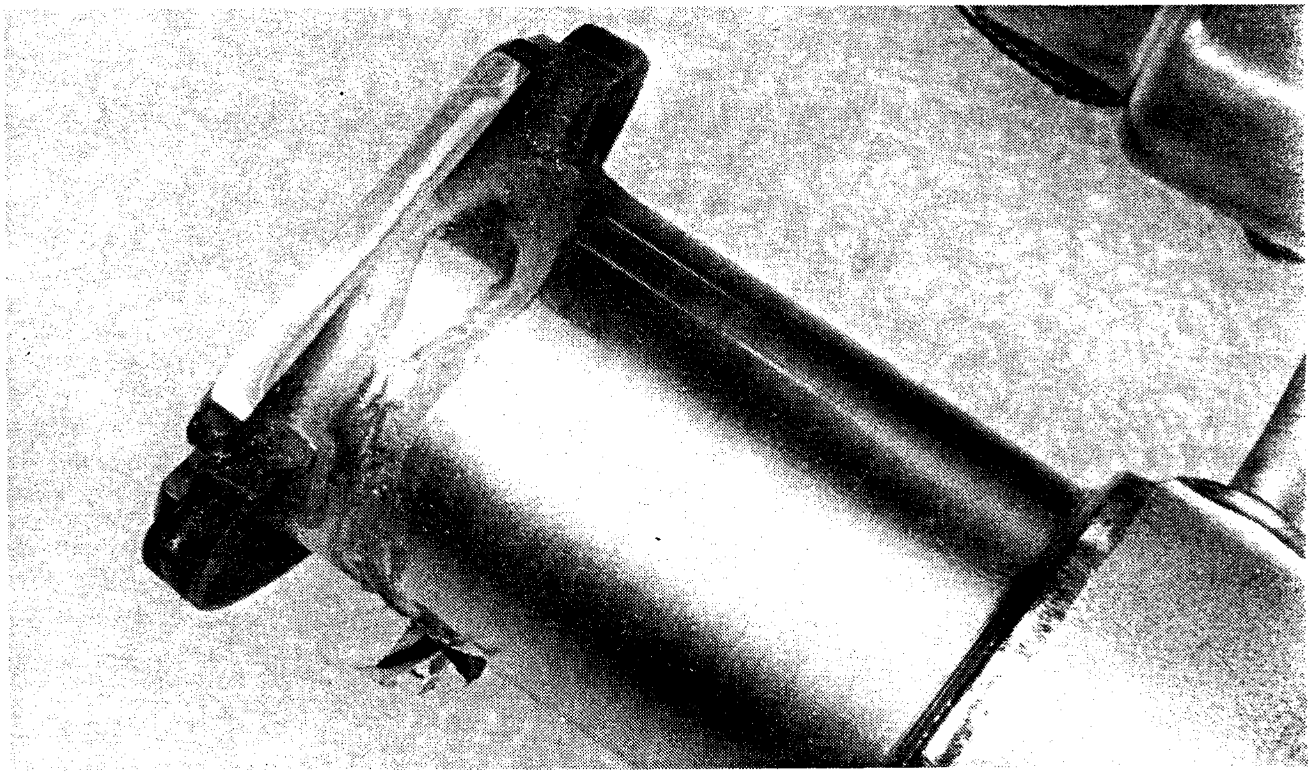
BENT RHENIUM GAS FEED TUBE



11197-53 3253-17

Figure 2-41

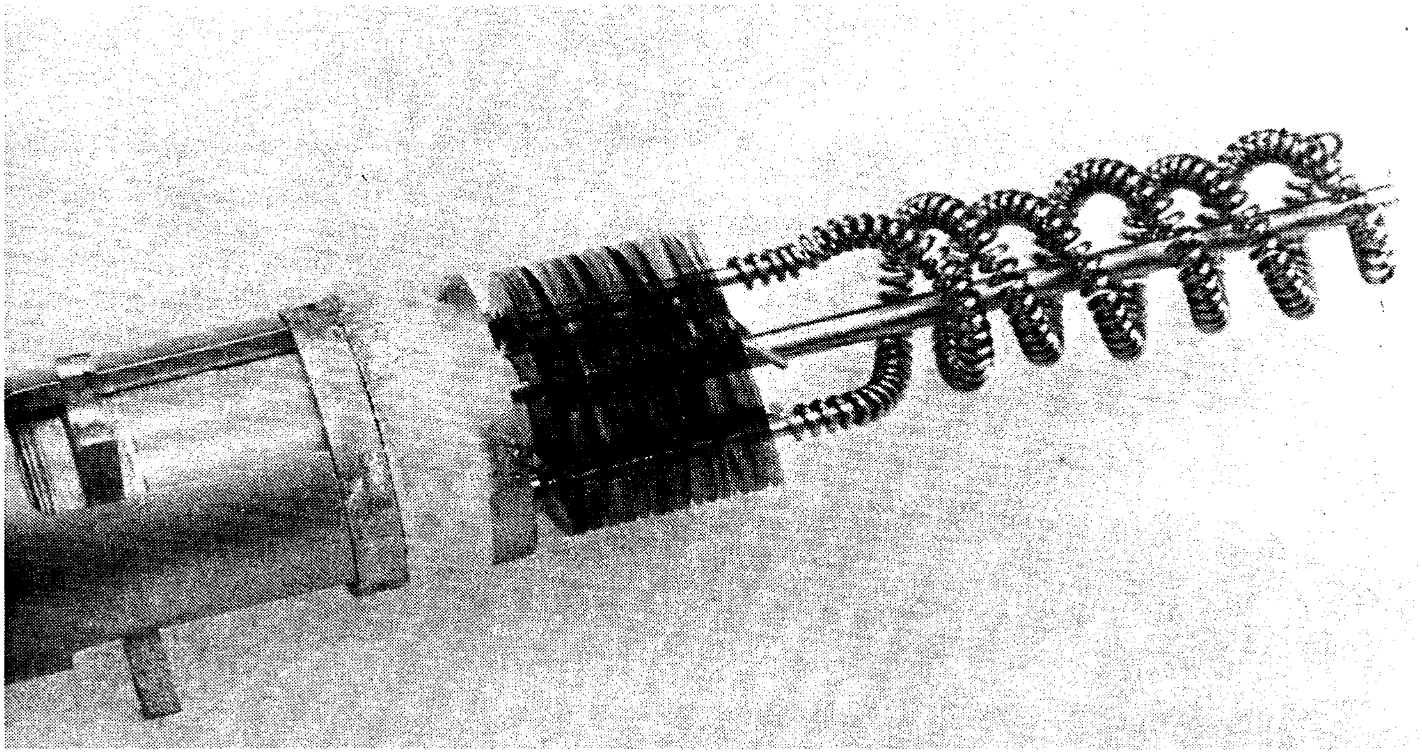
MOLTEN METAL SOLIDIFIED ON BARRIER TUBE



11197-52 3253-16

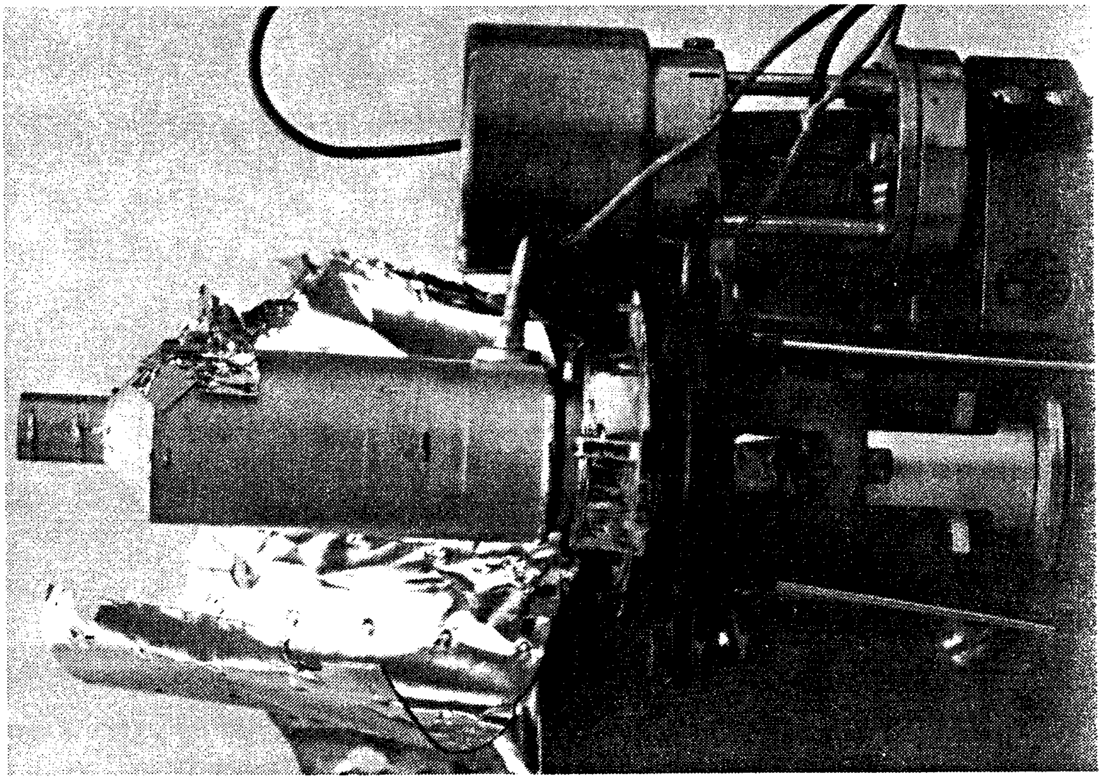
Figure 2-42

HEATER SUBASSEMBLY FOLLOWING TEST

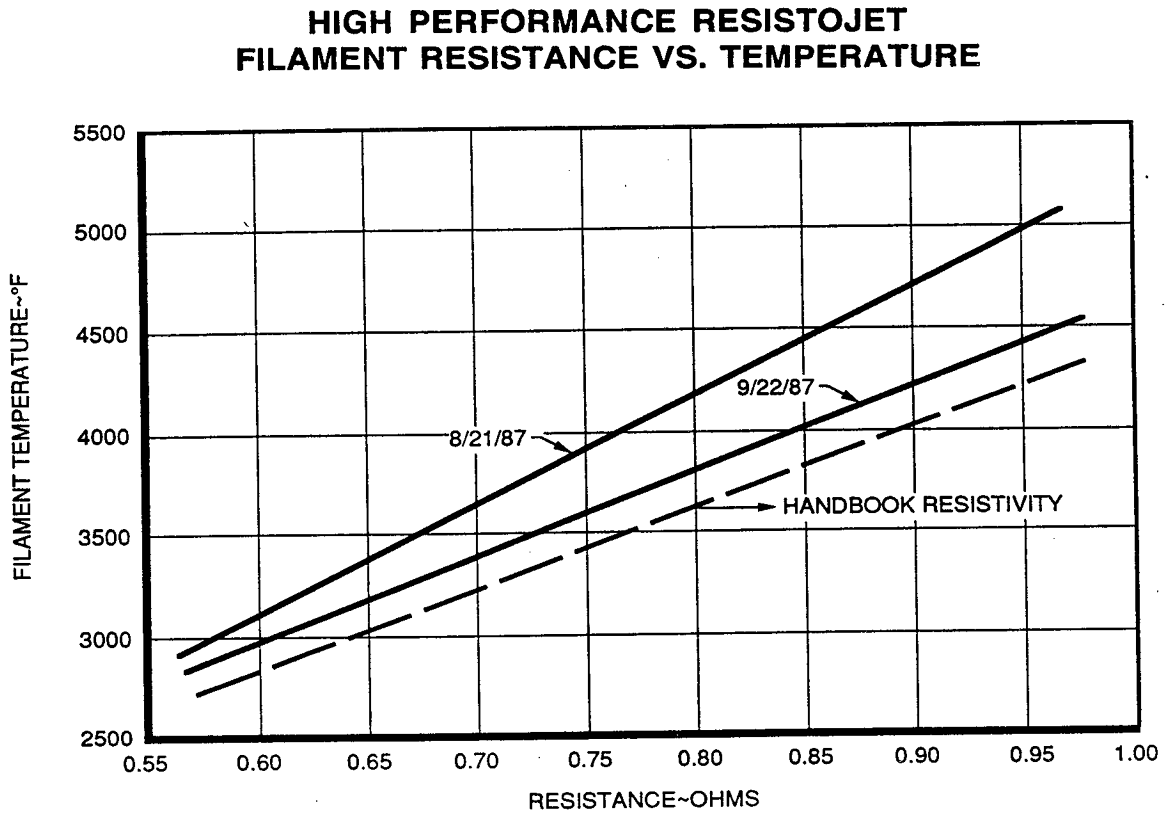


11197-55 3253-12 **Figure 2-43**

RHENIUM HX FOLLOWING PARTIAL DISASSEMBLY



11197-54 3253-17 **Figure 2-44**



C11232-31 **Figure 2-45**

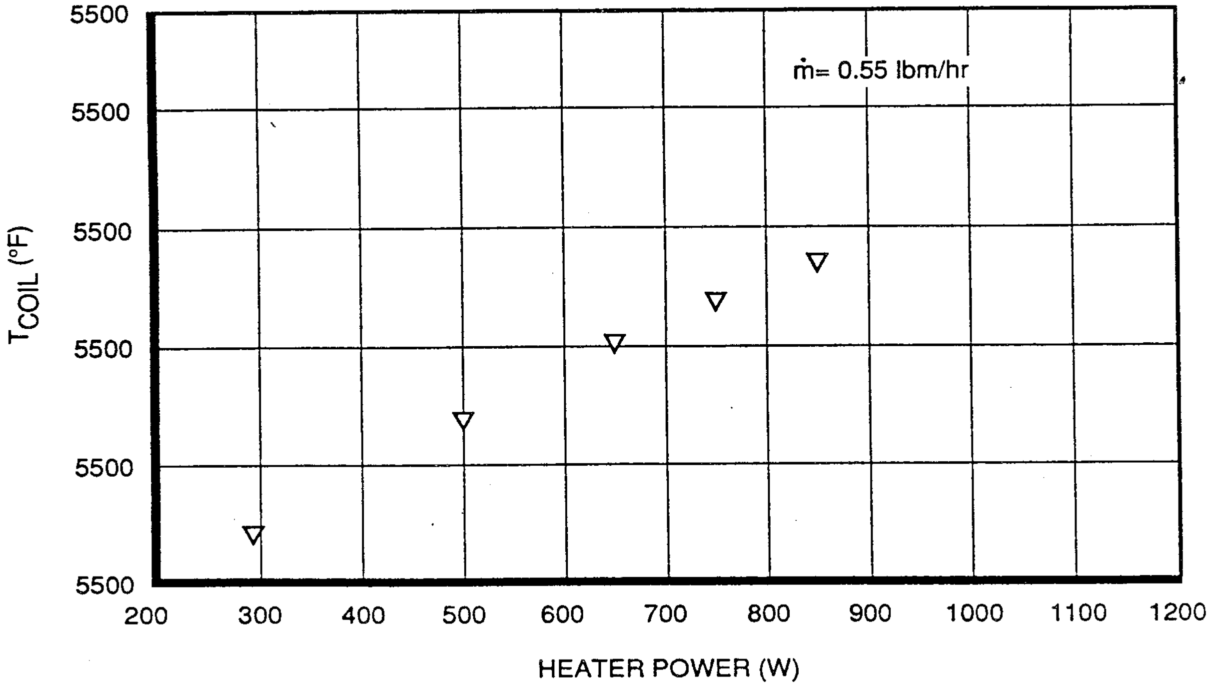
This correlation was used to calculate the filament temperatures in Table 2-10. Filament temperatures calculated are considerably lower than those from the original correlation, which was used in the data sheets of Appendix B. Even at 850 W, the filament temperatures do not approach the temperatures needed to test the sealed cavity concept for evaporation retardation.

2.2.3.7 Review of Test Results

The performance data gathered on the 25 successful runs were disappointing. Measured specific impulse values at 750 W were in the range of 310 to 315 sec, rather than the 330 to 335 sec values anticipated. This poor performance was attributed to energy losses from the thruster which were much higher than expected from thermal analysis at hard vacuum. Predicted performance was derated to near the measured values when an empirical model for conductive heat losses was included in the thermal model.

Figure 2-46 presents measured filament temperature plotted against measured heater power. From these results, it is clear that neither the performance nor material temperature goals of the original test program were realized with the present apparatus. These limitations led to a revision of the test goals described below.

HIGH PERFORMANCE RESISTOJET
SEALED-CAVITY TEST RESULTS



C11232-32

Figure 2-46

2.2.4 Results and Conclusions from Phase II

At this point in the program NASA-LeRC agreed to conduct an evaluation of material creep at high temperature. The task was eliminated from the HPSPR program. In addition, NASA-LeRC agreed to conduct experiments on N_2H_4/wire compatibility and this task was also eliminated from the HPSPR program.

Since the data from these tasks were critical for continuing work on radiative heater concepts, a decision was made to suspend all other program activities for a period of approximately 10 months during the collection of this data.

During this period of time members of the user community provided input indicating that greater thrust efficiency at moderate power was needed by near term spacecraft for N-S stationkeeping missions. Immersed heater designs are inherently better in this regard. This input to NASA-LeRC led to the next phase of the program. The creep and wire compatibility data were not incorporated into the HPSPR program and is outside the scope of this report.

2.2.4.1 Review of Test Goals

The original goals of the sealed-cavity thruster tests, as defined by NASA and RRC during the restructuring of the Phase II program plan are listed below, in order of importance:

1. Demonstration of 750 W sealed-cavity operation at enhanced performance levels (greater than 330 sec Isp) for an extended period of time, arbitrarily set at 250 hours.

2. Evaluation of the creep performance of HIP'ed rhenium at the heat exchanger temperatures necessary for 330 sec Isp and above. Examination of limited rhenium creep data available in the literature indicates that a steady-state outer body temperature of 4200°F or higher will be required to induce measurable creep with a reasonable test duration (100 to 200 hours).
3. Evaluation of the effect of a pressurized cavity on heater filament evaporation rates. Examination of the sometimes conflicting tungsten evaporation rates available in the literature indicates that a steady-state filament temperature of 5000°F or higher will be required to demonstrate significant evaporation retardation with a reasonable test duration.
4. Evaluation of long-term compatibility of rhenium with hydrazine decomposition products at temperature.
5. Evaluation of other effects of the pressurized cavity, such as axial heat conduction and heat exchanger inner-body creep.

It was clear from the test results that goal number 1 was not possible with the sealed-cavity heater design. It was also clear from the results of the earlier "fast-track" tests with a vented cavity heater that performance levels above 330 sec Isp at 750 W was achievable when the constraint to use an existing heat exchanger was removed.

A review of test goals eliminated goal number 1 above, and retained the remaining goals in the order listed. However, test results indicated that heat exchanger outer body temperatures and heater filament temperatures necessary to achieve the remaining goals were not achievable with the sealed cavity thruster. A parametric study using an updated thermal model was undertaken to determine whether minor improvements to the thruster design could improve performance enough to meet the test goals.

2.2.4.2 Thermal Analysis

The wide discrepancy between the sealed-cavity test results and the thermal model predictions pointed out the need for an examination of the thermal model to determine the cause of the discrepancy. The goals of this study were two-fold:

1. Bring thermal model predictions into better agreement with the sealed-cavity test results.
2. Suggest hardware or test modifications which would allow required temperatures to be achieved in future tests.

To address the first goal, three tasks were completed:

1. Comparison of the actual hardware drawings and model to verify the conductive interface used between the mounting bracket and the thrust stand.
2. Recalculation of the conductance network within the sealed-cavity heater sub-assembly per the hardware drawings as built.
3. Recheck the radiative connections between the heat exchanger outer surfaces and the ambient environment.

Although minor modifications were made to the model as a result of these investigations, no significant changes in predicted temperatures or performance resulted.

The only way the model could be made to predict performance near the sealed-cavity test results was by invoking assumptions which led to gas conduction/convection losses significantly higher than had been thought reasonable. This high-conduction assumption (Case 1) was consistent with thermal models used on several previous programs at RRC. However, it was not consistent with the results of the fast-track tests. Fast-track test results correlated well with a similar thermal model in which very low gas conduction losses were assumed. This dilemma remains unresolved.

An effort was made to increase surface emissivities assumed by the model in order to reduce various surface temperatures. Somewhat better agreement was achieved by this method, although unrealistically high emissivities must be assumed in some cases to get reasonable agreement with test results. Without more definitive emissivity data for specific thruster surfaces, further attempts at better agreement with measured surface temperatures would be little more than an exercise in curve fitting. This effort was therefore discontinued.

In general, the model underpredicted performance and overpredicted most external temperatures. Surface emissivities were pushed as high as was justifiable in light of literature data, and the large amounts of heat rejected from the thruster via ambient gas conduction. Predicted performance can be adjusted by assuming a different nozzle efficiency. However, reducing the predicted external temperatures without unrealistic assumptions concerning surface emissivities was not possible. Surface emissivity data specific to the Mo/41Re heater assembly and the rhodium plated heat exchanger outer can would be very helpful in this regard. The largest unknown in this entire analysis was the validity of the assumptions used for gas conduction heat losses.

One aspect of the model that warrants revisiting is the correlation between the radiation view factors used and the actual hardware in the region of the heater subassembly. Due to the complexity of the geometry in this region and the various materials used, it is possible that the radiative losses from this region were considerably higher than predicted by the model.

2.3 PHASE III — IMMERSED HEATER THRUSTER EXPERIMENTS

In the original Phase III plan the resistojet design was to be updated to incorporate Phase II results. Following approval of a design review, two thrusters and associated tooling and test equipment were to have been fabricated and assembled.

Based on the results of the sealed cavity tests in Phase II the HPSPR program was redirected to pursue an immersed heater resistojet (similar to the TRW HiPEHT design) concept following a joint decision between NASA-LeRC and RRC. The immersed heater design was expected to have an advantage over the radiative design by means of a higher electrical-to-thrust conversion efficiency. If higher efficiencies were obtained, higher I_{sp} levels (315 to 325 seconds) were expected at relatively low power levels (450 to 600 Watts). The combination of higher performance at lower power would provide a unique capability with a high potential for the thruster to be utilized in a flight program. For this phase, the program had an I_{sp} goal of 315 seconds and a life goal of 100,000 lb-sec. total delivered impulse. The performance and life goals were to be achieved with a power input of no more than 750 W.

The primary technical challenge was the reduction or elimination of heat exchanger (HX) degradation with life noted in IR&D testing during 1988 (Roberts, 1988). Material loss from the tungsten heater filament, and subsequent redeposition of that material within the HX cavity caused unacceptable degradation of the HX at I_{sp} levels near 315 seconds. Analysis indicated that operation at filament temperatures exceeding 4200°F resulted in excessive filament mass loss. The design effort modified the HX injector and close-coupled the HX to an MR-501 type gas generator (GG).

Drawings for the immersed heater thruster are included in Appendix D.

2.3.1 Gas Generator to HX Coupling

The close-coupled HX/GG design concept was based on test and manufacturing experience at RRC, TRW and NASA-LeRC. The design incorporated flight-type structural, thermal, and interface features where possible. Limited thermal analyses were performed to ensure that seal temperatures were within limits, and that the support structure did not increase thermal conductive losses.

The MR-501 design GG outlet was modified to incorporate a face-seal interface with the HX to allow easy replacement of the HX. A gas tight seal was required which would withstand thermal cycling from ambient to 1400°F. A metal "V-ring" type of seal was selected over a grafoil seal to avoid reactions between N_2H_4 decomposition gases and carbon. The V-seal material selected was Hastalloy X with a soft nickel coating which is compatible with N_2H_4 decomposition products and has adequate yield strength at temperatures well above 1400°F.

A filter to prevent particulates from the GG from reaching the heater filament was incorporated just downstream of the GG exit. A chamber pressure (P_c) tap was incorporated between the GG and the HX.

The primary structural support of the HX was via the GG flange interface. Therefore the GG support was designed to be structurally adequate for this purpose and to minimize the thermal soak-back from the GG and the HX to the propellant valve.

2.3.2 Heat Exchanger Description

The immersed heater HX consists of three main parts:

1. Heater
2. Nozzle body
3. Adaptor tube interface

The heater included the filament, support post, and electrical pass-through. Mo/50Re tubing was used for the electrical pass-through assembly. The nozzle body encloses the heater filament, injects the propellant into the HX cavity, and expands the flow out the nozzle. The adaptor tube feeds decomposed N_2H_4 from the gas generator to the nozzle body injector, and also provides structural support for the HX assembly. One HX and four heaters using the TRW HiPEHT design were procured.

TRW applied extensive immersed heater design experience to the identification of HX design modifications focused on altering the injector flow field to enhance heat transfer from the wire into the exhaust gas. Injector port location, diameter, and orientation relative to the heater filament, as well as the number of injection ports were possible variables. A redesign of the HX body cross-section and a reduction in the HX body diameter were also considered and rejected. Details of the injector redesign analysis are included in Appendix F.

The principal change from the HiPEHT configuration was replacing the injector slot with an array of holes. The nozzle body and injector design are shown in Figure 2-47. The injector ports were sized to a nominal diameter of 0.010 in. to closely match the discharge coefficient of the HiPEHT.

2.3.3 Gas Generator

RRC supplied a standard MR-501 type GG for use in the program. For the thrust levels likely with the immersed HX, the standard MR-501 gas generator life expectancy was sufficient to meet a 100,000 lb-sec life requirement. A mating flange was added to the design. The modified GG is shown in Figure 2-48. The support hardware obtained from RRC for use during this Phase included:

- Gas generator
- Mounting structure
- Shielding
- Tooling
- Fluid resistor
- Propellant valve

The overall assembly is shown in Figure 2-49. An adaptor plate was made to support the input electrical leads for attachment to the heat exchanger. To accommodate the MR-501 mount structure geometry, the HX gas inlet tube was lengthened from 0.81 to 1.25 inches. Immediately downstream of the GG bed plate three 100 X 100 mesh screens formed the GG outlet filter. The outlet/adaptor was welded to the GG. A pressure tap was brazed in place.

2.3.4 Immersed Heater Thruster Testing with N_2H_4

The test using the new HX was planned to meet the following objectives:

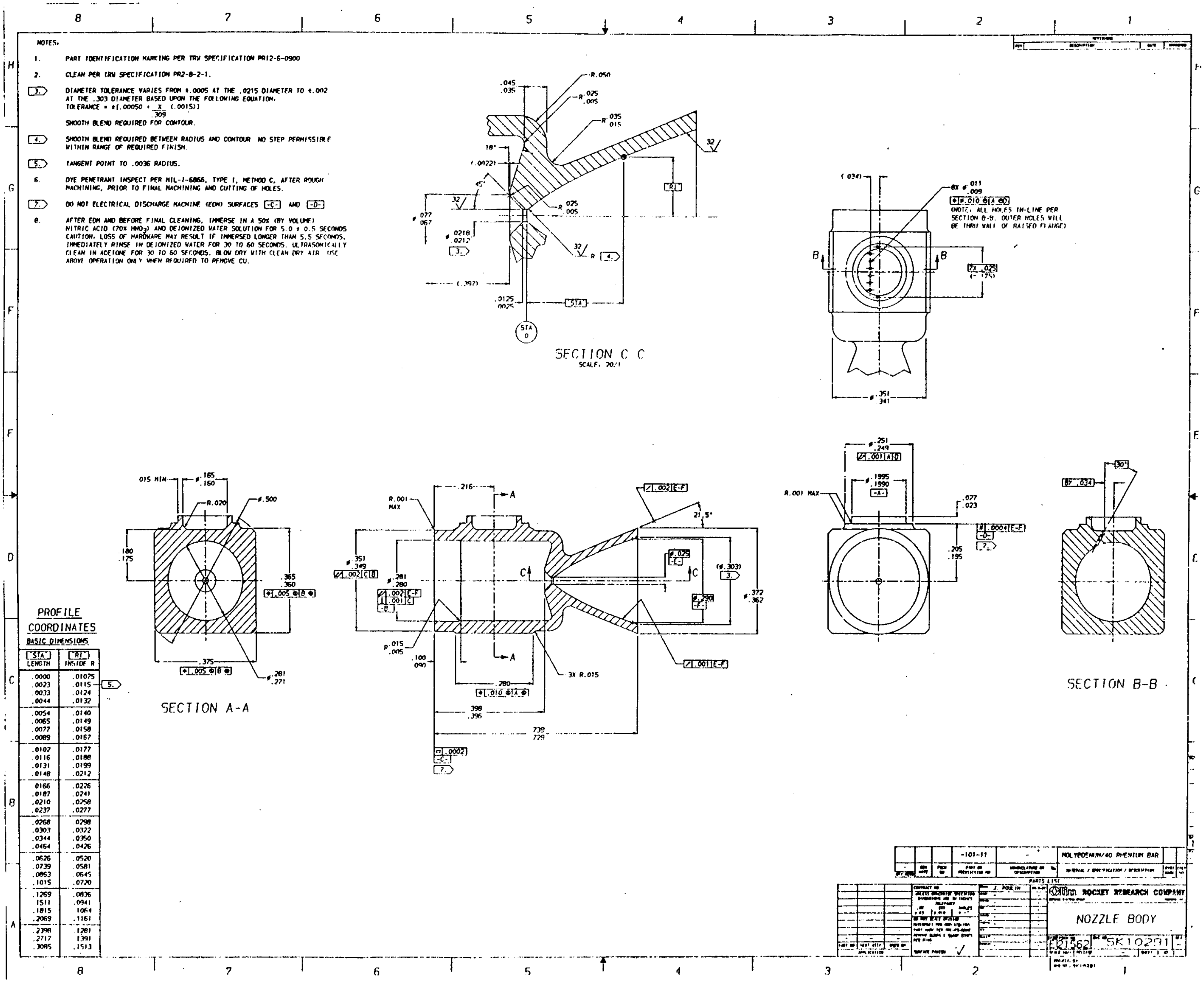
a. Determine the maximum allowable heater temperature to minimize HX degradation.
b. Determine the effects of the injector modification. Data from previous IR&D testing using the unmodified HiPEHT HX design were compared to the data from this test.

The basic flow of testing planned is shown in Figure 2-50. A performance map of the IR&D thruster was completed prior to installation of the immersed heater thruster to verify operating points and validate the test set-up. The IR&D thruster had a slot injector and a standard hot gas transfer tube from the gas generator.

2.3.4.1 Fuel and Pump/Chamber System

The testing was performed in RRC's altitude chamber number 6, which is shown schematically in Figure 2-51. The altitude chamber is a single wall, 98-ft^3 vacuum tank connected to two high-capacity mechanical vacuum pumps with 3,850 and 2,630 cfm capacity. Mechanical pumps maintained the cell pressure to less than 150 mtorr throughout testing.

IMMERSED HEATER NOZZLE BODY DESIGN



NOTES:

1. PART IDENTIFICATION MARKING PER TRW SPECIFICATION PR12-6-0900
2. CLEAN PER TRW SPECIFICATION PR2-8-2-1.
3. DIAMETER TOLERANCE VARIES FROM ±.0005 AT THE .0215 DIAMETER TO ±.002 AT THE .303 DIAMETER BASED UPON THE FOLLOWING EQUATION:
   TOLERANCE = $\pm[.00050 + \frac{X}{.309}(.0015)]$
   SMOOTH BLEND REQUIRED FOR CONTOUR.
4. SMOOTH BLEND REQUIRED BETWEEN RADIUS AND CONTOUR NO STEP PERMISSIBLE WITHIN RANGE OF REQUIRED FINISH.
5. TANGENT POINT TO .0036 RADIUS.
6. DYE PENETRANT INSPECT PER MIL-I-6866, TYPE I, METHOD C, AFTER ROUGH MACHINING, PRIOR TO FINAL MACHINING AND CUTTING OF HOLES.
7. DO NOT ELECTRICAL DISCHARGE MACHINE (EDM) SURFACES -C- AND -D-
8. AFTER EDM AND BEFORE FINAL CLEANING, IMMERSE IN A 50% (BY VOLUME) NITRIC ACID (70% HNO_3) AND DEIONIZED WATER SOLUTION FOR 5.0 ± 0.5 SECONDS CAUTION: LOSS OF HARDWARE MAY RESULT IF IMMERSED LONGER THAN 5.5 SECONDS. IMMEDIATELY RINSE IN DEIONIZED WATER FOR 30 TO 60 SECONDS. ULTRASONICALLY CLEAN IN ACETONE FOR 30 TO 60 SECONDS. BLOW DRY WITH CLEAN DRY AIR. USE ABOVE OPERATION ONLY WHEN REQUIRED TO REMOVE CU.

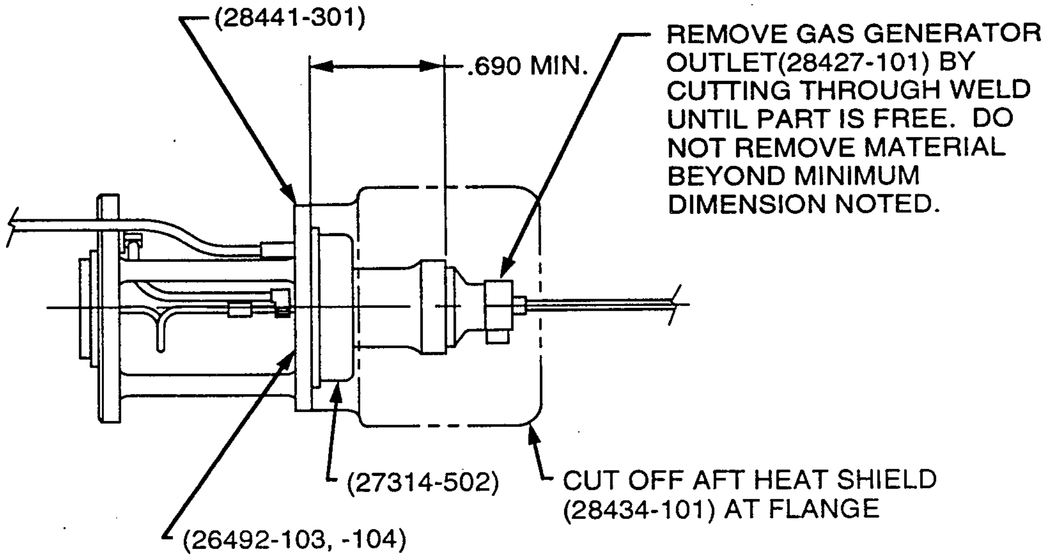
PROFILE COORDINATES

BASIC DIMENSIONS

STA LENGTH	R1 INSIDE R
.0000	.01075
.0023	.0115
.0033	.0124
.0044	.0132
.0054	.0140
.0065	.0149
.0077	.0158
.0089	.0167
.0102	.0177
.0116	.0188
.0131	.0199
.0148	.0212
.0166	.0226
.0187	.0241
.0210	.0258
.0237	.0277
.0268	.0298
.0303	.0322
.0344	.0350
.0464	.0426
.0626	.0520
.0739	.0581
.0853	.0645
.1015	.0720
.1269	.0836
.1511	.0941
.1815	.1064
.2069	.1161
.2398	.1281
.2717	.1391
.3085	.1513

Figure 2-47

GAS GENERATOR MODIFICATION SEQUENCE



-101-11

MAKE FROM ASSEMBLY OBTAINED
BY REMOVING GAS GENERATOR FROM
EHT ASSEMBLY (28420-305)

Figure 2-48

IMMERSED HEATER THRUSTER ASSEMBLY

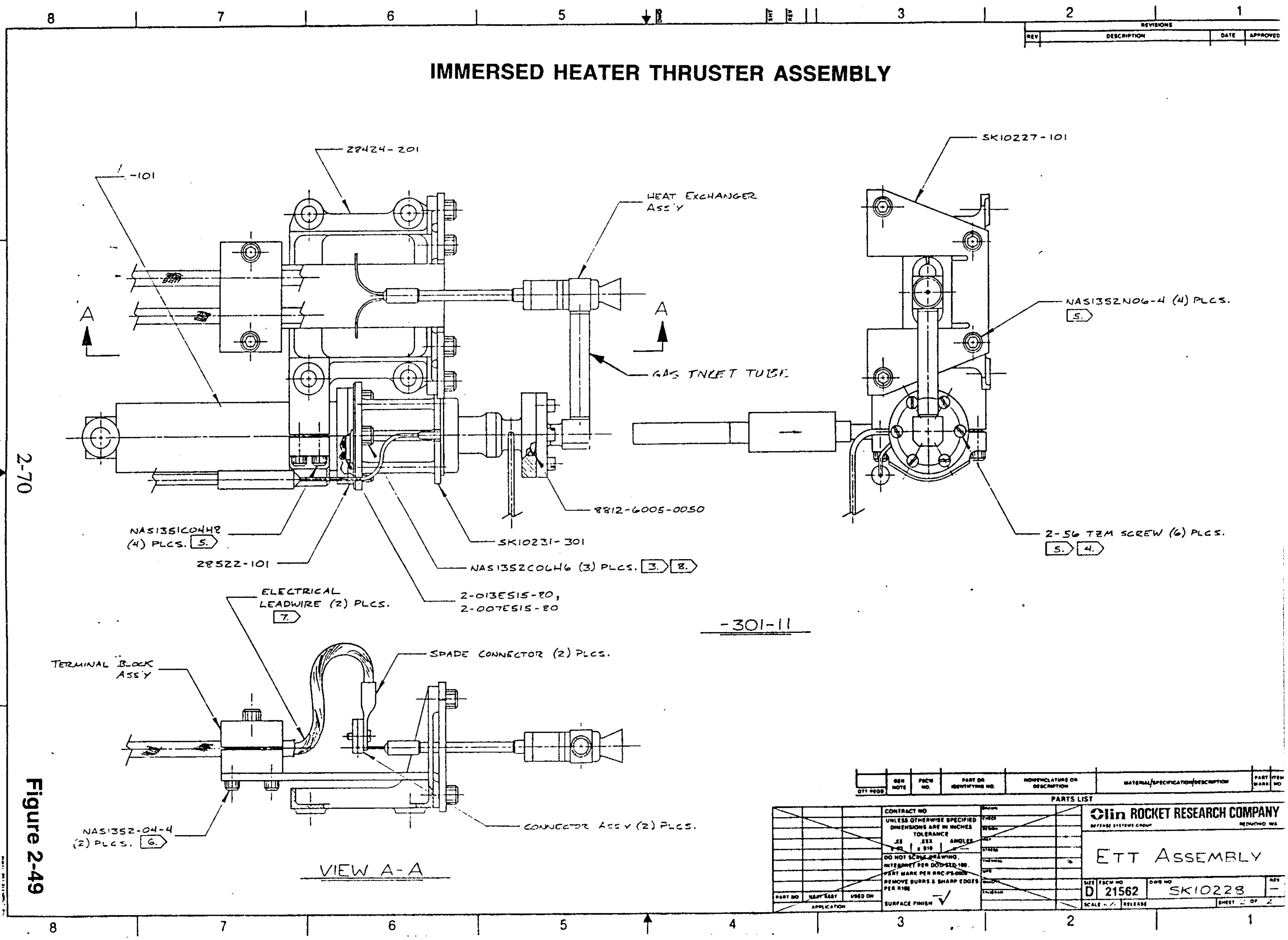


Figure 2-49

IMMERSED HEATED THRUSTER
TEST FLOW PLAN

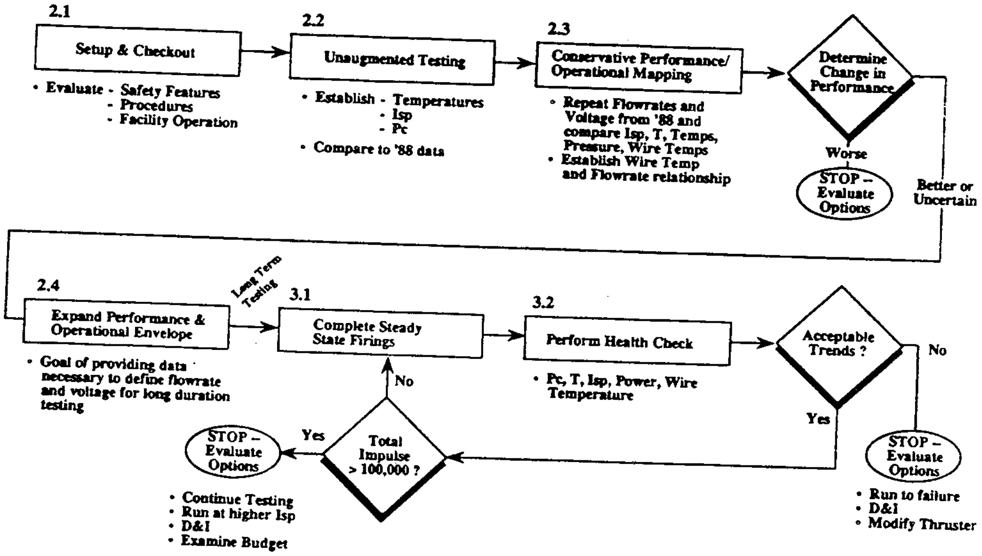


Figure 2-50

N2H4 PROPELLANT SYSTEM THRUST STAND AND TEST CELL

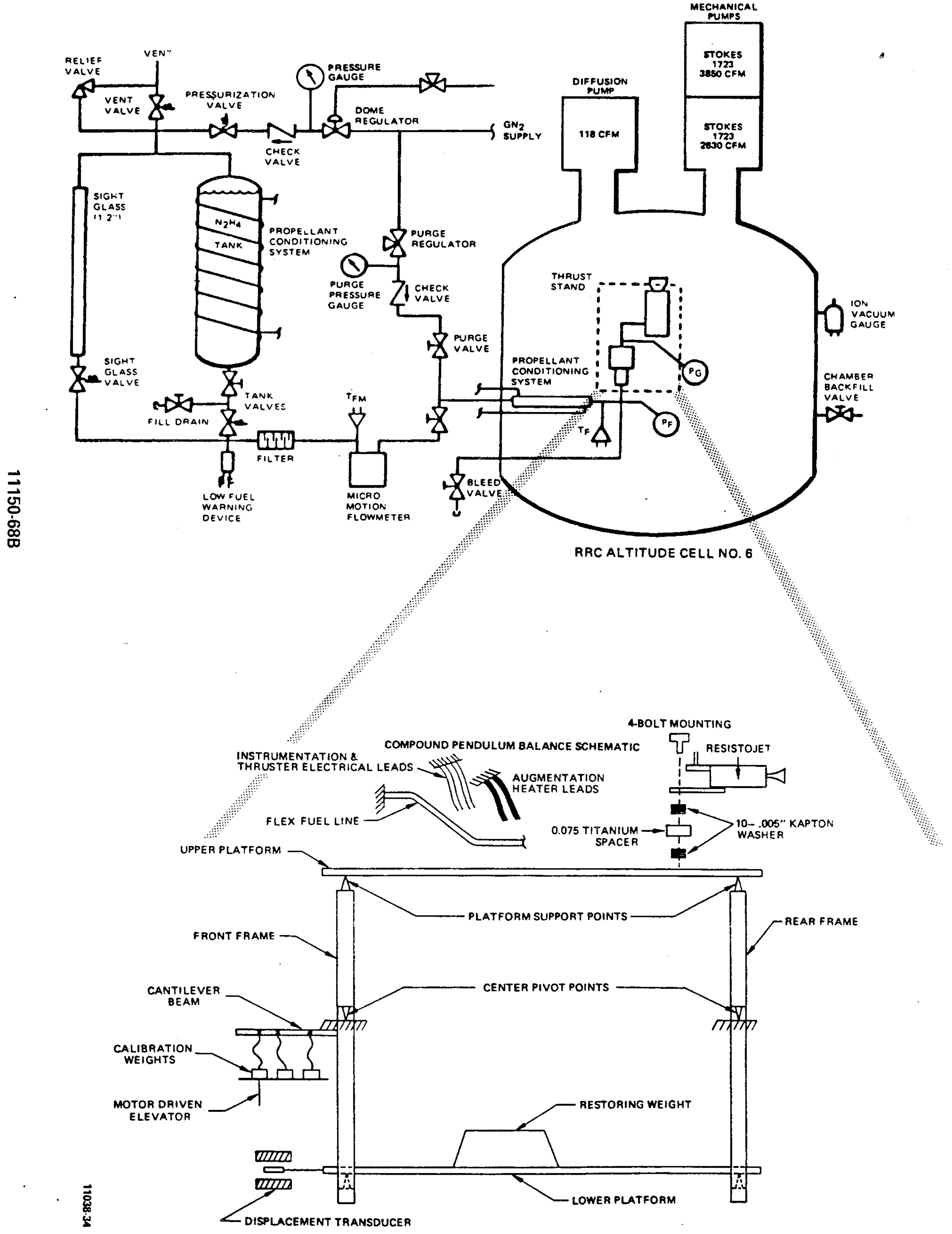


Figure 2-51

Prior to connecting the inlet line to the thruster, propellant samples were taken for chemical and particulate analysis to certify the propellant system cleanliness. All testing was completed using hydrazine meeting MIL-P-26536C, Amendment 2, High Purity Grade.

2.3.4.2 Performance Mapping

Tests were conducted to establish a trend of I_{sp} versus wire resistance (temperature) at various flow rates. Each test lasted for approximately 30 minutes to ensure that thermal equilibrium was reached. The first testing objective was to repeat the low filament temperature (higher flow rate, lower voltage) operating points obtained in previous IR&D testing. Additional tests including a broader range of feed pressures and voltages were completed to determine the performance envelope of the redesigned thruster. The specific objective was to determine filament temperatures at an I_{sp} of 315 seconds and greater. These data were used to determine the life test conditions.

The IR&D version of the immersed heater thruster was tested to validate the performance measurements of the test cell setup. Good agreement was achieved with 1988 data. Additional performance mapping was performed. Trends of I_{sp} as a function of specific energy (power/mass flow, P/m-dot) were established for three mass flow rates. Performance testing of the new immersed heater thruster established I_{sp} trends as a function of P/m-dot for several mass flow rates as shown in Figure 2-52. The results indicated a possibility of completing a life test using a shallow blow-down (300 to 200 psia) of 100,000 lbf-sec at an I_{sp} greater than or equal to 315. The peak power would be about 720 watts. Performance of the new thruster and the IR&D thruster were virtually identical. No performance improvement was obtained from the design changes.

Testing prior to the beginning of the life test resulted in a test anomaly characterized by increased P_c and decreased mass flow rate. A crystalline metallic material was observed in the throat, shown in Figure 2-53. Testing was stopped pending identification of the material. The thruster was removed from the test cell, decontaminated and the crystalline material in the throat was subjected to SEM analysis. There was also streaky black material deposited in the nozzle. The SEM analysis showed that the material in the throat was tungsten. Trace quantities of titanium and calcium were also found. The source of these materials was unknown.

Following the hardware failure a meeting was held with TRW to review the test results and form a consensus for future action. Five options were considered:

1. Resume parametric or life characterization testing using the immersed heater thruster to fully characterize the failure (i.e. determine damage thresholds, test anhydrous propellant, test with Argon, put witness plates in the plume).
2. Lower the wire temperature to a "safe" level and continue the life test at a lower performance level (e.g. 306 sec I_{sp}).
3. Modify the injector to improve the Reynolds number and/or change the filament wire to tungsten/rhenium wire and determine the performance of the new thruster.

IMMERSED HEATER THRUSTER
SPECIFIC IMPULSE AS A FUNCTION OF SPECIFIC ENERGY

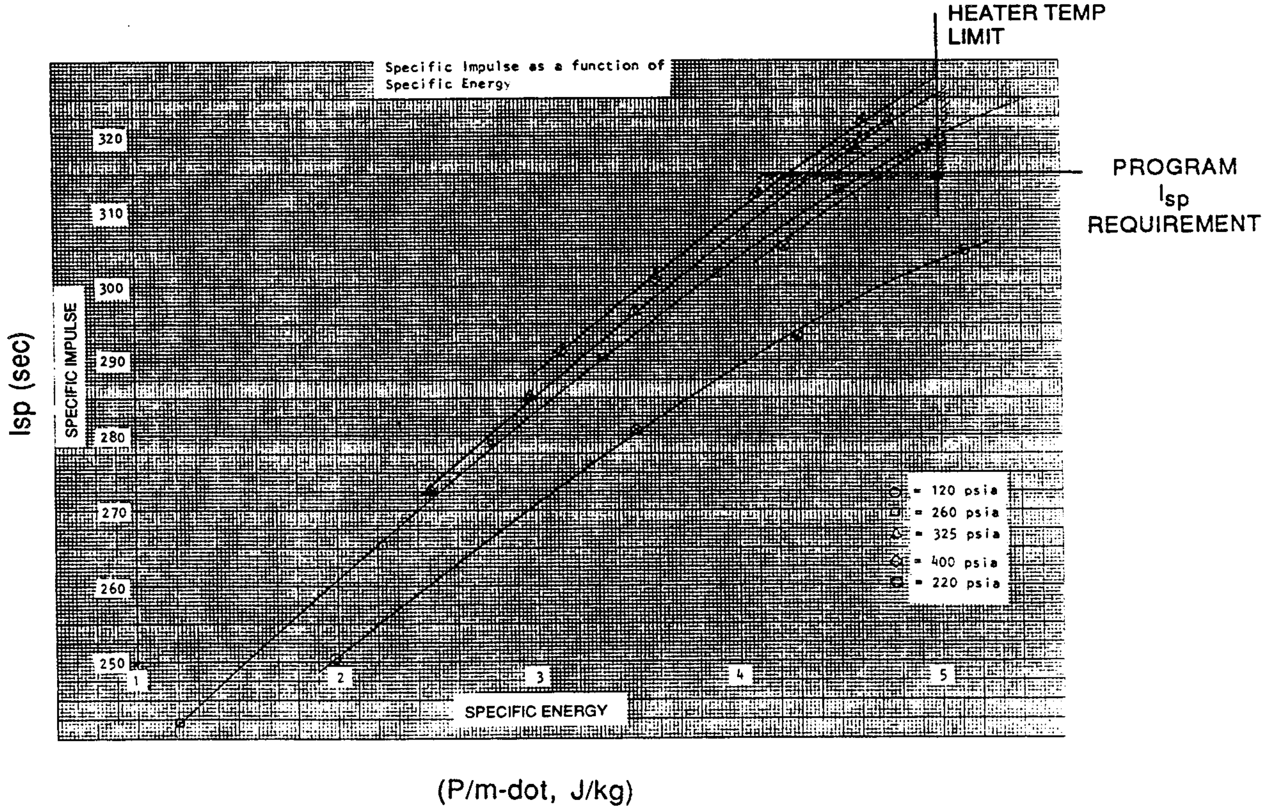


Figure 2-52

CLOSEUP OF IMMERSED HEATER THRUSTER NOZZLE SHOWING CRYSTALLINE MATERIAL IN THROAT

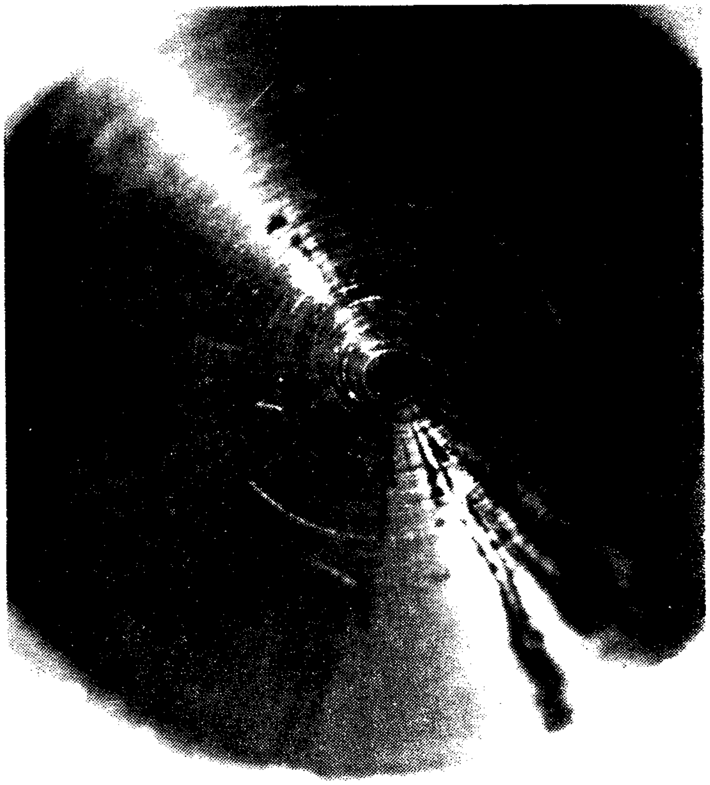


Figure 2-53

4. Complete a low power, high mass flow performance test of the rhenium heat exchanger vented radiative wire (i.e. "fast track") thruster. Possibly enter a life test.
5. Perform a material characterization test (e.g. tungsten, tungsten/rhenium, and other wire over a range of temperatures in decomposition products for several hundred hours).

The recommendations of the meeting were the following:

1. Summarize power, thrust, efficiency, and I_{sp} data for the immersed heater thruster, the vented radiative wire thruster and other low power EP devices. Present a summary to spacecraft managers and assess mission sensitivities to these parameters.
2. Based on the outcome of the above assessment assemble and test either a further improved version of the immersed heater thruster or the vented radiative wire EHT.

Figure 2-54 compares I_{sp} as a function of specific energy (p/m-dot) for the "fast track" and immersed heater thrusters. Specific energy for the immersed heater thruster (immersed heater thruster) is limited by the allowable wire temperature. Figure 2-55 shows that the immersed wire thruster is capable of greater thrust levels than the radiative wire thruster. Without flow over the filament the radiative wire thruster can tolerate higher wire temperatures. Figure 2-56 illustrates the relationship of thrust efficiency to specific impulse. The radiative wire offers high specific impulse but produces less thrust for equivalent power than the immersed wire thruster.

HIGH PERFORMANCE STORABLE PROPELLANT RESISTOJET PROGRAM

Specific Impulse as a Function of Specific Power

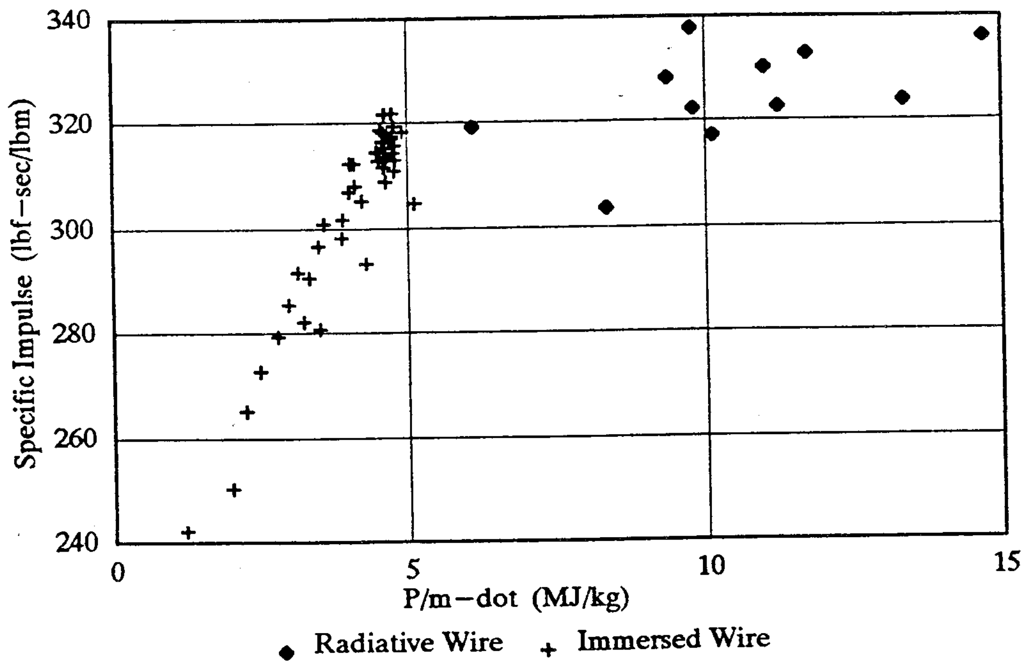


Figure 2-54

HIGH PERFORMANCE STORABLE PROPELLANT RESISTOJET PROGRAM

Thrust as a Function of Heater Temperature

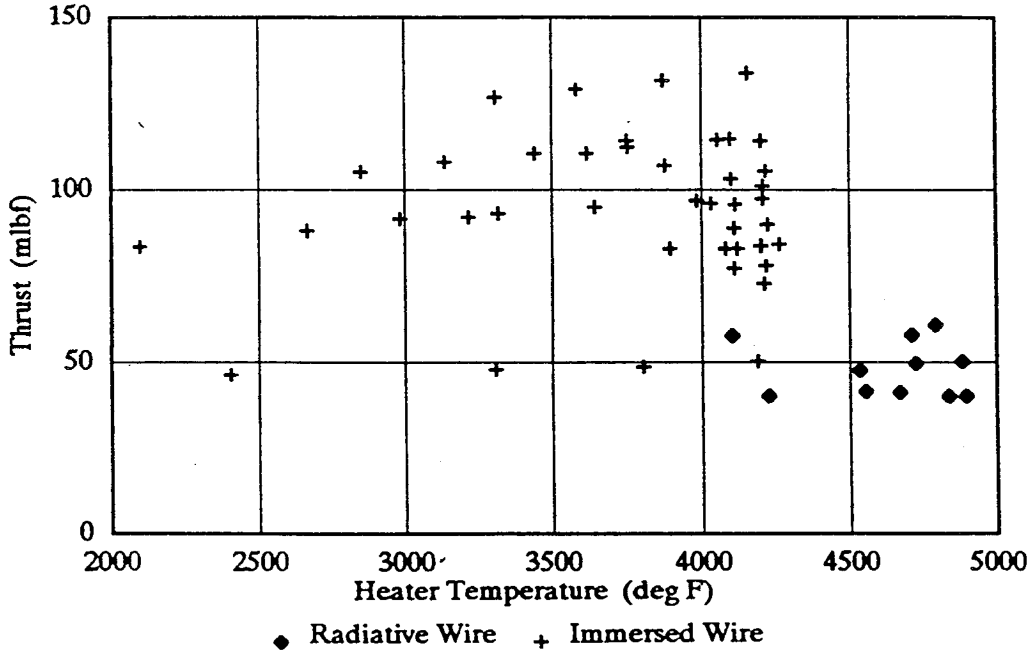


Figure 2-55

HIGH PERFORMANCE STORABLE PROPELLANT RESISTOJET PROGRAM

Efficiency as a Function of Specific Power

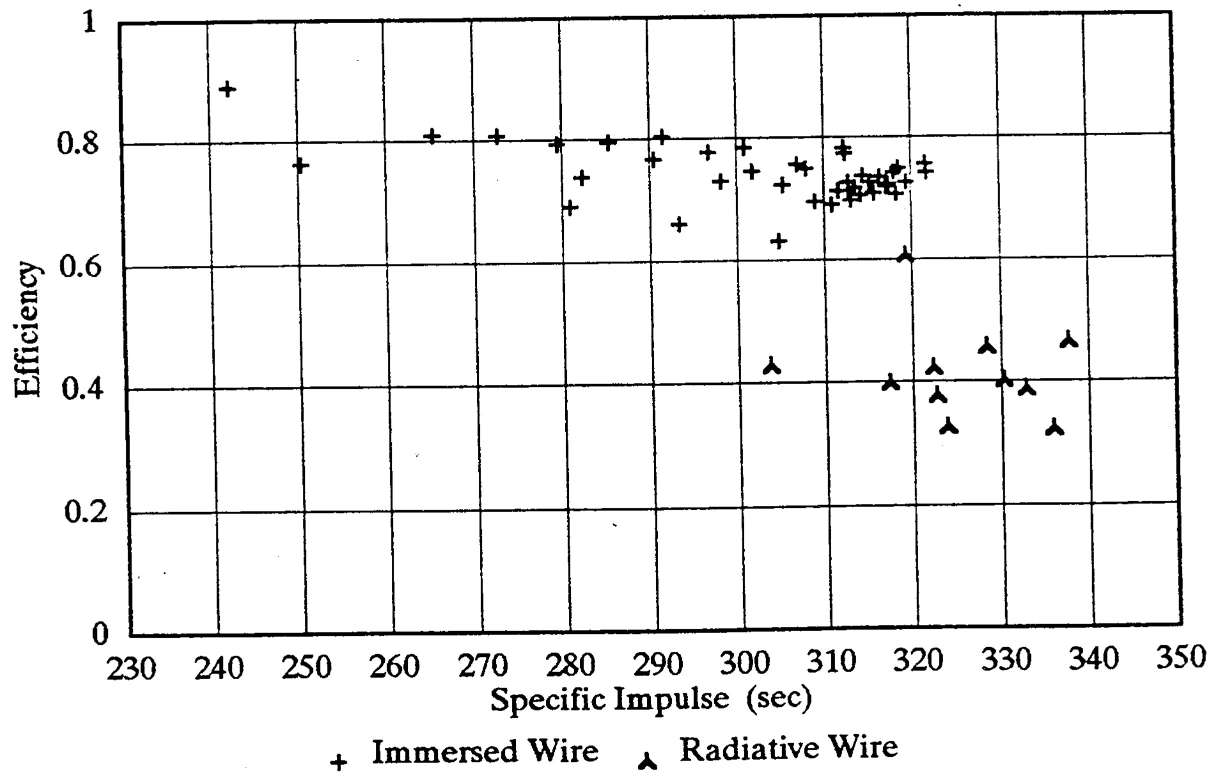


Figure 2-56

2.3.5 Immersed Heater Follow-up Testing

After reviewing the above results the recommendations were amended as follows:

1. Resume parametric or life characterization using the immersed heater thruster and fully characterize the failure.
2. Lower the wire temperature to a "safe" level (e.g. 3900°F and continue the life test at a lower performance level (e.g. 310 sec I_{sp}). Continue this test until program resources are depleted.

The immersed heater thruster was reinstalled in the test cell. Argon testing was attempted first. Five tests were completed with filament temperatures ranging from 3800° to 4200°F. At 4200°F, there was a gradual downward drift of the heater current. Following the test the cold resistance had changed from 0.343 ohms to 0.395 ohms. No crystalline material was observed in the throat or elsewhere. The thruster was blue indicating that gO_2 may have reacted with the molybdenum in the Mo/41Re nozzle body. The witness plates shattered so that data were not obtained as planned

The original plan was to complete the argon analysis and start N_2/H_2 testing. However, the results of the argon testing showed that testing with N_2 would introduce unacceptable risk of additional damage to the hardware. A decision was made to proceed with H_2 testing. Test software was modified to compensate for heater resistance changes. The slope of the resistance vs. temperature curve was modified to compensate for mass loss in previous testing. Two H_2 test series were completed at 250 and 500 W with filament temperatures up to 4300°F with no heater degradation. An NH_3 test series was completed and there was no heater degradation.

A special Ultra-Pure N_2H_4 propellant sample was obtained with lower than usual trace quantities of CO_2 and H_2O. This propellant minimized sources of atomic oxygen that was suspected as a mechanism causing filament degradation.

A separate feed system for the Ultra-Pure N_2H_4 propellant was constructed to assure that the specially prepared anhydrous propellant absorbed no water from the ambient atmosphere. The feed system was cleaned, dried, and purged with dry GN_2. The special propellant was shipped in reagent bottles. For propellant loading the bottles were tapped in a GN_2 atmosphere with a dual hole stopper. Propellant was vacuum transferred into the feed system. In this way the only material the propellant was exposed to was dry GN_2.

An unaugmented burn-in using the special N_2H_4 was completed. The unaugmented N_2H_4 P_c had returned to the value recorded prior to the Ar tests (179 vs 186 psia). This suggested that testing with reducing gases (i.e. H_2 and NH_3) had restored the hardware to its original condition. Most likely a small amount of material deposited around the throat was eliminated by testing with these gases.

The Ultra-Pure N_2H_4 propellant test was performed at filament temperatures of 4000°F and 4100°F. A decline in current at constant voltage indicated further heater mass loss. The conclusion drawn for N_2H_4 was that any heater temperature that would produce an acceptable I_{sp} resulted in unacceptable filament mass loss rates. A cold resistance check revealed the resistance was still 0.395 ohms. Evidently, the declining current at constant voltage was a more sensitive indication of heater mass loss than the cold resistance.

2.3.6 Analysis of Filament Mass Loss Mechanism

Using a chemical kinetics program the quantities of oxygen bearing species in the N_2H_4 decomposition products were estimated. Atomic oxygen was of particular concern since it is the most reactive specie. Argon with 1 ppm oxygen produces an O-atom concentration 3 orders of magnitude higher than hydrazine with 0.5 percent water at the typical filament temperature. Hydrogen with 0.5 ppm oxygen produces an O-atom concentration 3 orders of magnitude lower than hydrazine with 0.5 percent water at the filament temperature. Figure 2-57 presents the results of this analysis for compositions of the gases used in the test sequence. Pressure had only a minor effect on the concentration level.

A close examination of the argon test data revealed that the heater degradation began to appear at a 4000°F filament temperature. A complete set of data plots for the top 3 temperatures were generated and are presented in Figure 2-58. The negative slopes clearly seen for the 4100° and 4200°F cases correspond to heater mass loss.The H_2 test data do not show current declines. Cold resistance measurements also showed that there was no additional mass loss.

Testing of the immersed heater thruster performance with argon, H_2 at 230 W, H_2 at 500 W, and NH_3 are summarized as follows:

Isp for Resistojet Gas Test Cases (sec)

	Filament Temperature (°F)					
Case	**3800**	**3900**	**4000**	**4100**	**4200**	**4300**
Argon	123	124	126	126	123	—
H_2 250 W	461	472	474	482	490	483
H_2 500 W	—	—	527	537	536	—
NH_3	246	241	240	242	252	—

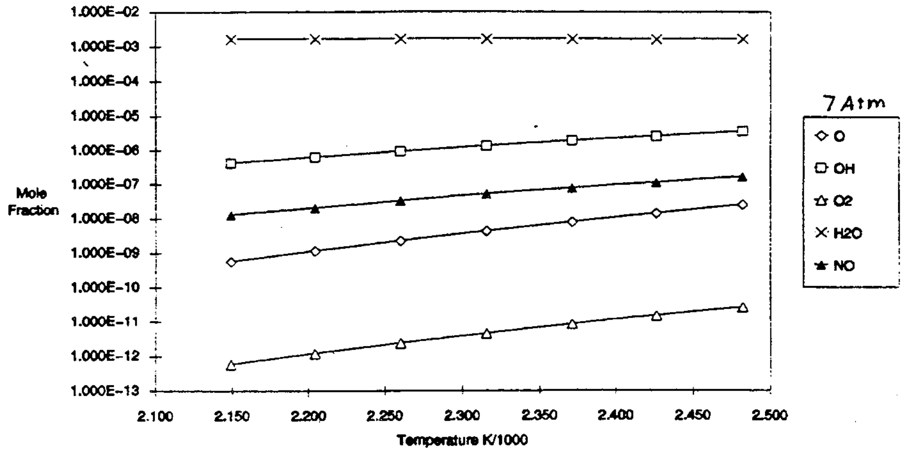
Time at Temperature (min)

	Filament Temperature (°F)					
Case	**3800**	**3900**	**4000**	**4100**	**4200**	**4300**
Argon	33	46	44	41	178	0
H_2 250 W	80	78	68	70	131	71
H_2 500 W	0	0	70	71	71	0
NH_3	106	67	77	68	72	0
Total (hrs)	3.7	3.2	4.3	4.2	7.5	1.2

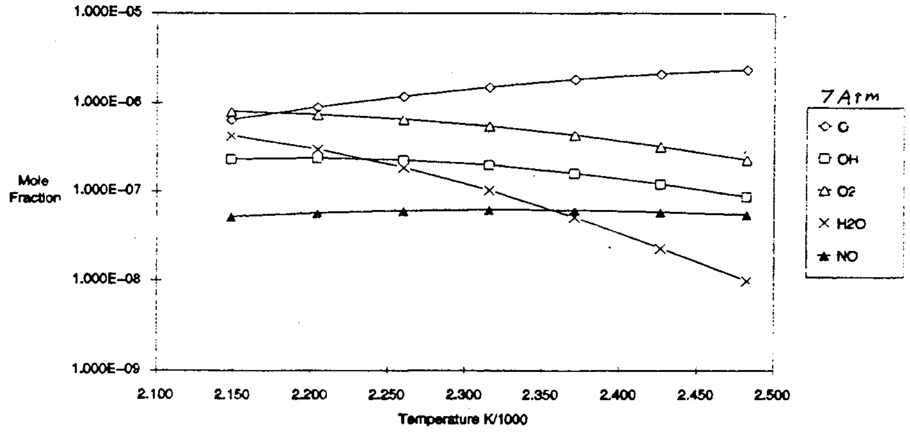
C-2

CONCENTRATION OF OXYGEN BEARING SPECIES FOR THREE PROPELLANTS

Equilibrium Composition of 0.5% Water in N2H4



Equilibrium Composition
of 1PPM Water & 1PPM O2 in Argon



Equilibrium Composition
of 1PPM Water & 0.5 PPM O2 in Hydrogen

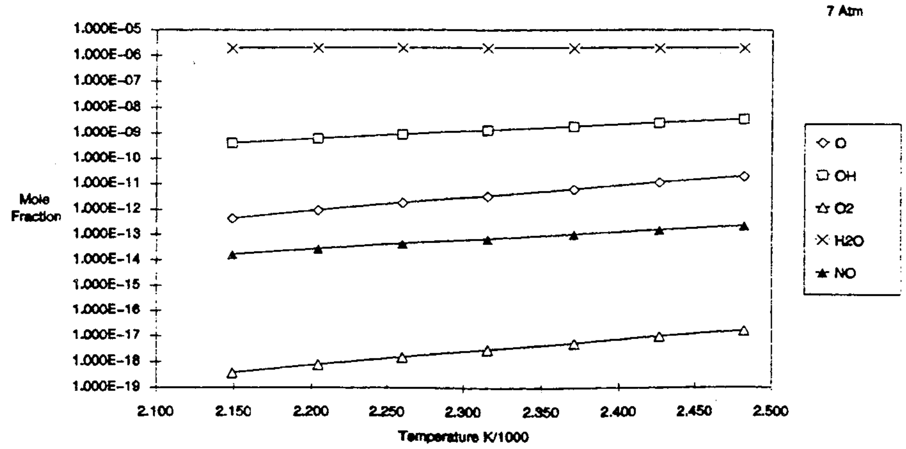
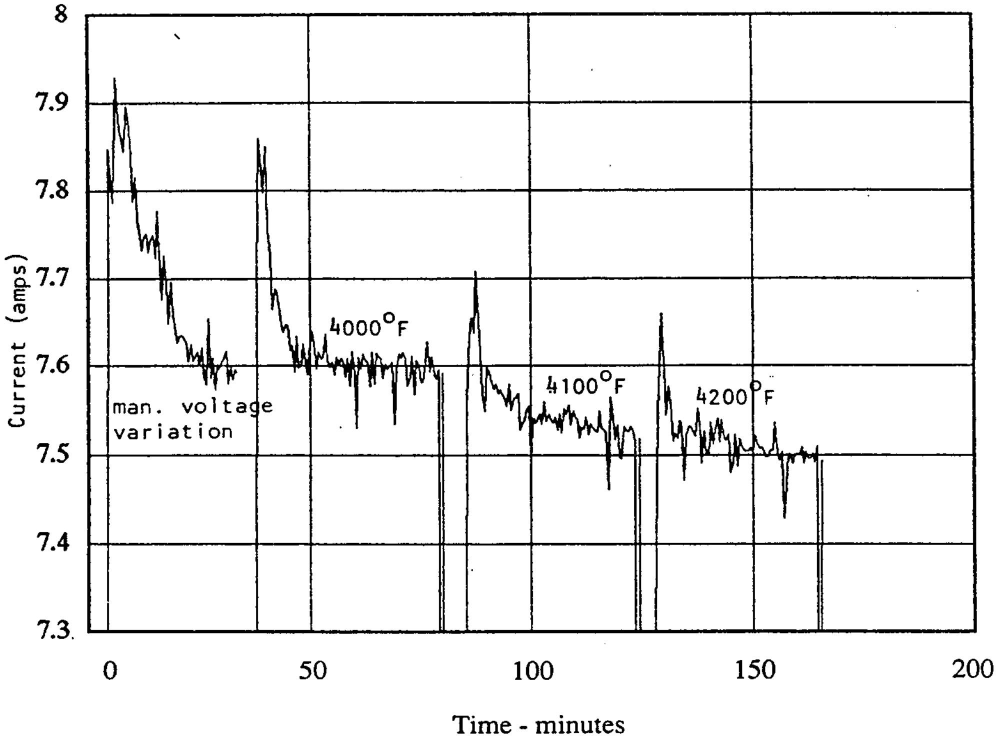


Figure 2-57

CURRENT AS A FUNCTION OF TIME WITH HEATER DEGRADATION OCCURING (Ar) AND WITHOUT SIGNIFICANT HEATER DEGRADATION (250W H_2)

Ar



250 H_2

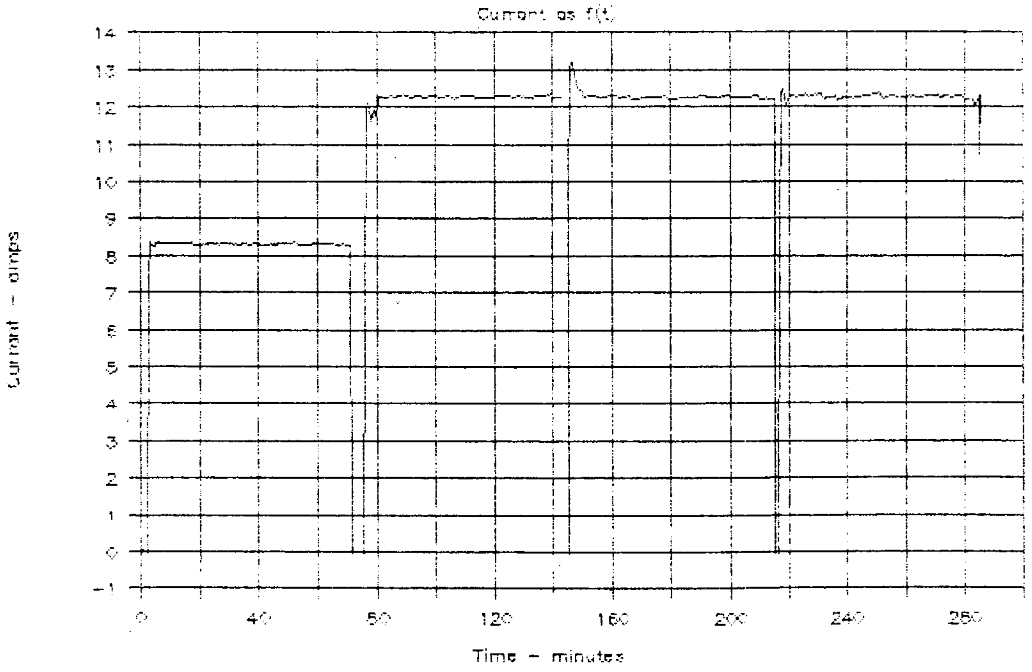


Figure 2-58

There was a grand total of 24.1 hours of testing at temperature in the gas test cases. The first 5.7 hours with argon resulted in a 15% heater degradation. The remaining total of 18.4 hours resulted in no additional measurable heater degradation.

2.3.7 Results and Conclusions from Phase III

The key measured variable for the N_2H_4, H_2, NH_3, and Ar tests turned out to be current at constant voltage. Decreases in current were proportional to the loss of mass from the heater filament wire. During constant power testing, the voltage was continuously adjusted to compensate for heater variation. This masked the current decline effect. During the argon test series voltage was held constant and current was allowed to vary.

Figure 2-59 illustrates the current traces for each of the gas and dry N_2H_4 tests at 4100°F (4000° and 4200°F are similar). The current decay is not visually apparent due to the scale. However, minor changes in a one hour test have major implications for a 100,000 lb-sec impulse requirement. Some of the variation noted is caused by mass flow variation due to regulator cycling when using lower pressure gas cylinders.

Regression analysis of these curves was performed. The start and stop transients were eliminated by calculating regression equations only for "constant" voltage data points. One hypothesis was that atomic oxygen was related to heater degradation. Using values of 1 ppm for oxygen, 0.5 ppm for water, and 0.5 ppm for carbon dioxide for the gases tested, the pressure for test cases, and a temperature of 4100°F, a chemical kinetics code was used to determine the O-atom concentration. The results were as follows:

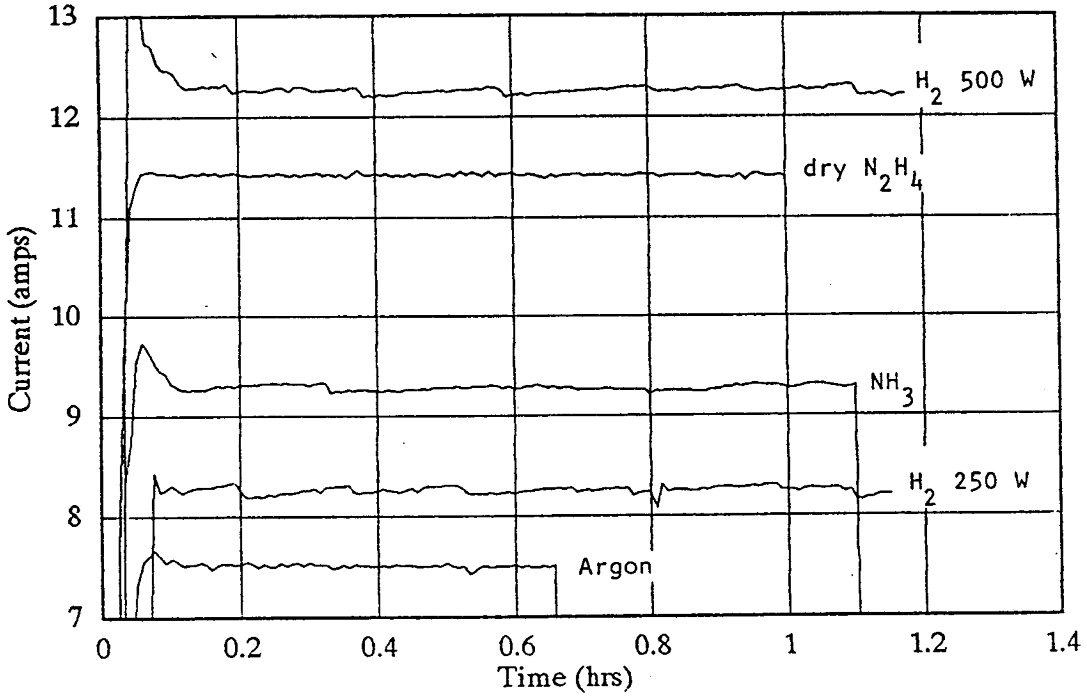
Test condition	O-Atom mole Fraction
Argon	2.74×10^{-6}
H_2 at 250 W	1.08×10^{-10}
H_2 at 500 W	5.29×10^{-11}
NH_3	5.17×10^{-11}
Dry N_2H_4	1.15×10^{-8}

The second plot in Figure 2-59 presents the heater degradation rates derived from the regression analysis plotted as a function of O-atom concentration, all 4100°F. The data confirm the hypothesis that increases in O-atom concentration result in greater heater degradation rates. The figure also indicates that at 4100°F no propellant would be acceptable for a life test. For instance, dry hydrazine (0.15% water by weight) would have a 78% current decline in a 400-hour test. Clearly, the heater element would fail long before the end of the test. Even the minimum degradation rate would result in a 17% current decay in 400 hours.

In conclusion, an I_{sp} of 315 cannot be attained with the immersed heater thruster unless the filament temperature is greater than 4100°F. However, at that temperature there are unacceptable rates of heater degradation.

ATOMIC OXYGEN EFFECTS ON IMMERSED HEATER FILAMENTS

High Performance Storable Propellant Resistojet
Current Drift Over Time at 4100 deg. F



High Performance Storable Propellant Resistojet
dI/dt vs. [O] for Various Gases

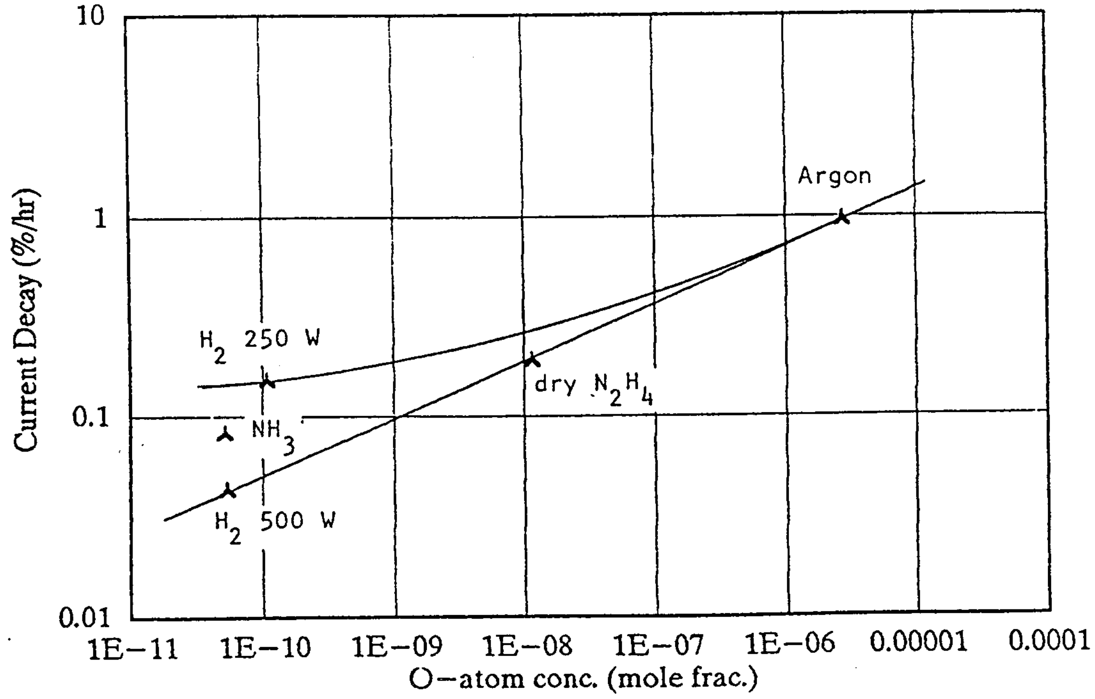


Figure 2-59

2.4 PHASE IV — MATERIALS AND GAS GENERATOR EXPERIMENTS

At the completion of the immersed heater test series it was apparent that the thruster was not suitable for a life test due to unacceptable rates of heater mass loss at acceptable performance levels. A number of new options to conclude the technical effort on the program were considered including:

1. Evaluation of materials.
    a. One proposed materials effort was to evaluate materials selected to avoid O-atom degradation at high temperature in N_2H_4 decomposition products. For instance, rhenium additions to tungsten were predicted to help resist O-atom attack. Iridium or other refractory metal coatings were another approach.
    b. Throughout the immersed heater thruster test, the leak performance of the heater passthrough seal was suspect. Another materials test program proposed was to characterize joining and sealing techniques for refractory metals and ceramics (perhaps with braze seals) at moderate temperature in N_2H_4 decomposition products.
    c. An effort was proposed to develop the application of high emissivity coatings to refractory metals (i.e. tungsten).
2. Low flow gas generators exhibit combustion instability due to minimal injector pressure drop and limited life due to feed-tube blockage. Low-flow resistojets needed improvements to existing gas generator designs to extend life and improve stability, and an effort was proposed to test a candidate design.
3. An ammonia performance characterization test of the TRW/ETT was proposed.
4. Another proposal was made to rebuild and test the rhenium heat exchanger EHT in an attempt to meet the program performance requirements.
5. Finally, a proposal was made to build and test an immersed heater thruster with W/3Re wire and a higher Reynolds number injector.

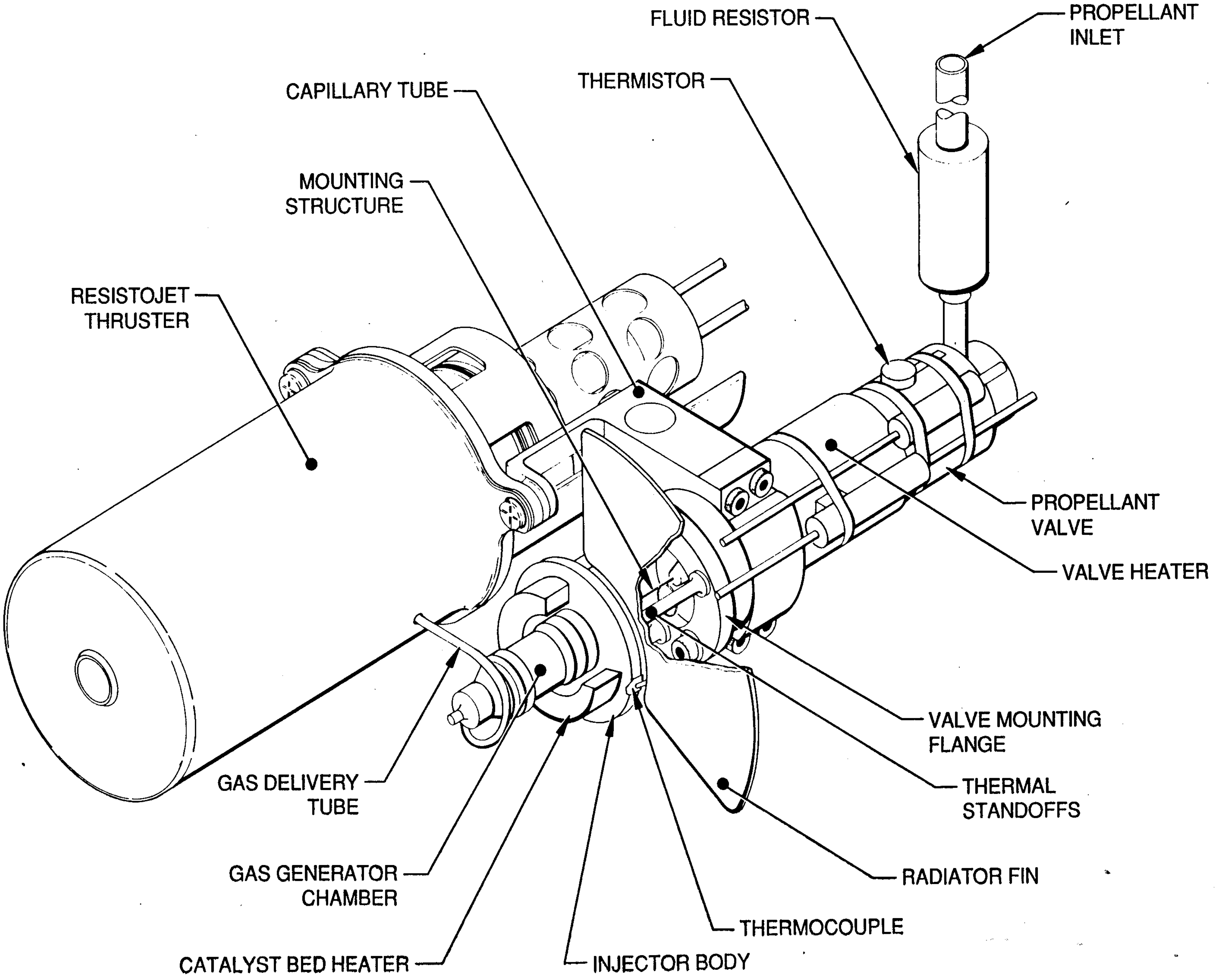
The HPSPR program was redirected to demonstrate an enhanced hydrazine catalyst bed for electrothermal thruster applications and investigate thruster material/hydrazine decomposition product interactions.

2.4.1 Gas Generator Demonstration

RRC provided a proprietary design gas generator, illustrated in Figure 2-60, at no cost to the HPSPRP program. This gas generator had a number of design enhancements to increase its life. The gas generator was transferred to the HPSPRP following assembly, vibration and functional tests. The HPSPRP performed a life test with a goal of 850 hours of hot firing time over a blow-down range of 300 to 220 psia. An outlet heater with an orifice sized to control flow simulated an electrothermal thruster during the life test.

The gas generator was installed in RRC Cell #6. The test configuration consisted of the gas generator (GG), valve/fluid resistor, and a resistance heater assembled to an MR-501 mounting structure. The heater, mounted in place of the thruster, was sized to provide electrothermal thruster heat loads simulating electrothermal thruster firing thermal environment.

RRC ADVANCED GAS GENERATOR



11232-56

Figure 2-60

2.4.1.1 Gas Generator Test Results

Initial firing performance mapping consisted of 30 and 60-minute steady-state burns to characterize gas generator performance. Approximately 12 hours of total firing time were accumulated. Initial runs were conducted to correctly size an orifice for the GG outlet. Since the GG was not coupled to a thruster for this testing, orifices were installed in incremental sizes until representative values of GG chamber pressure (P_c) over the desired flow rate range were achieved. An outlet orifice diameter of 0.014-in. was selected. Baseline data were acquired in this configuration.

GG steady-state performance was consistently stable throughout these runs with smooth chamber pressure and flow characteristics. The life test was on a 24-hour-per-day basis using computer control. The feed pressure blowdown schedule shown in Table 2-11 was followed.

Table 2-11
LIFE TEST FEED PRESSURE BLOWDOWN SCHEDULE

	P_f (psia)	Duty Cycle (hrs on/off)	Firings	Hours
Performance	220—300	0.5/AR	17	12
BOL Block	300	1–1.25/0.5–0.25	AR	178
MOL Block	257	1.25/0.25	344	430
EOL Block	220	1.25/0.25	184	230

As noted in Table 2-11, an adjustment in the duty cycle was made during the beginning-of-life block from 1 hour on/0.5 hour off to 1.25 hour on/0.25 hour off. This change was made after the temperature profiles on cool down were evaluated during the initial cycles of the life test. Within an 0.25-hour off period, the catalytic chamber temperature cooled below the minimum limit (200°F) required to restart the GG. Based on this evidence, the duty cycle was adjusted slightly. The total run time in a 24-hour period was therefore increased from 16 to 20 hours.

Life test data are shown in Figures 2-61 through 2-63. Figure 2-61 shows the chamber pressure and flow rate levels which correspond to the BOL feed pressure block. Small excursions in the data are due to differences in feed pressure levels established when the propellant tank is pressurized following refueling or test shutdowns. Figure 2-62 shows gas generator catalytic chamber temperature. The large drop in temperature between 36 and 41 hours was traced to a faulty thermocouple attachment which was repaired. The measured chamber temperatures between 900° and 950°F were consistent with expected values.

The quantity $P_f\text{-}P_c/\dot{m}^2$ shown plotted in Figure 2-63 is useful for observing changes in pressure losses in the test hardware. Of specific interest is the pressure drop through the GG injector, which is typically very small at the arcjet flow rates. If the pressure losses through both the fluid resistor and valve are assumed to remain constant, an increase or decrease in $P_f\text{-}P_c/\dot{m}^2$ can be associated with a change in GG pressure drop. For example, life-limiting

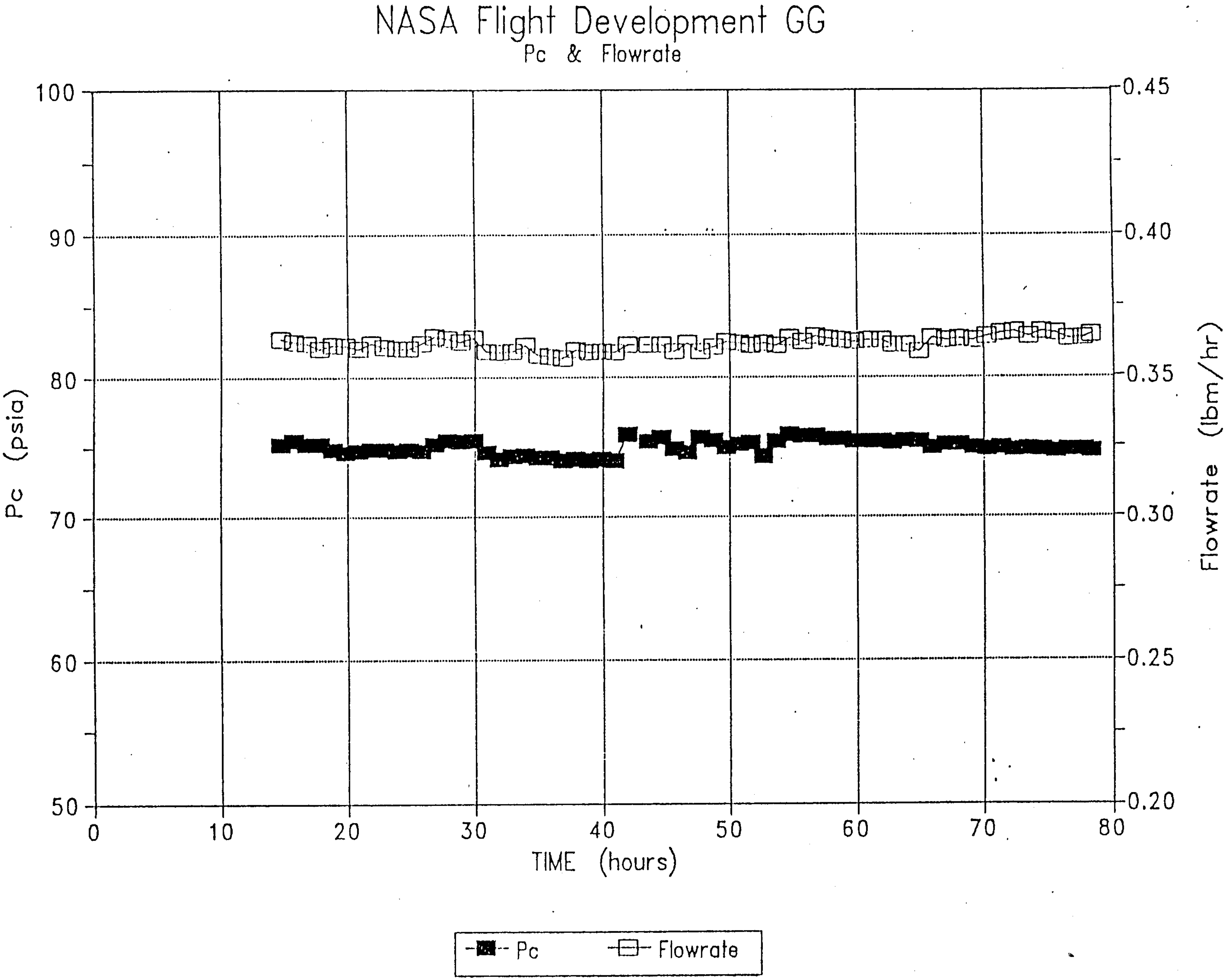

NASA Flight Development GG
Pc & Flowrate
Pc (psia)
100
90
80
70
60
50
Flowrate (lbm/hr)
0.45
0.40
0.35
0.30
0.25
0.20
0
10
20
30
40
50
60
70
80
TIME (hours)
Pc
Flowrate

Figure 2-61

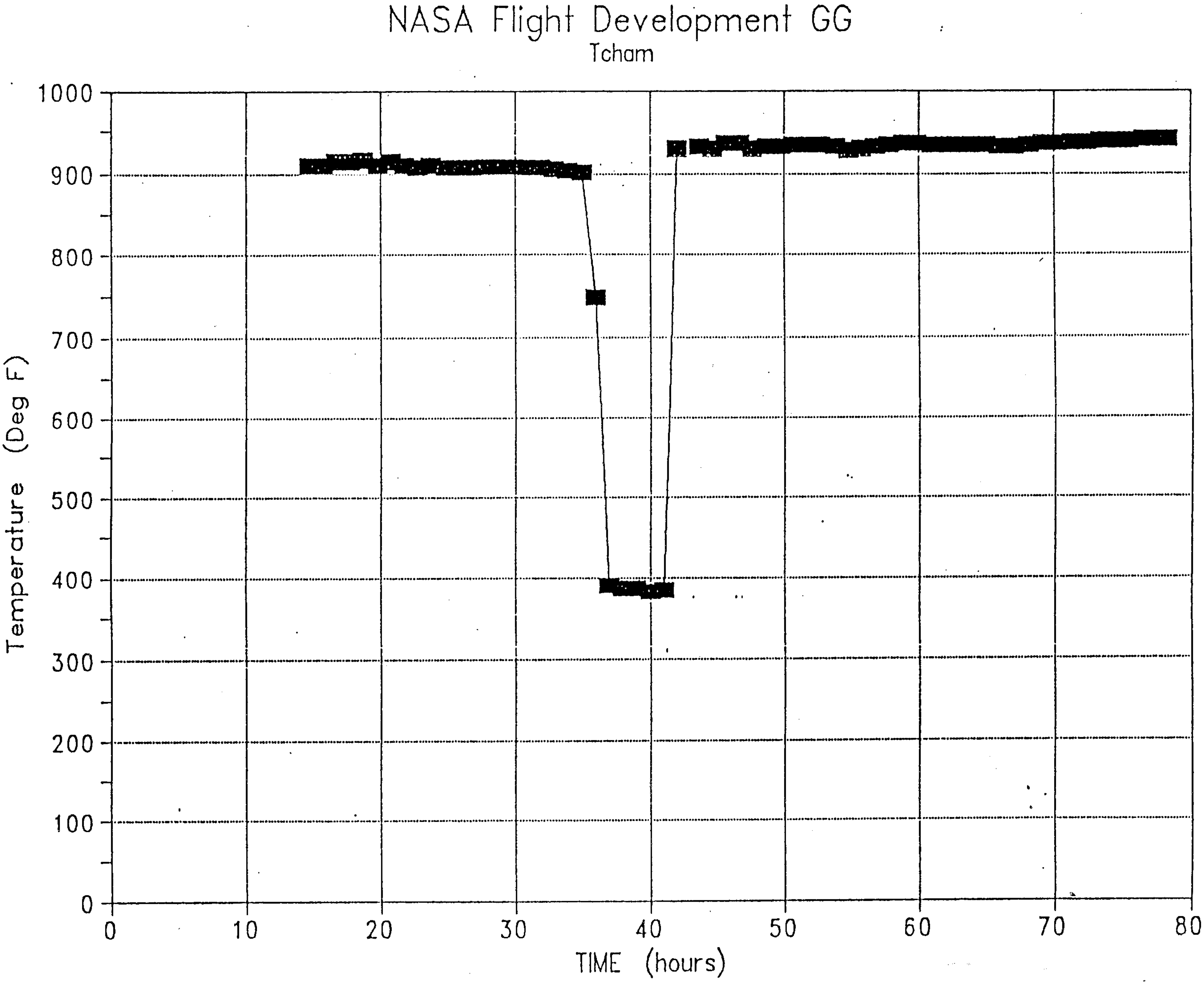

NASA Flight Development GG
Tcham
Temperature (Deg F)
0
100
200
300
400
500
600
700
800
900
1000
TIME (hours)
0
10
20
30
40
50
60
70
80

Figure 2-62

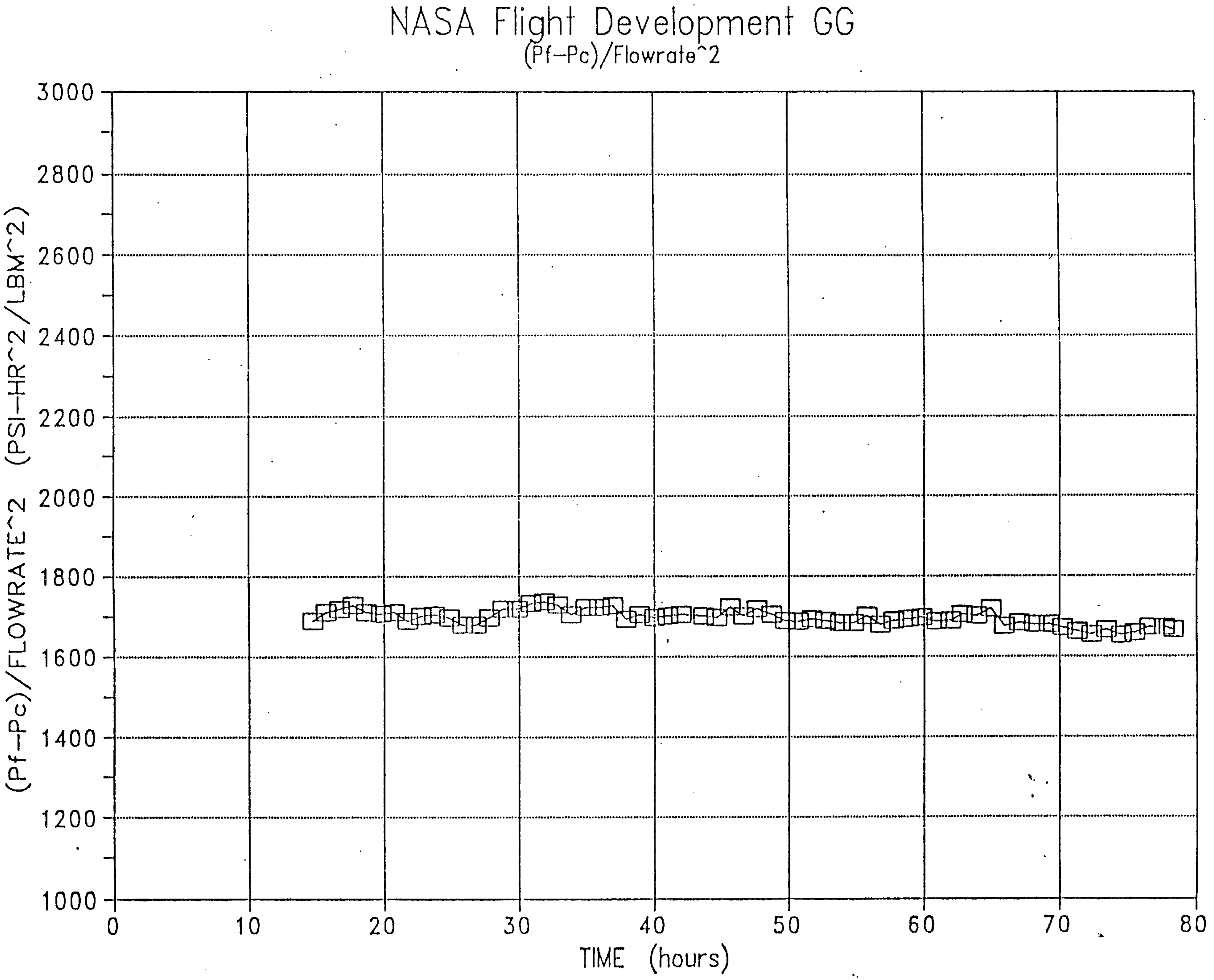

NASA Flight Development GG
(Pf–Pc)/Flowrate^2
(Pf–Pc)/FLOWRATE^2 (PSI–HR^2/LBM^2)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
0
10
20
30
40
50
60
70
80
TIME (hours)

Figure 2-63

clogging of injector flow manifests itself through a substantial increase in this parameter. Figure 2-63 indicates that consistent flow conditions through the GG were maintained with no detectable changes in injector pressure drop. No other measured data indicated degradation in GG performance.

Additional data are included in Appendix G. The following is a summary of the hot fire testing completed:

1. Demonstrated Capability

Total lifetime (hrs)	887
Total propellant throughput (lbm)	293
Total number of starts	730
Flow rate (lbm/hr)	0.360 to 0.305 in simulated blowdown

2. End-of-life gas generator condition
   - No detectable loss in performance
   - Flow rate vs. feed pressure characteristic agrees with beginning of life measurement.
   - Pressure drop through GG injector (i.e. $(P_f - P_c/\dot{m}^2)$) remains constant; no restrictive clogging is evident.
   - No chamber pressure roughness or oscillations.
   - Injector temperature maintained within expected design limit.
3. Conclusions
   - Significant additional life margin appears to exist.
   - High level of confidence has been established in this GG design to meet near term qualification requirements in the tested flow rate range and thermal environment.
   - Extended life testing and comprehensive disassembly and inspection are recommended.

2.4.2 Material/Hydrazine Decomposition Products Interaction Study

In electrothermal thrusters a variety of metals are exposed to N_2H_4 decomposition products at elevated temperatures. Testing with resistojets indicated that atomic oxygen (AO) in N_2H_4 decomposition products attacks tungsten filaments. Several candidate materials and coatings were targeted for test evaluation to address various parts affected by AO attack in N_2H_4 decomposition products. Coupon and filament tests were conducted to evaluate various material problems. Table 2-12 is a summary of these parts and materials.

2.4.2.1 Coupon Test Results

Coupons needed to complete the materials testing were fabricated (1 by 1 cm each). For coupon tests N_2H_4 decomposition products with AO were simulated using NH_3 saturated with H_2O. This was accomplished by bubbling the NH_3 through liquid H_2O. The saturated gas continuously passed over the coupon samples in a tube furnace that heated the coupons to temperatures close to electrothermal thruster internal temperatures (2100°F). Samples of

Table 2-12
MATERIALS AND APPLICABILITY IN ELECTROTHERMAL THRUSTERS

Material	Problem	Type of Part	Type of Test
Mo/41	Attack Creep	Thruster body Injectors Heat exchanger body	Coupon
W 100	Evaporation AO attack	Heater Anodes	Filament coupon
W/3Re	New material	Heater	Filament
W/25Re	New material	Thruster body Anode Heat exchanger body	Coupon
Ir coating (on W)	New process	Injectors Anodes	Coupon
Ir coating (on Mo41Re)	New process	Injectors Anodes Heat exchanger body	Coupon
Rhenium	Machining Availability Cost	Heat exchanger body Injectors	Coupon

tungsten (W100), tungsten-rhenium (W/25Re), molybdenum-rhenium (Mo/41Re), rhenium (Re), and iridium chemically vapor deposited on tungsten (Ir CVD W) that had previously been exposed to the same conditions under a commercial arcjet program effort were processed for an additional 390 hours during this test. All samples were exposed to 493 hours at 2100°F 25°F in moist ammonia containing 1% water. Table 2-13 provides the test results.

All samples held up quite well, except the Mo/41Re which lost considerably more weight and had a serious fracture problem. The iridium coating on the tungsten began to flake off at about 150 hours. Iridium coating of on Mo41Re was not tested.

The tungsten sample with a 0.001-in. thick chemically vapor deposited iridium was exposed to thermal cycling between 2100° and 200°F. Testing was accomplished by cycling the part on a shuttle into and out of a tube furnace held at 2125°F. A nitrogen atmosphere was provided to protect the part at high temperature and an increased flow over the part during cooling to help accelerate cooling. Table 2-14 lists the results of testing on these samples:

Table 2-13
TESTING @ 2100°F WITH 1% MOISTURE IN AMMONIA

Sample	103 Hrs % Wt Gain/Loss	493 Hrs % Wt Gain/Loss
IrCVDW	+0.0078	+0.026*
W/25Re	+0.0087	0
Mo/41Re	-0.205	-0.366
Re	+0.0038	+0.015
W100	-0.022	-0.026

Sample	Appearance
IrCVDW	● Ir coating unchanged. Bare W showed dull greying. Fractured surface was black. No visible cracks.
W/25Re	● Polished surface still had some reflective properties. No visible cracks.
Mo/41Re	● Polished surface still had some reflectivity. Sample had cracks that appeared to penetrate through the piece, i.e. cracks continued from one surface into the adjoining surface.
Re	● Strip had original appearance and is reflective. No visible cracks.
W100	● Polished surface was totally nonreflective, dull, grey. No visible cracks.

Table 2-14
CYCLING BETWEEN 2100° AND 200°F UNDER A NITROGEN ATMOSPHERE

Cycles	Wt (g)	% Wt Gain	Appearance
0	42.0164	—	● Typical "white" Ir color
55	42.0153	-0.0026	● Reddish brown on top OD
103	42.0149	-0.0036	● Reddish brown increasing. Upstream 40% ID has smoother appearance.
205	42.0163 (42.0148 – chips)	-0.0002	● Coating flaking and chipping on upstream end. Reddish brown area increasing.
302	42.0103	-0.0145*	● Severe flaking. Upstream bore coating is loosened. Reddish brown surface on all exposed W substrates.

* This value includes change due to lost flakes

Earlier IR&D testing of Ir CVD W and Re CVD W showed that the Re CVD W was not satisfactory while the Ir CVD W showed crack formation thought to be due to a heavy coating of iridium. A thinner coating sample was also tested. This sample showed promise until a reddish brown coloration started to form. The nitrogen flow was at a lower level than on an earlier test, and air could enter the apparatus where the thermocouple/pushrod exited the apparatus. The sample was only about three inches away from the thermocouple exit port into which air could possibly back flow during the entire cooling cycle. The nitrogen flow was controlled by boil-off of LN_2. This flow apparently was not adequate to purge air from the T/C port. The type of coating, cracking noted on the earlier tested part was not found on the latest tested part. All test samples exhibited some form of failure.

2.4.2.2 Filament Test Results

Tungsten and W3Re wire were selected for filament tests. Each filament was wound from a length of 20 mil wire 18 inches long. The wire was coiled around 1/16-inch diameter tungsten welding rod to maintain a constant filament diameter. A constant pitch of about 23 turns per inch was achieved by wrapping the wire beside a filler wire which was separated from the filament following the winding process. The pure tungsten wire required heating up to 400° to 500°F during winding to prevent splintering, whereas the tungsten/3% rhenium wire was wound at room temperature. The resulting filament length was 3 inches.

The test apparatus is illustrated schematically in Figure 2-64. The filaments were held at each end by a TZM clamp which provided a low resistance electrical connection. A short length of the 1/16-inch diameter tungsten welding rod was placed inside the filament at the clamps to provide additional clamping force. The TZM clamps were mounted to a common piece of alumina which provided mechanical support of the assembly and electrical isolation. The alumina was wrapped with a stainless steel radiation shield under 80% of the filament length to minimize possible cracking due to the high level of heat loading. Two separate pairs of copper lead wires were fastened to each of the filament assemblies to provide both power and voltage measurements across the filament. The filaments were placed inside a 2-inch diameter, 4-foot long quartz tube with water cooled aluminum end plates which provided a sealed interface for the electrical and gas feedthroughs. One end of the quartz tube was used as the gas outlet, and the other as the gas inlet. On the outlet end, the gas line was routed into a bucket of water to provide a slightly higher than atmospheric pressure within the quartz tube. Each filament was powered by a DC power supply operating in voltage control mode. The output current of each power supply was measured by the voltage drop across a low resistance shunt. The voltage drop across each filament and the two current shunts were recorded on a 4-channel strip chart recorder. An optical pyrometer was used to measure the filament temperature during testing. A correction of roughly 500°F for the emissivity of the tungsten and transmissivity of the quartz was applied to the pyrometer readings as follows:

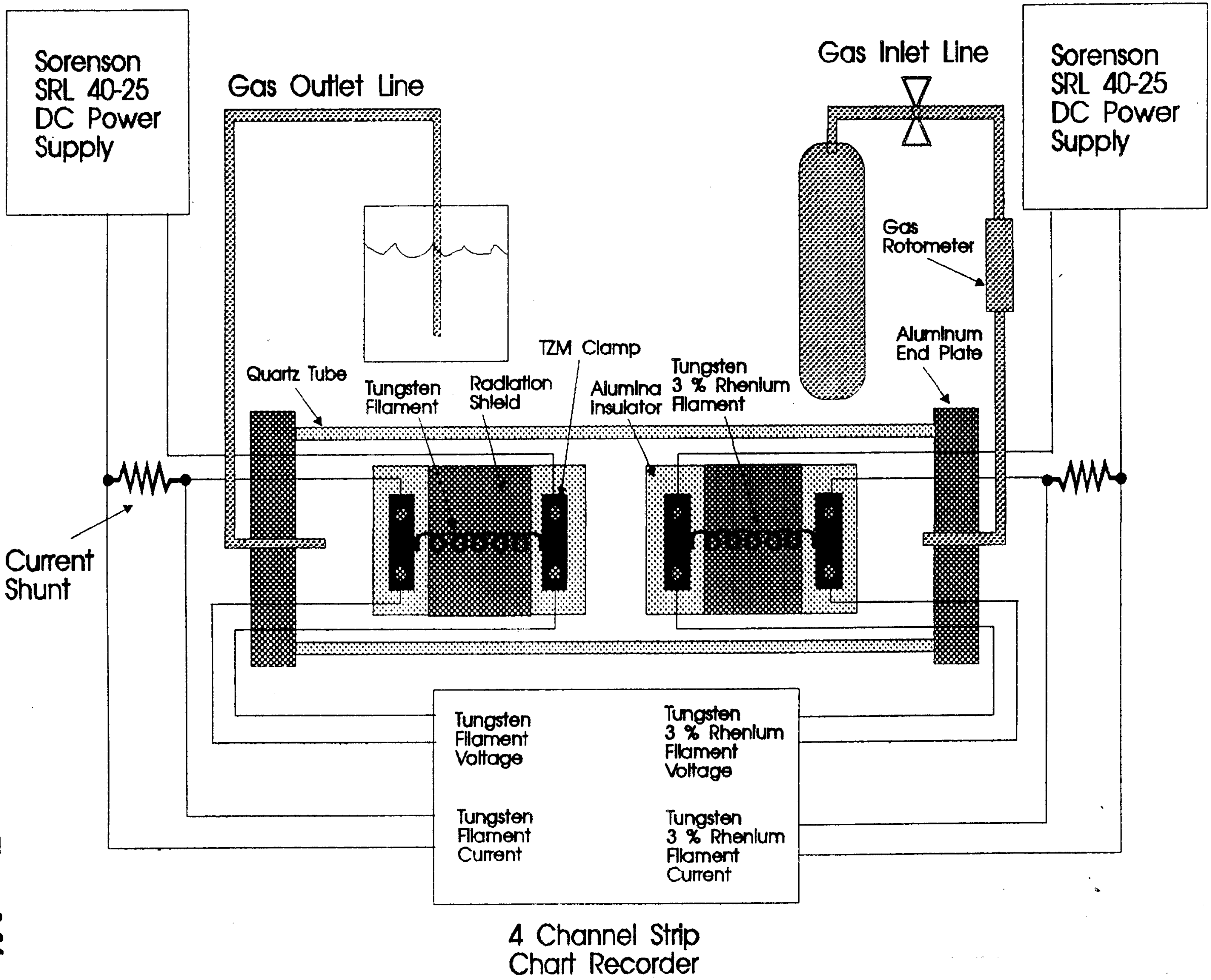
$$(1/T_t) = (1/T_p) + (w/C)(\ln(\varepsilon t))$$

where:

T_t = true temperature (K)

T_p = pyrometer indicated temperature (K)

Figure 2-64



Sketch of Experimental Apparatus

w = operating wavelength of pyrometer = 650×10^{-9} m
C = constant = hc/k = 0.0144 m-K
ε = emissivity of tungsten = 0.42 → 0.43 (2600 → 3200 K)
t = transmissivity of quartz = assumed constant at 0.92

Test Results

The filaments were first rapidly heated in a hydrogen environment with a gas flow rate of 1500 ml/min. The filament temperature was quickly raised to 4600°F and allowed to set for 3 minutes. The resulting electrical characteristics are tabulated below:

	Tungsten	Tungsten/3% Rhenium
Voltage (volts)	31.25	34.40
Current (amps)	24.40	25.00
Resistance (ohms)	1.281	1.376
Power (watts)	763	860

The filaments were then heated in an Argon environment (with 1.0 ppm O_2) with a gas flow rate of 1,000 ml/min. Each filament was maintained at a temperature of 4200°F while the resistance was monitored. After 38 hours at 4200°F, the resistance change of the pure tungsten filament was about 2.3%, and the tungsten/3% rhenium filament change was about 1.1%. The pure tungsten filament had sagged about 1/2 of an inch. In an attempt to increase the rate of degradation, the filaments were raised in temperature by 150°F. After one hour at the higher temperature, there was no measurable increase in resistance so the temperature was raised another 150°F. The test was then terminated after 17 hours at the 4500° level. No measurable change in resistance was seen, although the middle portion of the tungsten/3% rhenium filament was in contact with the radiation shield covering the alumina insulator due to sagging. Table 2-15 shows the results.

Table 2-15
TUNGSTEN AND TUNGSTEN/3% RHENIUM FILAMENT TEST RESULTS

Tungsten					Tungsten/3% Rhenium				
Volts	Amps	Ohms	Watts	Temp	Hours	Volts	Amps	Ohms	Watts
21.6	17.8	1.213	385	4200	0	22.0	17.8	1.236	392
21.6	17.5	1.234	378	4200	6	22.0	17.75	1.239	391
21.6	17.4	1.241	376	4200	32	22.0	17.6	1.250	387
24.0	18.25	1.315	438	4350	1	22.9	18.0	1.272	412
25.3	18.94	1.336	479	4500	17	24.5	18.75	1.307	459

The total accumulated time was 56 hours. After about 38 hours, a buildup of tungsten residue on the inner surface of the quartz tube made accurate pyrometer measurements difficult. Following test shutdown, visual observations showed a colorful dendritic buildup of material on the TZM clamps, steel mounting bolts, and tungsten weld rod tip. Samples were obtained for future material analysis. The filaments were observed under an optical comparator which showed a reduction in wire diameter only at the free ends closest to the clamps where the temperature gradient occurred. Measurements showed the pure tungsten filament experienced a wire diameter loss of 1 mil compared to a loss of 2 mil on the tungsten/3% rhenium filament.

The post-exposure wire examination was accomplished using dimensional wire analysis, scanning electron microscope analysis (SEM), and metallographic cross section analysis. The dimensional analysis was accomplished using an optical comparator to establish the wire diameter at five locations along the filaments length. The SEM analysis was performed on sections of the filaments removed from each end. This region of the filament was selected for SEM evaluation because dimensional data showed that the most mass loss occurred nearest the filament/test fixture interface.

With the completion of the SEM examination, the end segments of each filament were mounted for metallographic examination which allowed the correlation of SEM surface findings and observations with those obtained from the wires cross sections. All metallographic findings of interest were documented via photomicrographs.

Examination Results

The W/3Re filament lost more in cross section than the W218 (GTE standard lamp filament alloy) wire filament, as documented in Figure 2-65. Both filaments lost the most cross section in the cooler transition areas at each end of the filaments where the test fixture interface reduced the operating test temperature. This condition is most likely caused by the instability of the wire oxide that forms at the higher temperatures.

Evidence of thermal etching was observed on both filaments and redeposition and tungsten crystals was detected on the W218 filament. Documentation of the SEM surface examination findings is presented in Figures 2-66 through 2-70. The W/3Re wire surface formed surface voids which is evidence of localized thermal corrosion/oxidation of the wire substrate. The depth of penetration of these surface voids was established through the metallographic cross sectioning of the exposed filament material.

The cross sections of the exposed filament material revealed that incomplete wire recrystallization was produced during the filament thermal setting procedure. This would explain the cause of the wire sagging seen on the W218 filament, where little to no sagging is normally observed under the same thermal exposure conditions and durations. The cross sections of the filament material also revealed that the W/3Re wire subsurface voids had a depth of penetration of 0.0015 inch. The evidence of this void formation is documented in Figures 2-71 and 2-72.

Conclusion

Based on the observed post-test wire conditions, it can be stated that the W/3Re wire did not reveal any improved resistance to oxygen attack under the laboratory conditions used in this exposure test. The W/3Re wire was found to have lost more surface material as revealed by

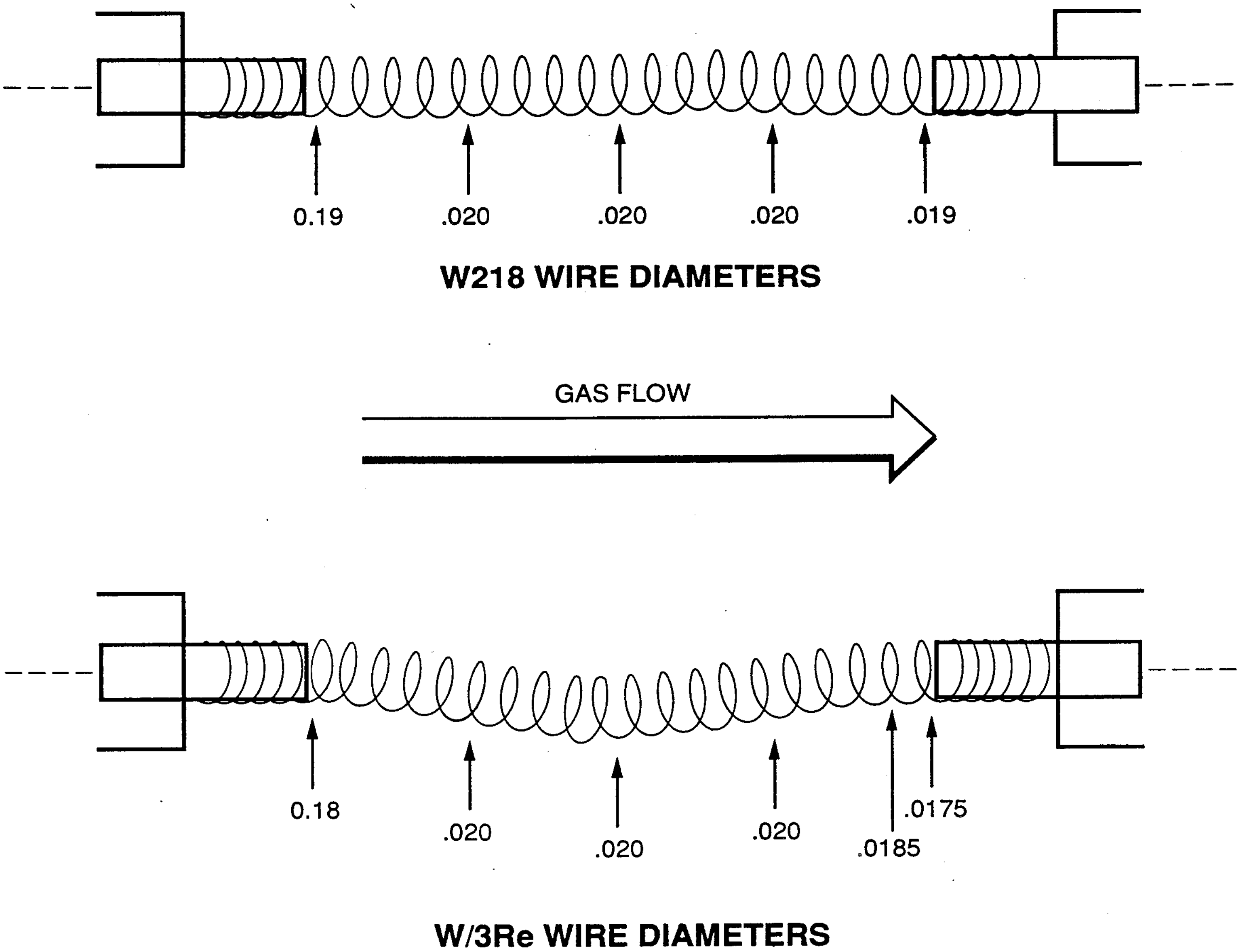

0.19
.020
.020
.020
.019
W218 WIRE DIAMETERS
GAS FLOW
0.18
.020
.020
.020
.0185
.0175
W/3Re WIRE DIAMETERS

Figure 2-65

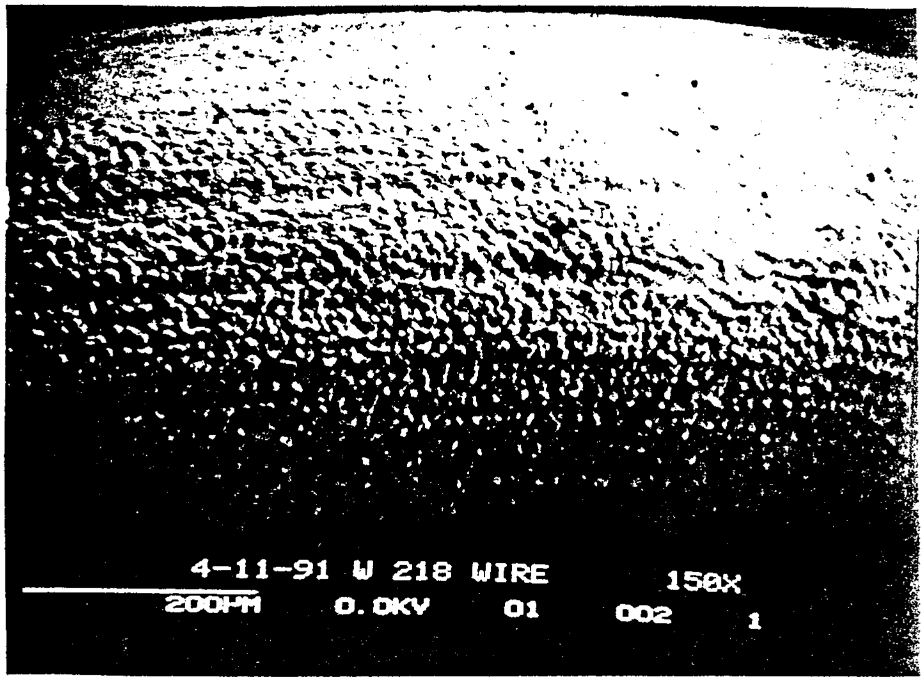


Figure 2, SEM photomicrograph of W218 tungsten wire at a location near the test fixture/wire interface. Photograph documents the formation of tunsten crystals developing on the wire surface in the cooler regions of the coil. This condition was observed at both ends of the test coil.

Figure 2-66

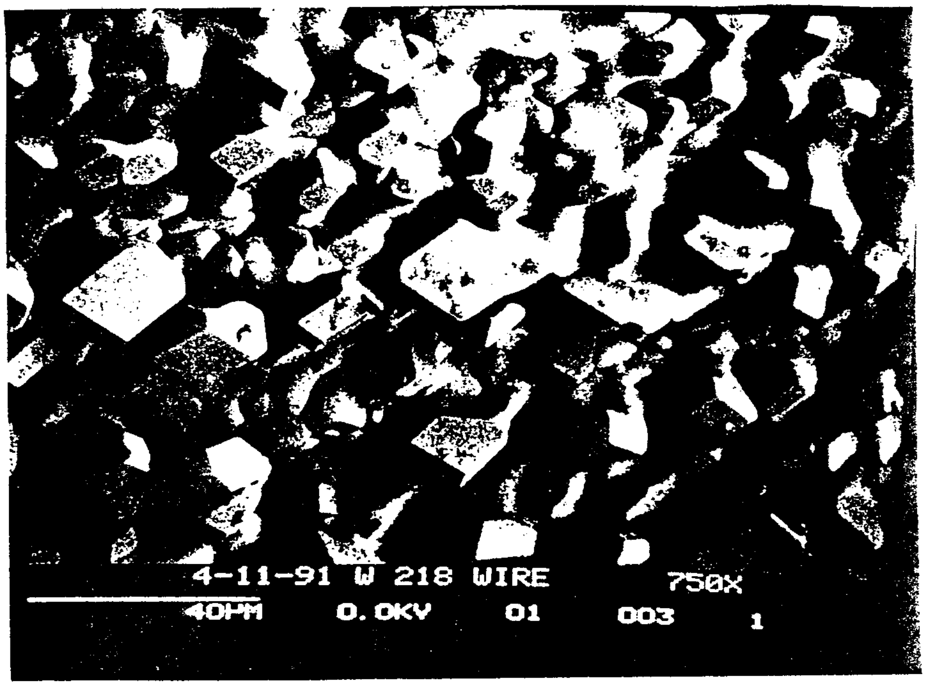


Figure 3, SEM photomicrograph of the same area as figure 2, but at higher magnification. Photograph reveals details of tunsten crystal deposit topography. Crystals are formed by either vapor deposit or chemical vapor deposit mechanism produced by the labortory test enviornment.

Figure 2-67

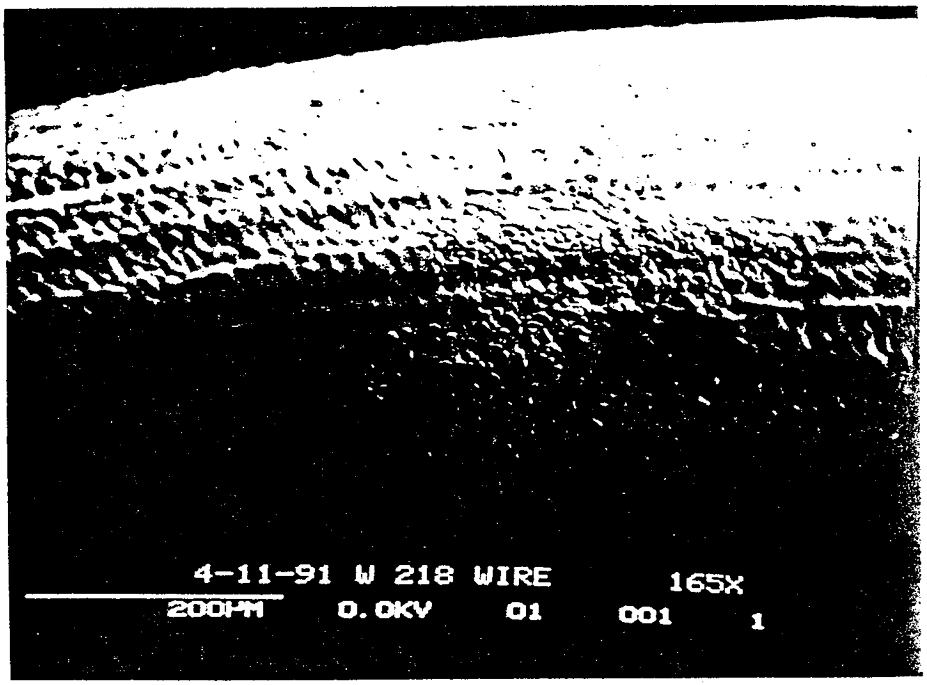


Figure 4, SEM photomicrograph of the W/3Re wire at a location near the test fixture/wire interface. The photograph documents the typical surface conditions and evidence of surface void formations.

Figure 2-68

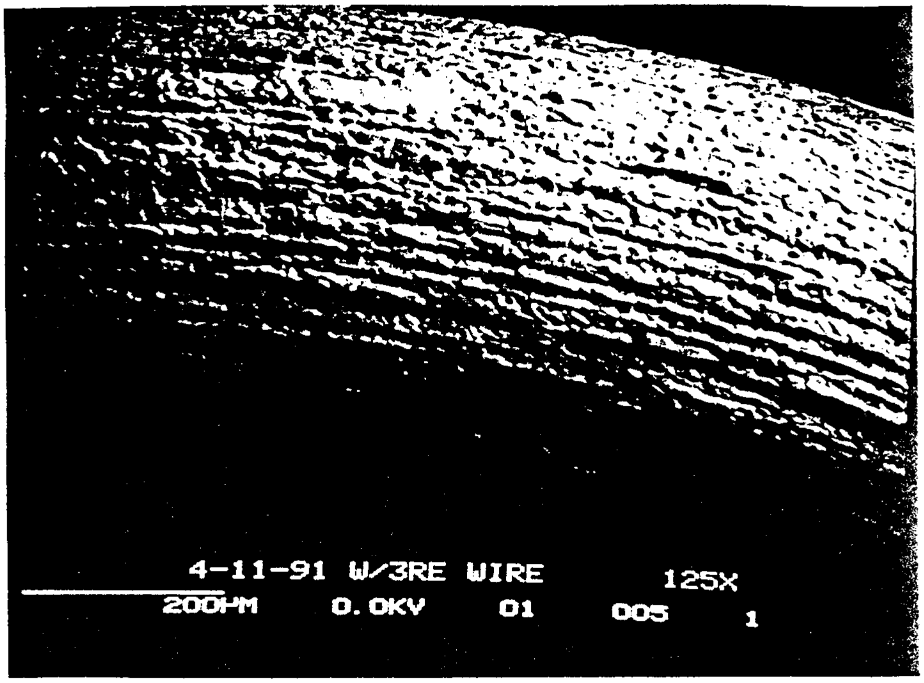


Figure 5, SEM photomicrograph of W/3Re wire at a location in the high temperature region of the coil. Photograph indicates evidence of thermal etching and extensive surface void formation.

Figure 2-69

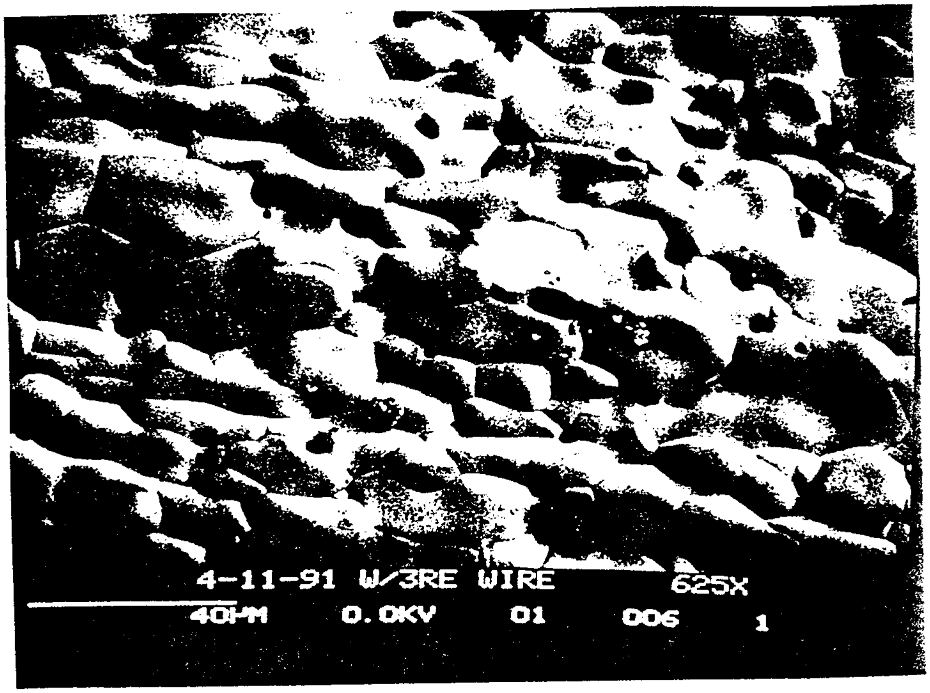


Figure 6, SEM photomicrograph of the same area as documented in figure 5 but at higher magnification. Photograph reveals effects of thermal etching, surface wire grain size and surface void formation.

Figure 2-70

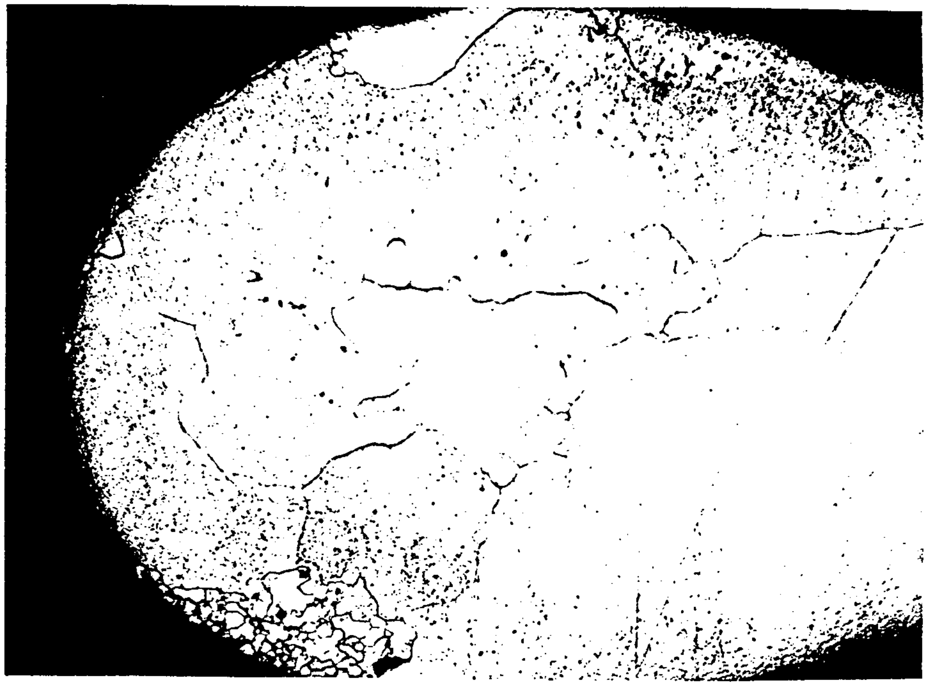


Figure 7, Photomicrograph of W218 wire cross section that reveals a duplex microstructure, with both large recrystallized grains and fine equiaxed non-recrystallized grains. This cross section was obtained near the test fixture/coil interface and is in the same location as that of the SEM surface examination.

Etched, 200x

Figure 2-71

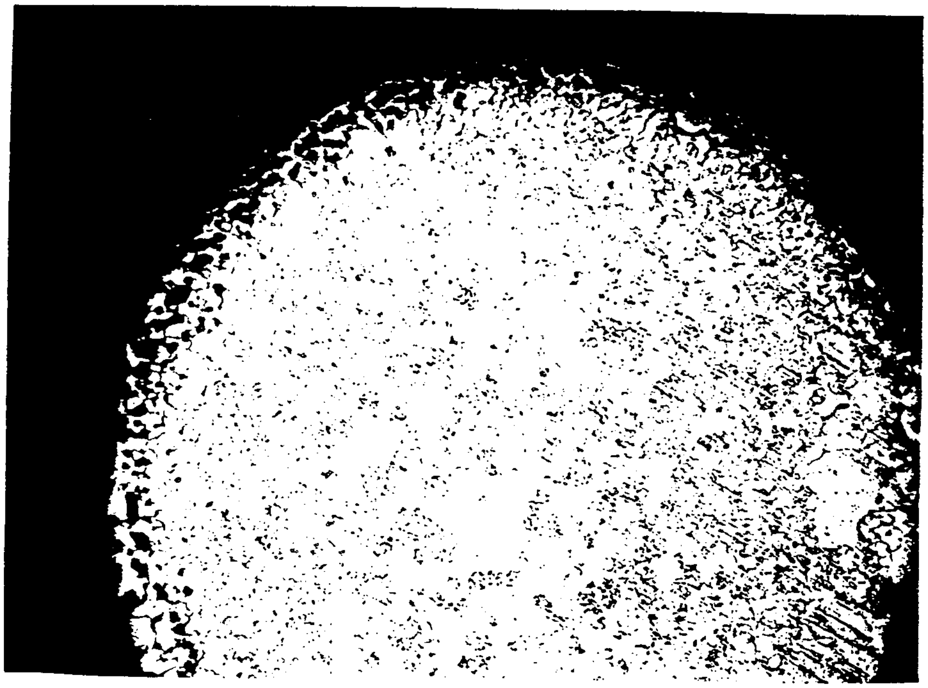


Figure 8, Photomicrograph of the W/3Re wire cross section revealing surface and subsurface void formation typical of the exposed wire. Some grain recrystallization is evident, but most grain remain fine and equiaxed. Void formations would indicated a lack of thermal corrosion resistance in the argon test environment.

Etched, 200x

Figure 2-72

the post-exposure wire diameter examination. The W218 wire filament material was found to be more resistant to the laboratory test exposure environment, and produced the smallest wire diameter changes. One observation seen only on the W218 wire was the development of vapor deposited/chemical vapor deposited tungsten crystals on the cooler ends of the filaments near the fixture/filament interface.

Overall, no significant advances in material technology were achieved in these tests. Several coatings were shown not to have good resistance to attack. The filament wire currently used in production EHT thrusters was shown to be better than W/3Re wire.

3.0 CONCLUSIONS

The following are the notable accomplishments of the HPSPR program:

1. Advanced the understanding of low Reynolds number nozzles. Fabricated nozzles for NASA cold gas study and performed analysis in support of the study. Resulted in NASA TM-89858.
2. Comprehensive performance mapping of vented cavity, sealed cavity, and immersed filament resistojets were completed. Performance limits of each configuration were determined. An extensive data base in the moderate power (500 to 850 W) range for I_{sp}, thrust efficiency, and thermal performance was obtained for the three thruster configurations.
3. High temperature tungsten filaments for three resistojet configurations were characterized. Material loss rates and mechanisms were investigated.
4. A better understanding of refractory metals was obtained. The mechanisms of attack of N_2H_4 decomposition products were explored. The effects of high temperature atomic oxygen were investigated. Metals studied included rhenium, tungsten, Mo/41Re, and Mo/3Re.
5. Conducted a life test of an advanced low flow gas generator. The life test ultimately achieved 887 hours and the gas generator demonstrated reduced feed tube plugging.

3.1 BACKGROUND FOR KEY ACCOMPLISHMENTS

Results obtained in the HPSPR program are wide ranging and contribute to understanding within a number of propulsion disciplines.

Low Reynolds number nozzles continue to be used in resistojets, arcjets and low thrust chemical thrusters. The cold gas nozzle test results using H_2 and N_2 generated in association with the HPSPR program are useful data for thruster design development. Both the cold gas data and the thruster data collected during HPSPR program resistojet testing show that empirically derived data are preferable over available numerical models for the selection of nozzle designs. The study further illustrates that at low Reynolds number, nozzle configuration has a minimal effect on performance.

Comprehensive performance mapping of vented cavity, sealed cavity, and immersed filament resistojets completed in the HPSPR program will allow comparisons between these technologies in the future. This data base will also allow comparisons with arcjet thrusters and other electrothermal thrusters.

Filament material loss rates are the principal performance limit for resistojets. Sealed cavity heater designs can exhibit lower mass loss rates than vented cavity designs. Immersed heater filament mass loss rates are prohibitive at high performance temperatures.

The improved understanding of refractory metals obtained in the HPSPR program can potentially benefit any user of high temperature materials. The mechanisms of chemical attack of N_2H_4 decomposition products is of interest to arcjet design as well as resistojet design. The observations made during the HPSPR program testing led to a better understanding of the effects of high temperature atomic oxygen. These chemical reactions may account for a portion of the observed material loss in any high temperature media containing oxygen bearing species. Hydrazine generally has trace quantities of H_2O, CO_2, and O_2.

The gas generator technology supported by the life test in the HPSPR program is already in use in a flight qualification program for a commercial spacecraft.

3.2 THEORY OF TUNGSTEN EVAPORATION AND DIFFUSION

Of the program key accomplishments discussed above none have a more direct effect on resistojet design than an increased understanding of the behavior of high temperature tungsten filaments.

Results of the program confirm the fundamental sublimation and diffusion behavior for tungsten wire presented in Figure 2-2. The resulting design limits presented in Figure 2-3 were confirmed as well. It is of interest to compare the three design approaches that were tested.

Table 3-1 presents a summary of the theoretical underpinnings for the three approaches. For the vented cavity approach the filament mass loss rate is moderate and is driven by simple sublimation and diffusion of tungsten away from the wire. The heat transfer model is also simple. However, the resulting thermal efficiency is the lowest of the three approaches. The stated performance approximates the flight thruster qualification values.

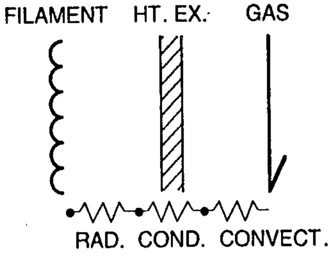
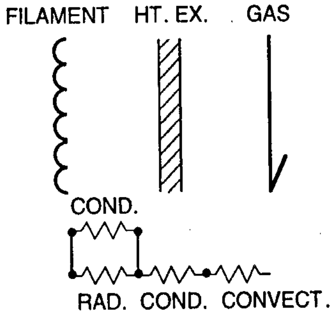
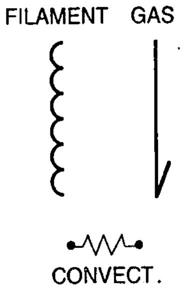
For the sealed cavity, the viscous boundary layer steepens the tungsten gas concentration gradient, thereby reducing sublimation. This should result in either longer filament life or higher filament temperatures and higher performance. The heat transfer from the filament to the heat exchanger wall is enhanced by the presence of the gas. This raises the heat exchanger wall temperature and promotes thermal efficiency. The negative effects of higher wall temperatures are lower creep life and higher thermal losses. During testing the thermal loss effect masked any potential performance benefit. Due to the thermal failure of support hardware the expected enhanced life was not demonstrated.

For the immersed heater, filament mass loss rates are driven by forced convective removal of the tungsten boundary layer. Higher mass loss rates were demonstrated with the immersed heater design than seen with the radiative cavity designs at equivalent filament temperatures. The heat transfer is considerably better than that produced with the heat exchanger approaches, resulting in a high thermal efficiency. Filament mass loss drives down both I_{sp} and life.

3.3 PERFORMANCE LIMITS OF RESISTOJETS

Figure 3-1 presents a graphical summary of performance for resistojets and arcjets. Both plots indicate that the specific energy of arcjets is considerably higher than for resistojets. This means that the power required to run an arcjet for equivalent mass flow rates is higher

Table 3-1
RESISTOJET DESIGN EFFECTS ON FILAMENT BEHAVIOR

DESIGN APPROACH	FILAMENT MASS TRANSPORT	HEAT TRANSFER	PERFORMANCE		
VENTED CAVITY	Ideal sublimation and diffusion to a vacuum. $-\dot{m} = \exp\left(C_1 - \frac{C_2}{T}\right)$		Isp 305	Life >100,000 lbf-sec	Eff 40%
SEALED CAVITY	Viscous boundary layer limits diffusion. Increased Tungsten partial pressure decreases sublimation rate. $-\dot{m} = \frac{1}{F}\left[\exp\left(C_1 - \frac{C_2}{T}\right)\right]$ F = f (P, T, MW) MW = Mol. Wt. F empirically derived		Isp 340	Life ?	Eff 40%
IMMERSED HEATER	Forced convective removal of tungsten. Decreased tungsten partial pressure increases sublimation rate. $-\dot{m} = r\, h_D \,(W_o - W_\infty)$ h_D = mass transfer coeff. W = concentration at filament and in free stream		Isp 300	Life 50,000 lbf-sec	Eff 75%

PERFORMANCE COMPARISONS OF RESISTOJETS AND ARCJETS

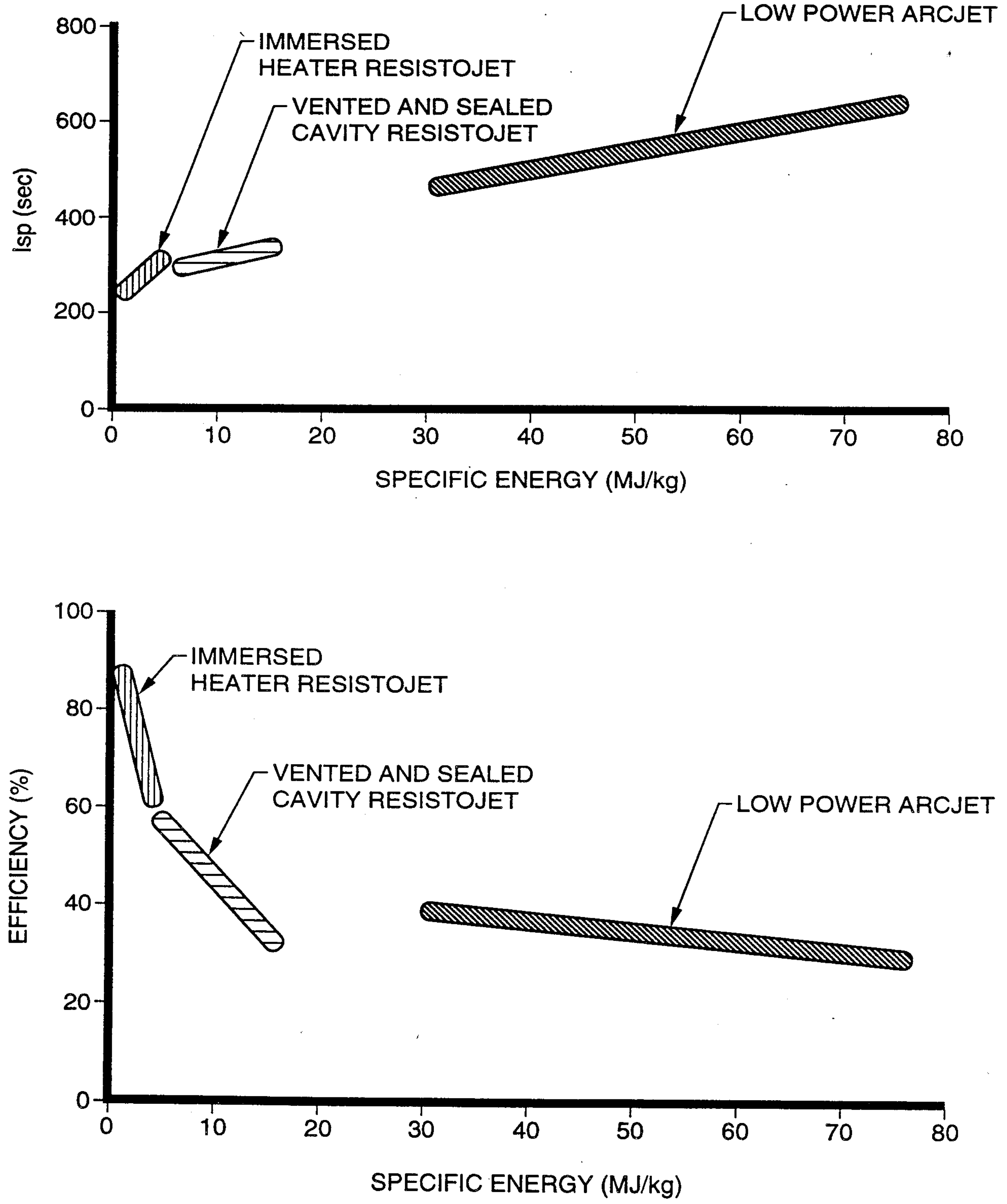


Figure 3-1

than for resistojets. One result, illustrated in the upper plot, is higher I_{sp} since more total electrical power gets into the exhaust. Efficiencies of arcjets, shown in the lower plot, are on average lower than resistojets.

The conclusion to be reached is that the selection of either a resistojet or an arcjet is very application specific. If the spacecraft is power limited, and if the thruster efficiency is more important than I_{sp}, the resistojet should be considered. If higher power levels are available, and higher I_{sp}'s are required, the arcjet is favored.

3.4 SIGNIFICANCE OF THE CURRENT EFFORT

This program provided a demonstration of the limits of resistojet technology development. Applications requiring I_{sp}'s greater than 400 seconds must look to arcjets or other technology. It was shown that resistojets can achieve I_{sp}'s in the range of 340 to 350 seconds. However, lifetimes associated with these performance levels were prohibitively short. Levels of I_{sp} in the range of 310 to 320 seconds are feasible with acceptable lifetimes.

Solving the heat loss problems of the sealed cavity configuration appear to have more pay-off than further work on the immersed heater configuration.

3.5 POTENTIAL FOR FUTURE WORK

Resistojets continue to be used in spacecraft applications, primarily for North-South station keeping of spacecraft in geosynchronous equatorial orbit. For high power spacecraft, arcjets appear to have a clear performance advantage and will likely replace resistojets. The advantage for arcjets is not as clear-cut for low power, small spacecraft. The relatively simple power conditioning, light weight, and low cost of resistojets provide advantages for these applications.

Further increases in performance with minor modification to existing resistojet designs appear feasible from the results of the HPSPR program. For instance, the vented cavity thruster tested in Phase 2 achieved performance 10% higher than existing qualified designs.

Space Station Freedom gas and liquid waste disposal may well rely on resistojets. Extended life, materials selection, compatibility with a range of waste fluids, power handling, and performance optimization are all areas that could benefit from future work in this technology area.

3.6 HARDWARE DISPOSITION

The sealed cavity hardware was never reassembled. The rhenium heat exchanger, piece parts, components, and raw materials required for reassembly are in storage at RRC.
The immersed heater thruster was removed from the gas generator. Piece parts, components, and raw materials required for reassembly are available. Four additional immersed heater assemblies are also available. All of this hardware will be shipped to NASA-LeRC at program close-out.

4.0 REFERENCES

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APPENDIX A

"Fast Track" Data

ROCKET RESEARCH COMPANY DATE: 1 Mar 1987 1

HELIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RU

UNREDUCED DATA (volts)

THRUST RUN	THRUST ZERO	<-------- STEP 1	THRUST CALIBRATION STEP 2	STEP 3	STEP 4	STEP 5	----- STEP
2.570	+.597	+1.810	+3.069	+4.288	+3.117	+1.871	+.6

f(run)	Pf(0)	Ps(run)	Ps(0)	Palt(run)	Palt(
.013790	+.000012	+.023956	+.000001	+.000045	+.000

RECORDED TEMPERATURES (degrees F)

Tf	Tc	T16	Tb	Tv	Tn
+71.7	+1120.2	+457.1	+1140.2	+133.9	+15
Th	Tspare	Tspare	Tspare	Tspare	Tspa
+89.3	+32.0	+32.0	+32.0	+0.0	+

REDUCED DATA

(exit) q. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Pe psia		Palt psia
.06228	.000623	.000626	285.6	51.7	0.0	.0065
HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
.94	2.506	0.0	0.0000	0.0	.00000	0.0
IGHT GLASS bs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000	.94107	47.851	48.253			
CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9466	1.4973	3966.4	6532.4	1071.1	0.000	184.6

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OCKET RESEARCH COMPANY                                   DATE:  1 MAY 1987 11:45:
HENIUM HEAT EXCHANGER - BASELINE HEATER                          SN# 001  RUN#

                              UNREDUCED DATA (volts)
HRUST     THRUST    <-------            THRUST CALIBRATION             -------
RUN        ZERO     STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------    ------     ------     ------     ------     ------     ------
2.267     +.591     +1.814     +3.072     +4.308     +3.089     +1.842      +.604

f(run)       Pf(0)           Ps(run)        Ps(0)        Palt(run)      Palt(0)
-------     --------        --------      --------       --------       --------
.012000     -.000118        +.007250      +.000001       +.000020       +.00000

                        RECORDED TEMPERATURES (degrees F)
 Tf            Tc             T16            Tb             Tv             Tm

------       -------        -------        -------        -------        -------
 +77.2       +1148.7        +1491.4        +1171.3        +224.0         +581.9
 Th          Tspare         Tspare         Tspare         Tspare         Tspare

-------      -------        -------        -------        -------        -------
1293.1        +32.0          +32.0          +32.0          +0.0           +0.0

                                  REDUCED DATA
(exit)     A(throat)  A(throat)    Pf         Ps                      Palt
            COLD       COR.
sq. in.    sq. in.    sq. in.     psia       psia                    psia
--------   --------   --------   --------   --------   --------   --------
 .06228    .000623    .000637     96.7       45.5        0.0       .0032
HEATER     HEATER     HEATER     HEATER     HEATER     HEATER       Pf
                                                        WIRE       DELTA
 volts      amps       watts      ohms       temp        dia        psia
--------   --------   --------   --------   --------   --------   --------
 25.47     19.616      499.5     1.2982     4287.4     .00000       0.0

EIGHT      MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------   --------   --------   --------
0.00000    .47730     40.514     40.715

 CD         Cf         C*        REYNOLDS     GAS        PSP        ISP
                                  NUMBER     TEMP.
                      ft/sec                 deg. f                 sec.
--------   --------   --------   --------   --------   --------   --------
[illegible]003     1.4365     6878.1     1687.3     3676.4     12.269     307.1
```

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HENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 Ru

UNREDUCED DATA (volts)

HRUST RUN	THRUST ZERO	THRUST CALIBRATION STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP
.301	+.583	+1.821	+3.053	+4.307	+3.093	+1.844	+.5

f(run)	Pf(0)	Ps(run)	Ps(0)	Palt(run)	Palt(
.012000	-.000187	+.007260	+.000001	+.000016	+.000

RECORDED TEMPERATURES (degrees F)

Tf	Tc	T16	Tb	Tv	Tr
+81.0	+1167.6	+1608.9	+1193.7	+242.4	+65

Tn	Tspare	Tspare	Tspare	Tspare	Tspr
1440.5	+32.0	+30.0	+30.0	+0.0	+

REDUCED DATA

(exit) s. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Ps psia		Palt psia
.06228	.000623	.000638	96.8	45.8	0.0	.0073

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
28.80	20.842	600.2	1.3817	4550.6	.00000	0.0

IGHT LASS bs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000	.47048	41.275	41.466			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
3985	1.4547	7017.5	1622.0	3937.8	14.474	317.3

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OCKET RESEARCH COMPANY                                   DATE:  1 May 1987 14:20:52

HENIUM HEAT EXCHANGER - BASELINE HEATER                           SN# 001   RUN#  4


                          UNREDUCED DATA (volts)
HRUST     THRUST    <--------            THRUST CALIBRATION            --------
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-----     ------     ------     ------     ------     ------     ------     ------
2.263     +.556     +1.797     +3.025     +4.253     +3.042     +1.817      +.548

f(run)      Pf(0)             Ps(run)        Ps(0)          Palt(run)       Palt(0)
-------   --------           --------       --------        --------       --------
.012000   -.000273           +.007215       +.000001        +.000013       -.000004


                    RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv             Tm

------        -------        -------        -------        -------        -------
 +84.3        +1178.3        +1671.5        +1209.4        +257.5         +690.6

 Th           Tspare         Tspare         Tspare         Tspare         Tspare

------        -------        -------        -------        -------        -------
1485.0         +32.0          +32.0          +32.0          +0.0           +0.0



                              REDUCED DATA
(exit)     A(throat)  A(throat)    Pf         Ps                      Palt
            COLD       COR.
sq. in.    sq. in.    sq. in.     psia       psia                    psia
--------   --------   --------   --------   --------   --------   --------
 .06228    .000623    .000639     96.3       46.1        0.0        .0029

HEATER     HEATER     HEATER     HEATER     HEATER     HEATER       Pf
                                                       WIRE        DELTA
 volts      amps       watts      ohms       temp       dia         psia
--------   --------   --------   --------   --------   --------   --------
 30.38     21.410     650.4      1.4189     4667.8     .00000       0.0

IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------   --------   --------   --------
0.00000    .46017     41.058     41.236

 CD          Cf         C*       REYNOLDS     GAS        PSP         ISP
                                  NUMBER      TEMP.
                       ft/sec                 deg. f                 sec.
--------   --------   --------   --------   --------   --------   --------
 3957       1.4365     7225.4     1531.7     4081.9     15.772      322.6
```

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OCKET RESEARCH COMPANY DATE: 1 May 1987

HENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RUN

UNREDUCED DATA (volts)

HRUST RUN	THRUST ZERO	STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP
		THRUST CALIBRATION					
2.538	+.578	+1.809	+3.056	+4.290	+3.073	+1.870	+.58

f(run)	Pf(0)	Ps(run)	Ps(0)	Palt(run)	Palt((
.013173	-.000296	+.009400	+.000001	+.000020	-.0000

RECORDED TEMPERATURES (degrees F)

Tf	Tc	T16	Tb	Tv	Tm
+84.1	+1176.7	+1630.3	+1201.5	+243.0	+66

Th	Tspare	Tspare	Tspare	Tspare	Tspa
1451.2	+32.0	+32.0	+32.0	+0.0	+

REDUCED DATA

(exit) s. in.	A(throat) COLD sq. in.	A(throat) OPR. sq. in.	Pf psia	Ps psia		Palt psia
.06229	.000623	.000637	121.0	50.6	0.0	.0079

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp.	HEATER WIRE dia	Pf DELTA psia
30.04	21.836	655.5	1.3755	1531.0	.00000	0.0

IGHT LASS bs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000	.53161	47.338	47.582			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9051	1.5103	6844.1	1871.3	3704.1	13.784	322.7

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OCKET RESEARCH COMPANY                                      DATE:  5 May 1987 09:13:35
HENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001  RUN#

                              UNREDUCED DATA (volts)
HRUST     THRUST      <-------            THRUST CALIBRATION                -------->
RUN       ZERO        STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------      ------     ------     ------     ------     ------     ------
2.507     +.874       +2.084     +3.308     +4.540     +3.339     +2.119     +.871

f(run)      Pf(0)           Ps(run)        Ps(0)        Palt(run)      Palt(0)
--------  --------        --------       --------      --------       --------
.012000   -.000135        +.006610       +.000039      -.000025       -.000041


                    RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv             Tm

------        -------        -------        -------        -------        -------
 +79.5        +1183.9        +1801.8        +1225.0        +253.3         +745.0

 Th             Tspare         Tspare         Tspare         Tspare         Tspare

------        -------        -------        -------        -------        -------
1600.9          +32.0          +32.0          +32.0          +0.0           +0.0


                              REDUCED DATA
(exit)      A(throat)   A(throat)    Pf          Ps                      Palt
            COLD        COF.
s. in.      sq. in.     sq. in.      psia        psia                    psia
--------    --------    --------     --------    --------    --------    --------
 .06228     .000623     .000640      89.0        45.6        0.0         .0077

HEATER      HEATER      HEATER       HEATER      HEATER      HEATER      Pf
                                                             WIRE        DELTA
 volts      amps        watts        ohms        temp        dia         psia
--------    --------    --------     --------    --------    --------    --------
 33.22      22.566      749.7        1.4723      4836.4      .00000      0.0

IGHT        MICRO       THRUST       THRUST
LASS        MOTION      MEAS         VAC
bs/hr       lbs/hr      mlbs         mlbs
--------    --------    --------     --------    --------    --------    --------
 0.00000    .44546      39.899       40.068

 CD         Cf          C*           REYNOLDS    GAS         PSP         ISP
                                     NUMBER      TEMP.
                        ft/sec                   deg. f                  sec.
--------    --------    --------     --------    --------    --------    --------
 3928       1.4117      7380.0       1447.4      4260.8      18.712      323.8
```

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OCKET RESEARCH COMPANY                                     DATE:  5 May 1987 09:5
HENIUM HEAT EXCHANGER - BASELINE HEATER                             SN# 001  RUN

                           UNREDUCED DATA (volts)
HRUST     THRUST    <-------           THRUST CALIBRATION                   -------
RUN        ZERO     STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP
------    ------    ------    ------    ------    ------    ------    ------
2.547     +.914     +2.150    +3.370    +4.581    +3.375    +2.155     +.92

f(run)        Pf(0)          Ps(run)        Ps(0)          Palt(run)      Palt(0
--------      --------       --------       --------       --------       -------
.011677       -.000231       +.007263       +.000039       -.000022       -.0000

                      RECORDED TEMPERATURES (degrees F)
 Tf           Tc           T16          Tb           Tv           Tm
------       -------      -------      -------      -------      -----
 +81.4       +1157.5      +1541.4      +1181.7      +225.7       +590
 Th           Tspare       Tspare       Tspare       Tspare       Tspar
------       -------      -------      -------      -------      -----
1408.9         +32.0        +32.0        +32.0        +0.0         +0

                               REDUCED DATA
(exit)    A(throat)  A(throat)    Pf        Ps                  Palt
            COLD       COR.
s. in.    sq. in.    sq. in.     psia      psia                psia
-------   --------   --------   --------  --------  --------  --------
 .06228    .000623    .000637    96.4      44.7       0.0      .0077
HEATER    HEATER     HEATER     HEATER    HEATER    HEATER     Pf
                                                     WIRE      DELTA
 volts     amps       watts      ohms      temp      dia       psia
-------   --------   --------   --------  --------  --------  --------
 25.41    19.676      499.9     1.2912    4265.2    .00000      0.0

IGHT      MICRO      THRUST     THRUST
LASS      MOTION     MEAS       VAC
bs/hr     lbs/hr     mlbs       mlbs
--------  --------   --------   --------  --------  --------  --------
0.00000   .47480     39.767     40.000

 CD        Cf         C*        REYNOLDS   GAS       PSP       ISP
                                NUMBER     TEMP.
                      ft/sec               deg. f              sec.
 -----    --------   --------   --------  --------  --------  --------
 .9008    1.4362     6794.3     1705.1    3577.3    12.497    303.3
```

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CKET RESEARCH COMPANY                                                   DATE:  5 May 1987 10:34:30

ENIUM HEAT EXCHANGER - BASELINE HEATER                                           SN# 001  RUN#  8


                                    UNREDUCED DATA (volts)
RUST     THRUST    <-------              THRUST CALIBRATION                    -------
UN       ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-----    -------   -------    -------    -------    -------    -------    -------
.999     +.948     +2.160     +3.397     +4.627     +3.431     +2.211     +.564

(run)        Pf(0)           Ps(run)         Ps(0)              Palt(run)      Palt(0)
-------     --------         --------        --------           ---------      --------
.014000     -.000273         +.010050        +.000039           -.000020       -.000056


                       RECORDED TEMPERATURES (degrees F)
Tf            Tc            T16           Tb            Tv            Tm

------       -------       -------       -------       -------       -------
+83.4        +1181.9       +1735.5       +1218.5       +240.8        +710.5

Th           Tspare        Tspare        Tspare        Tspare        Tspare

------       -------       -------       -------       -------       -------
1558.4        +32.0         +32.0         +32.0         +0.0          +0.0


                                    REDUCED DATA
(exit)     A(throat)   A(throat)    Pf          Ps                      Palt
           COLI        ORF.
. in.      sq. in.     sq. in.      psia        psia                    psia
-------    --------    --------    --------    --------    --------    --------
.06228     .000623     .000639     127.9       53.6        0.0         .0061

HEATER     HEATER      HEATER      HEATER      HEATER      HEATER      Pf
                                                           WIRE        DELTA
volts      amps        watts       ohms        temp        dia         psia
-------    --------    --------    --------    --------    --------    --------
33.06      22.692      750.2       1.4568      4787.6      .00000      0.0

IGHT       MICRO       THRUST      THRUST
LASS       MOTION      MEAS        VAC
bs/hr      lbs/hr      mlbs        mlbs
-------    --------    --------    --------    --------    --------    --------
0.00000    .54279      50.052      50.433

CD         Cf          C*          REYNOLDS    GAS         PSP         ISP
                                   NUMBER      TEMP.
                       ft/sec                  deg. f                  sec.
-----      --------    --------    --------    --------    --------    --------
.9038      1.5107      7123.8      1819.3      4032.5      14.874      334.5
```

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OCKET RESEARCH COMPANY                                      DATE:  5 May 1987 11:1

HENIUM HEAT EXCHANGER - BASELINE HEATER                             SN# 001  RUN

                              UNREDUCED DATA (volts)
HRUST     THRUST   <--------              THRUST CALIBRATION                      ------
RUN       ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5      STEP
------    ------     ------     ------     ------     ------     ------      ------
3.022     +.976      +2.191     +3.428     +4.633     +3.452     +2.219      +.9

f(run)       Pf(0)           Ps(run)         Ps(0)            Palt(run)       Palt((
---------    ---------       ---------       ---------        ---------       ------
.014000      -.000291        +.010050        +.000039         -.000020        -.000


                          RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv            Tm

-------       -------        -------        -------        -------       -----
 +85.0        +1163.9        +1789.6        +1222.9        +239.7        +72

 Th           Tspare         Tspare         Tspare         Tspare        Tspa

-------       -------        -------        -------        -------       -----
1590.7          +32.0          +32.0          +32.0          +0.0        +


                                  REDUCED DATA
(exit)     A(throat)  A(throat)     Pf          Ps                        Palt
            COLD       COR.
s. in.     sq. in.    sq. in.     psia        psia                       psia
--------   --------   --------   --------   --------     --------     --------
 .06228    .000623    .000639     127.9       53.7          0.0          .0046

HEATER     HEATER     HEATER     HEATER      HEATER       HEATER        Pf
                                                           WIRE         DELTA
 volts      amps      watts       ohms        temp         dia          psia
--------   --------   --------   --------   --------     --------     --------
 34.49     23.198     800.0      1.4866      4881.4       .00000        0.0


IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------   --------     --------     --------
0.00000    .54222     49.830     50.116


 CD          Cf          C*       REYNOLDS     GAS           PSP          ISP
                                  NUMBER       TEMP.
                       ft/sec                  deg. f                     sec.
 -----    --------    --------    --------    --------     --------     --------
 .9036     1.4993      7140.3      1812.2      4052.8       15.963       332.7
```

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OCKET RESEARCH COMPANY                                        DATE: 5 May 1987 11:51:36

HENIUM HEAT EXCHANGER - BASELINE HEATER                            SN# 001  RUN# 10


                           UNREDUCED DATA (volts)
HRUST     THRUST   <-------            THRUST CALIBRATION            ------->
RUN       ZERO      STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
-----     ------    ------    ------    ------    ------    ------    ------
2.594     +.947     +2.164    +3.397    +4.618    +3.411    +2.184    +.933

f(run)       Pf(0)             Ps(run)       Ps(0)         Palt(run)     Palt(0)
--------     --------          --------      --------      --------      --------
.011737      -.000295          +.006520      +.000039      -.000020      -.000043


                       RECORDED TEMPERATURES (degrees F)
 Tf           Tc           T16          Tb           Tv           Tn

------       -------      -------      -------      -------      -------
 +85.2       +1189.9      +1972.3      +1236.0      +257.9       +764.5

 Th           Tspare       Tspare       Tspare       Tspare       Tspare

------       -------      -------      -------      -------      -------
1645.0         +32.0        +32.0        +32.0       +0.0         +0.0


                              REDUCED DATA
(exit)      A(throat)   A(throat)    Pf         Pc                     Palt
             COLD        COR.
s. in.      sq. in.     sq. in.      psia       psia                   psia
-------     --------    --------    --------   --------   --------   --------
 .06228     .000623     .000642      58.0       45.2        0.0        .0039

HEATER      HEATER      HEATER      HEATER     HEATER     HEATER       Pf
                                                           WIRE       DELTA
 volts       amps        watts       ohms       temp        dia        psia
-------     --------    --------    --------   --------   --------   --------
 34.54      23.172       800.5      1.4908     4894.6     .00000       0.0

IGHT        MICRO       THRUST      THRUST
LASS        MOTION      MEAS        VAC
bs/hr       lbs/hr      mlbs        mlbs
-------     --------    --------    --------   --------   --------   --------
0.00000     .43195      40.052      40.295

 CD          Cf          C*         REYNOLDS    GAS         PSP        ISP
                                    NUMBER      TEMP.
                         ft/sec                 deg. f                 sec.
 -----      --------    --------    --------   --------   --------   --------
 .8899      1.4319      7546.1      1347.3     4462.6     19.865     335.8
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OCKET RESEARCH COMPANY                                         DATE:  5 May 1987 13:2
HENIUM HEAT EXCHANGER - BASELINE HEATER                               SN# 001  RUN#

                                UNREDUCED DATA (volts)
THRUST     THRUST    <-------              THRUST CALIBRATION                  -------
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5,     STEP 
------     ------     ------     ------     ------     ------     ------     ------
+2.568     +.954     +2.172     +3.398     +4.625     +3.412     +2.179       +.92

Pf(run)       Pf(0)            Ps(run)        Ps(0)            Palt(run)       Palt(0
--------    ---------         ---------     ---------          ---------       -------
-.011017    -.000257          +.006440      +.000039           -.000022        -.0000


                         RECORDED TEMPERATURES (degrees F)
  Tf              Tc               T16             Tb              Tv              Tm

-------         -------          -------         -------         -------         -----
 +89.7          +1193.2          +1847.3         +1240.1          +249.2          +761
  Th            Tspare           Tspare          Tspare          Tspare          Tspar

-------         -------          -------         -------         -------         -----
1627.9            +32.0            +31.9           +32.0            +0.0             +0


                                    REDUCED DATA
(exit)      A(throat)   A(throat)      Pf           Ps                          Palt
              COLI        COR.
s. in.      sq. in.     sq. in.       psia         psia                         psia
--------    --------    --------    --------     --------     --------      --------
 .06228     .000623     .000638       87.1         42.3          0.0          .0041

HEATER       HEATER      HEATER      HEATER       HEATER       HEATER          Pf
                                                                WIRE          DELTA
 volts        amps        watts       ohms         temp          dia           psia
--------    --------    --------    --------     --------     --------      --------
 33.33       22.516       750.5      1.4803       4861.5        .00000          0.0

IGHT         MICRO       THRUST      THRUST
LASS         MOTION       MEAS        VAC
bs/hr        lbs/hr       mlbs        mlbs
--------    --------    --------    --------     --------     --------      --------
0.00000      .43108      39.217      39.472

  CD           Cf          C*        REYNOLDS       GAS          PSP           ISP
                                      NUMBER       TEMP.
                          ft/sec                   deg. f                      sec.
 -----      --------    --------    --------     --------     --------      --------
 .8939       1.4969      7085.0      1477.3       3878.3       19.013        329.6
```

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OCKET RESEARCH COMPANY                                          DATE:  6 May 1987 11:27:2
HENIUM HEAT EXCHANGER - BASELINE HEATER                                   SN# 001  RUN# 1

                                  UNREDUCED DATA (volts)
HRUST     THRUST     <-------                THRUST CALIBRATION                   -------
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
2.935     +1.298     +2.506     +3.732     +4.915     +3.737     +2.527     +1.27

f(run)       Pf(0)          Ps(run)      Ps(0)      Palt(run)      Palt(0)
--------    --------       --------    --------    --------       --------
.012000     -.000065       +.007168    -.000016    -.000010       -.000030


                        RECORDED TEMPERATURES (degrees F)
 Tf            Tc            T16            Tb            Tv            Tm

-------      -------       -------       -------       -------       -------
 +79.0       +1145.1       +1553.4       +1170.3       +208.7        +576.3

 Tn          Tspare        Tspare        Tspare        Tspare        Tspare

------       -------       -------       -------       -------       -------
1402.8         +32.0         +32.4         +32.0          +0.0          +0.0


                                  REDUCED DATA
(exit)    A(throat)   A(throat)    Pf          Ps                        Palt
            COLD        COR.
s. in.    sq. in.     sq. in.     psia        psia                      psia
-------   --------    --------   --------    --------    --------     --------
 .06228    .000623     .000637     96.0        45.3         0.0         .0034

HEATER    HEATER      HEATER     HEATER      HEATER      HEATER         Pf
                                                          WIRE        DELTA
 volts     amps        watts      ohms        temp         dia         psia
-------   --------    --------   --------    --------    --------     --------
 25.29    15.768       500.4      1.2778      4223.0      .00000         0.0


IGHT      MICRO       THRUST     THRUST
LASS      MOTION      MEAS       VAC
bs/hr     lbs/hr      mlbs       mlbs
-------   --------    --------   --------    --------    --------     --------
0.00000    .47728     +0.033     +0.245


 CD          Cf          C*       REYNOLDS      GAS         PSP          ISP
                                   NUMBER      TEMP.
                       ft/sec                  deg. f                    sec.
 -----    --------    --------    --------    --------    --------     --------
 .9006     1.4261      6848.4      1696.5      3641.8      12.433       303.6
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ROCKET RESEARCH COMPANY                                         DATE:  6 May 1987 1710

RHENIUM HEAT EXCHANGER - BASELINE HEATER                               SN# 001   RUN

                            UNREDUCED DATA (volts)
THRUST     THRUST     <-------           THRUST CALIBRATION                        ------
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
-------    ------     ------     ------     ------     ------     ------     -----
+2.980     +1.249     +2.458     +3.691     +4.910     +3.711     +2.508     +1.24

Pf(run)       Pf(0)          Ps(run)         Ps(0)            Palt(run)       Palt(0
--------     --------        --------       --------          --------        ------
+.012000     -.000187        +.007073       -.000016          -.000010        -.0000


                        RECORDED TEMPERATURES (degrees F)
  Tf           Tc           T16           Tb            Tv            Tm

-------      -------      -------      -------       -------       -----
 +84.7       +1166.2      +1957.1      +1230.0        +253.2        +764

  Th          Tspare       Tspare       Tspare        Tspare        Tspar

-------      -------      -------      -------       -------       -----
+1642.2       +32.0        +32.0        +32.0          +0.0          +0


                                  REDUCED DATA
A(exit)    A(throat)  A(throat)     Pf          Ps                       Palt
             COLD       COF.
sq. in.    sq. in.    sq. in.      psia        psia                     psia
--------   --------   --------   --------    --------    --------     --------
 .06228    .000623    .000639      94.9        45.8         0.0          .0022

HEATER     HEATER     HEATER     HEATER      HEATER      HEATER        Pf
                                                          WIRE         DELTA
 volts      amps       watts      ohms        temp        dia          psia
--------   --------   --------   --------    --------    --------     --------
 34.57     23.132      799.7     1.4945      4906.2      .00000         0.0

SIGHT      MICRO      THRUST     THRUST
GLASS      MOTION     MEAS       VAC
lbs/hr     lbs/hr     mlbs       mlbs
--------   --------   --------   --------    --------    --------     --------
 0.00000    .45639     42.196     42.333

  CD         Cf         C*       REYNOLDS     GAS         PSP          ISP
                                  NUMBER      TEMP.
                       ft/sec                 deg. f                   sec.
 -----     --------   --------   --------    --------    --------     --------
 .8952      1.4851     7234.2     1517.7      4088.8      18.890        333.9
```

```
OCKET RESEARCH COMPANY                                   DATE:  6 May 1987 17:34:46

HENIUM HEAT EXCHANGER - BASELINE HEATER                          SN# 001  RUN# 14


                         UNREDUCED DATA (volts)
HRUST     THRUST     <-------              THRUST CALIBRATION              ------->
RUN       ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-----     ------     ------     ------     ------     ------     ------     ------
2.941     +1.258     +2.468     +3.719     +4.923     +3.739     +2.518     +1.249

f(run)       Pf(0)           Ps(run)        Ps(0)            Palt(run)     Palt(0)
-------    --------          --------      ---------         --------     ---------
.012000    -.000197          +.006990      -.000016          -.000010     -.000025


                         RECORDED TEMPERATURES (degrees F)
 Tf              Tc              T16              Tb              Tv              Tm

------         -------         -------         -------         -------         -------
 +88.7         +1188.8         +1819.2         +1230.5          +258.9          +751.1

 Th             Tspare          Tspare          Tspare          Tspare          Tspare

------         -------         -------         -------         -------         -------
1619.6           +32.0           +32.0           +32.0            +0.0            +0.0


                                    REDUCED DATA
(exit)      A(throat)    A(throat)     Pf          Ps                      Palt
              COLD         COR.
s. in.      sq. in.      sq. in.      psia        psia                    psia
-------     -------      --------    --------    ---------   --------    --------
 .06228     .000633      .000640       93.9        45.8         0.0        .0026

HEATER      HEATER       HEATER       HEATER      HEATER      HEATER        Pf
                                                               WIRE        DELTA
 volts        amps        watts        ohms        temp        dia          psia
-------     -------      --------    --------    --------    --------     --------
 33.29      22.544        750.5       1.4767      4850.1      .00000         0.0


IGHT        MICRO        THRUST       THRUST
LASS        MOTION        MEAS         VAC
bs/hr       lbs/hr        mlbs         mlbs
-------     --------     --------    --------    --------    --------    --------
0.00000      .44859       40.741      40.900


 CD           Cf            C*       REYNOLDS       GAS          PSP          ISP
                                      NUMBER       TEMP.
                          ft/sec                   deg. f                     sec.
 -----      --------     --------    --------    --------    --------    --------
 .8933       1.4337       7366.0      1460.3      4246.6      18.349        328.2
```

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OCKET RESEARCH COMPANY                                      DATE:  7 May 1987 0914

HENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001   RUN

                           UNREDUCED DATA (volts)
THRUST     THRUST    <--------           THRUST CALIBRATION                  ------
RUN        ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5,    STEP
-------    -------    -------    -------    -------    -------    -------    -----
+2.335     +.752     +1.970     +3.213     +4.425     +3.213     +1.970     +.75

f(run)       Pf(0)            Pg(run)        Pg(0)        Palt(run)      Palt(0
---------   ---------         ---------      ---------    ---------      -------
+.011707    -.000039          +.006905       -.000002     +.000000       -.0000


                        RECORDED TEMPERATURES (degrees F)
 Tf             Tc            T16            Tb             Tv            Tm

-------        -------       -------        -------        -------       -----
 +79.3         +1144.1       +1544.2        +1173.7         +210.4        +593

 Th            Tspare        Tspare         Tspare         Tspare        Tspar

-------        -------       -------        -------        -------       -----
1441.4          +32.0         +32.0          +32.0          +0.0          +0


                                  REDUCED DATA
(exit)     A(throat)   A(throat)    Pf          Ps                        Palt
            COLD        COR.
s. in.     sq. in.     sq. in.      psia        psia                      psia
--------   ---------   ---------   ---------   ---------   ---------   ---------
 .06228     .000623     .000637     92.8        44.1        0.0         .0004

HEATER     HEATER      HEATER      HEATER      HEATER      HEATER      Pf
                                                           WIRE        DELTA
volts      amps        watts       ohms        temp        dia         psia
--------   ---------   ---------   ---------   ---------   ---------   ---------
 25.37     19.710      500.0       1.2870      4252.1      .00000       0.0


IGHT       MICRO       THRUST      THRUST
GLASS      MOTION      MEAS        VAC
bs/hr      lbs/hr      mlbs        mlbs
--------   ---------   ---------   ---------   ---------   ---------   ---------
0.00000    .46648      38.794      38.942


 CD          Cf          C*         REYNOLDS     GAS          PSP         ISP
                                    NUMBER       TEMP.
                         ft/sec                  deg. f                   sec.
 -----     ---------   ---------   ---------   ---------   ---------   ---------
 .8998      1.4175      6821.4      1668.8      3601.2      12.839      300.5
```

Post F CAL N.G. - Data on F is questional

```
OCKET RESEARCH COMPANY                                    DATE:  7 May 1987 17:59:17

HENIUM HEAT EXCHANGER - BASELINE HEATER                        SN# 001   RUN# 1

                        UNREDUCED DATA (volts)
HRUST    THRUST   <-------          THRUST CALIBRATION                  ------->
RUN      ZERO     STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
------   ------   ------    ------    ------    ------    ------    ------
3.001    +.817    +2.032    +3.284    +4.485    +3.299    +2.093    +.832

f(run)       Pf(0)           Ps(run)      Ps(0)         Palt(run)     Palt(0)
--------     --------        --------     --------      --------      --------
.014233      -.000069        +.010101     -.000001      -.000010      -.000031


                    RECORDED TEMPERATURES (degrees F)
 Tf          Tc          T16          Tb          Tv          Tm

-------     -------     -------     -------     -------     -------
 +84.9      +1168.5     +1768.2     +1209.6     +217.0      +714.3

 Th          Tspare      Tspare      Tspare      Tspare      Tspare

-------     -------     -------     -------     -------     -------
1627.3       +32.0       +32.0       +32.0       +0.0        +0.0


                            REDUCED DATA
(exit)     A(throat)   A(throat)    Pf          Ps                      Palt
           COLI        COR.
s. in.     sq. in.     sq. in.      psia        psia                    psia
--------   --------    --------     --------    --------    --------    --------
 .06228    .000623     .000635      129.0       53.7        0.0         .0036

HEATER     HEATER      HEATER       HEATER      HEATER      HEATER      Pf
                                                            WIRE        DELTA
 volts      amps        watts        ohms        temp        dia         psia
--------   --------    --------     --------    --------    --------    --------
 34.40     23.270       800.6       1.4785      4855.9      .00000       0.0


IGHT       MICRO       THRUST       THRUST
LASS       MOTION      MEAS         VAC
bs/hr      lbs/hr      mlbs         mlbs
--------   --------    --------     --------    --------    --------    --------
0.00000    .54464      53.094       53.317


 CD          Cf          C*         REYNOLDS     GAS         PSP         ISP
                                    NUMBER       TEMP.
                         ft/sec                  deg. f                  sec.
 -----     --------    --------     --------    --------    --------    --------
 .9040     1.5938      7114.3       1828.1      4022.1      15.016      352.4
```

Thrust STAND MAL FUNCTING

```
OCKET RESEARCH COMPANY                                   DATE:  8 May 1987 13:54:

HENIUM HEAT EXCHANGER - BASELINE HEATER                          SN# 001   RUN#


                                 UNREDUCED DATA (volts)
HRUST     THRUST     <-------              THRUST CALIBRATION          -------
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
2.759     +1.090     +2.310     +3.561     +4.791     +3.581     +2.356     +1.101

f(run)      Pf(0)               Ps(run)       Ps(0)             Palt(run)   Palt(0)
--------  --------              --------      --------          --------    --------
.012000    -.000069             +.007176      +.000001          -.000010    -.00003


                        RECORDED TEMPERATURES (degrees F)
 Tf            Tc             T16            Tb             Tv             Tp

------       -------        -------        -------        -------        -------
 +87.6       +1147.9        +1550.2        +1177.8         +217.9         +583.
 Th            Tspare         Tspare         Tspare         Tspare         Tspare

------       -------        -------        -------        -------        -------
1443.0         +32.0          +32.0          +32.0           +0.0           +0.


                                    REDUCED DATA
(exit)     A(throat)   A(throat)     Pf          Ps                        Palt
              COLD        COR.
s. in.     sq. in.     sq. in.      psia        psia                      psia
-------    --------    --------    --------    --------    --------    --------
 .06228     .000623     .000638     95.9        45.3         0.0        .0044
HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                             WIRE        DELTA
 volts       amps        watts       ohms        temp        dia         psia
-------    --------    --------    --------    --------    --------    --------
 25.32      19.726      499.5       1.2838      4241.7      .00000        0.0


IGHT        MICRO       THRUST      THRUST
LASS        MOTION      MEAS        VAC
bs/hr       lbs/hr      lbs         lbs
-------    --------    --------    --------    --------    --------    --------
0.00000     .86780      40.826      40.701

  CD          Cf          C*       REYNOLDS      GAS          PSP         ISP
                                    NUMBER       TEMP.
                        ft/sec                  deg. f                    sec.
-------    --------    --------    --------    --------    --------    --------
 .8984      1.4418      6989.4      1621.6      3801.5      12.273      313.2
```

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OCKET RESEARCH COMPANY                                          DATE:  8 May 1987 14:37:05

HENIUM HEAT EXCHANGER - BASELINE HEATER                                  SN# 001   RUN# 18


                                  UNREDUCED DATA (volts)
HRUST      THRUST    <-------               THRUST CALIBRATION                       ------->
RUN        ZERO      STEP 1      STEP 2     STEP 3      STEP 4     STEP 5      STEP 6
------     ------    ------      ------     ------      ------     ------      ------
3.305      +1.257    +2.479      +3.707     +4.981      +3.781     +2.550      +1.255

f(run)        Pf(0)              Pa(run)       Pa(0)              Palt(run)      Palt(0)
--------      --------           --------      --------           --------       --------
.014000       -.000218           +.009993      +.000001           -.000010       -.000028


                         RECORDED TEMPERATURES (degrees F)
Tf             Tc            T16           Tb            Tv            Tn

-------        -------       -------       -------       -------       -------
 +92.4         +1187.1       +1743.7       +1222.3       +246.0        +719.0

Th             Tspare        Tspare        Tspare        Tspare        Tspare

-------        -------       -------       -------       -------       -------
1608.0           +32.0         +32.0         +32.0         +0.0          +0.0



                                       REDUCED DATA
(exit)       A(throat)    A(throat)    Pf          Pa                        Palt
             COLD         CORR.
s. in.       sq. in.      sq. in.      psia        psia                      psia
--------     --------     --------     --------    --------     --------     --------
 .06228      .000623      .000639      127.7       53.4         0.0          .0031

HEATER       HEATER       HEATER       HEATER      HEATER       HEATER       Pf
                                                                WIRE         DELTA
volts        amps         watts        ohms        temp         dia          psia
--------     --------     --------     --------    --------     --------     --------
 33.07       22.694       750.6        1.4574      4789.2       .00000       0.0

IGHT         MICRO        THRUST       THRUST
LASS         MOTION       MEAS         VAC
lbs/hr       lbs/hr       mlbs         mlbs
--------     --------     --------     --------    --------     --------     --------
0.00000      .54260       49.247       49.437

CD           Cf           C*           REYNOLDS    GAS          PSP          ISP
                                       NUMBER      TEMP.
                          ft/sec                   deg. f                    sec.
  -----      --------     --------     --------    --------     --------     --------
.9040        1.4866       7100.2       1826.0      4002.7       15.182       325.1
```

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OCKET RESEARCH COMPANY DATE: 8 May 1987 15:06

HENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RUN#

UNREDUCED DATA (volts)

HRUST RUN	THRUST ZERO	<------- STEP 1	STEP 2	THRUST CALIBRATION STEP 3	STEP 4	STEP 5	------- STEP 6
3.342	+1.277	+2.502	+3.733	+5.000	+3.814	+2.570	+1.314

f(run)	Pf(O)	Ps(run)	Pd(0)	Palt(run)	Palt(O)
.014000	-.000280	+.009978	+.000001	-.000018	-.00003

RECORDED TEMPERATURES (degrees F)

Tf	Tc	T16	Tb	Tv	Tm
+94.9	+1168.7	+1794.5	+1225.9	+243.0	+735.

Th	Tspare	Tspare	Tspare	Tspare	Tspare
1646.9	+32.0	+32.0	+32.0	+0.0	+0.

REDUCED DATA

(exit) s. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Ps psia		Palt psia
.06228	.000623	.000640	127.5	53.6	0.0	.0024

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
33.26	24.048	799.8	1.3831	4554.9	.00000	0.0

IGHT LASS bs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000	.53739	49.971	50.119			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9028	1.5006	7198.9	1778.7	4173.0	15.959	335.8

run terminated early because of
Heater shorting

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ROCKET RESEARCH COMPANY DATE: 11 May 1987 14:03:49

RHENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RUN# 2

UNREDUCED DATA (volts)

THRUST RUN	THRUST ZERO	<-------- STEP 1	STEP 2	THRUST CALIBRATION STEP 3	STEP 4	STEP 5	--------> STEP 6
-3.516	+1.134	+2.353	+3.622	+4.870	+3.648	+2.442	+1.174

Pf(run)	Pf(0)	Ps(run)	Ps(0)	Palt(run)	Palt(0)
+.015680	-.000059	+.013540	-.000003	+.000019	-.000037

RECORDED TEMPERATURES (degrees F)

Tf	Tc	T16	Tb	Tv	Tm
+80.1	+1159.7	+1404.1	+1184.5	+192.5	+506.5

Th	Tspare	Tspare	Tspare	Tspare	Tspare
1309.2	+32.0	+32.3	+32.0	+0.0	+0.0

REDUCED DATA

(exit) sq. in.	A(throat) COLT sq. in.	A(throat) COP. sq. in.	Pf psia	Ps psia		Palt psia
.06228	.000623	.000636	167.9	59.1	0.0	.0031

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
24.90	20.100	500.4	1.2387	4099.5	.00000	0.0

IGHT LASS bs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000	.65161	57.582	57.772			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9157	1.5693	6543.6	2408.4	3404.2	8.662	319.2

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OCKET RESEARCH COMPANY                                              DATE: 11 May 1987 14:30:

HENIUM HEAT EXCHANGER - BASELINE HEATER                                      SN# 001   RUN#


                                 UNREDUCED DATA (volts)
HRUST     THRUST     <--------            THRUST CALIBRATION                    ------->
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
2.784     +1.136     +2.359     +3.584     +4.810     +3.599     +2.387     +1.130

f(run)       Pf(0)          Ps(run)         Pd(0)            Palt(run)       Palt(0)
-------     --------        --------        ---------        ---------       --------
.011997     -.000134        +.007249        -.000003         -.000020        -.000035


                         RECORDED TEMPERATURES (degrees F)
 Tf              Tc              T16             Tb              Tv              Tm

------         -------         -------         -------         -------         -------
 +83.4          +1149.3         +1522.1         +1174.6         +211.8          +572.3

 Th             Tspare          Tspare          Tspare          Tspare          Tspare

------         -------         -------         -------         -------         -------
1410.1            +32.0           +32.0           +32.0            +0.0            +0.0


                                        REDUCED DATA
(exit)     A(throat)   A(throat)     Pf          Ps                        Palt
             COLD        CORR.
s. in.     sq. in.     sq. in.      psia        psia                      psia
-------    --------    --------    --------    --------    --------    --------
 .06228     .000623     .000635      96.7        45.6         0.0        .0076

HEATER     HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                            WIRE        DELTA
 volts      amps        watts       ohms        temp        dia         psia
-------    --------    --------    --------    --------    --------    --------
 25.39     19.678       499.6      1.2901      4261.7      .00000        0.0

IGHT       MICRO       THRUST      THRUST
LASS       MOTION       MEAS        VAC
bs/hr      lbs/hr       mlbs        mlbs
-------    --------    --------    --------    --------    --------    --------
0.00000     .47391      40.025      40.184

 CD          Cf          C*        REYNOLDS      GAS          PSP         ISP
                                    NUMBER       TEMP.
                        ft/sec                  deg. f                    sec.
-------    --------    --------    --------    --------    --------    --------
 .8995      1.4163      6934.5      1657.7      3742.1      12.432       305.3
```

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OCKET RESEARCH COMPANY                                     DATE: 11 May 1987 15:12:15
HENIUM HEAT EXCHANGER - BASELINE HEATER                            SN# 001  RUN#

                                UNREDUCED DATA (volts)
THRUST    THRUST    <-------           THRUST CALIBRATION                  ------->
 RUN       ZERO     STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------    ------     ------     ------     ------     ------     ------
+3.675    +1.285    +2.489     +3.737     +4.960     +3.768     +2.549     +1.259

f(run)        Pf(0)          Ps(run)         Ps(0)          Palt(run)      Palt(0)
--------     --------        --------       --------        --------       --------
+.016000     -.000246        +.013590       -.000003        -.000020       -.000037


                          RECORDED TEMPERATURES (degrees F)
 Tf            Tc             T16            Tb             Tv             Tn

-------      -------        -------        -------        -------        -------
 +85.9       +1191.2        +1660.2        +1219.8        +229.2         +690.7
 Th          Tspare         Tspare         Tspare         Tspare         Tspare

-------      -------        -------        -------        -------        -------
1525.0        +32.0          +32.0          +32.0          +0.0           +0.0


                                     REDUCED DATA
(exit)     A(throat)  A(throat)     Pf          Ps                       Palt
             COLD       COR.
s. in.     sq. in.    sq. in.      psia        psia                      psia
-------    --------   --------    --------    --------    --------    --------
 .06225    .000623    .000635     168.4        61.0         0.0        .0079

HEATER     HEATER     HEATER      HEATER      HEATER      HEATER        Pf
                                                           WIRE        DELTA
 volts      amps       watts       ohms        temp        dia          psia
--------   --------   --------    --------    --------    --------    --------
 32.77     22.876     749.6       1.4325      4710.7      .00000         0.0


IGHT       MICRO      THRUST      THRUST
LASS       MOTION     MEAS        VAC
bs/hr      lbs/hr     mlbs        mlbs
--------   --------   --------    --------    --------    --------    --------
0.00000    .63575     57.795      57.975


CD          Cf          C*        REYNOLDS      GAS         PSP          ISP
                                   NUMBER      TEMP.
                       ft/sec                  deg. f                    sec.
-----     --------    --------    --------    --------    --------    --------
.9118     1.5257      6922.9      2188.5      3848.2      12.930       378.3
```

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OCKET RESEARCH COMPANY                                       DATE: 11 May 1987 15:51:
HENIUM HEAT EXCHANGER - BASELINE HEATER                               SN# 001   RUN#

                              UNREDUCED DATA (volts)
HRUST     THRUST     <-------              THRUST CALIBRATION                  -------
RUN       ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    -------    ------     ------     ------     ------     ------     ------
3.827     +1.314     +2.532     +3.759     +5.016     +3.829     +2.573     +1.314

f(run)        Ff(0)          Fs(run)          Fs(0)          Palt(run)       Palt(0)
---------     ---------      ---------        ---------      ---------       -------
.016980       -.000307       +.014098         -.000003       -.000020        -.00003


                      RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv             Tm

------         -------        -------        -------        -------        -------
 +88.5         +1193.8        +1692.7        +1227.8        +236.4         +707.
 Th            Tspare         Tspare         Tspare         Tspare         Tspare

------         -------        -------        -------        -------        -------
1555.0           +32.0          +32.0          +32.0          +0.0           +0.


                                 REDUCED DATA
(exit)    A(throat)  A(throat)   Pf         Ps                     Palt
           COLD       COF.
s. in.    sq. in.    sq. in.     psia       psia                   psia
-------   --------   --------   --------   --------   --------   --------
.06228    .000623    .000640    174.2      64.9       0.0        .0027

HEATER    HEATER     HEATER     HEATER     HEATER     HEATER     Pf
                                                      WIRE       DELTA
volts     amps       watts      ohms       temp       dia        psia
-------   --------   --------   --------   --------   --------   --------
34.16     23.424     800.1      1.4583     4792.2     .00000     0.0

IGHT      MICRO      THRUST     THRUST
LASS      MOTION     MEAS       VAC
bs/hr     lbs/hr     mlbs       mlbs
--------  --------   --------   --------   --------   --------   --------
0.00000   .65004     60.795     60.964

CD        Cf         C*         REYNOLDS   GAS        PSP        ISP
                                NUMBER     TEMP.
                     ft/sec                deg. f                sec.
-----     --------   --------   --------   --------   --------   --------
.9106     1.5078     7204.6     2124.8     4215.9     13.125     337.6
```

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OCKET RESEARCH COMPANY                                          DATE: 12 May 1987 10:23:51

HENIUM HEAT EXCHANGER - BASELINE HEATER                                   SN# 001   RUN# 24


                                 UNREDUCED DATA (volts)
HRUST     THRUST     --------              THRUST CALIBRATION                    --------
RUN        ZERO      STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
------    ------     ------    ------    ------    ------    ------    ------
3.847     +1.291     +2.602    +3.839    +5.045    +3.852    +2.672    +1.383

f(run)      Pf(0)             Ps(run)      Ps(0)        Palt(run)     Palt(0)
--------   --------           --------    --------      --------      --------
.013222    +.000010           +.016013    -.000086      -.000045      -.000064


                          RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16             Tb             Tv             Tm

-------       -------        -------        -------        -------        -------
 +76.9        +1175.6        +1656.7        +1209.5        +210.6         +664.4

 Th           Tspare         Tspare         Tspare         Tspare         Tspare

-------       -------        -------        -------        -------        -------
1526.3         +32.0          +32.0          +32.0          +0.0           +0.0


                                     REDUCED DATA
(exit)     A(throat)  A(throat)    Pf          Ps                       Palt
            COLD       OP.
s. in.     sq. in.    sq. in.     psia        psia                     psia
--------   --------   --------   --------    --------    --------     --------
 .06228    .000623    .000638     164.1       60.5         0.0         .0072

HEATER     HEATER     HEATER     HEATER      HEATER      HEATER        Pf
                                                          WIRE        DELTA
 volts      amps       watts      ohms        temp        dia         psia
--------   --------   --------   --------    --------    --------     --------
 32.74     22.922     750.4      1.4282      4697.2      .00000        0.0


IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------    --------    --------     --------
0.00000    .63260     59.922     60.123


 CD          Cf          C*       REYNOLDS      GAS         PSP          ISP
                                   NUMBER       TEMP.
                       ft/sec                   deg. f                  sec.
 -----     --------   --------   --------    --------    --------     --------
 .9118     1.5967     6894.6     2189.6      3811.4      12.481        342.1
```

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```
OCKET RESEARCH COMPANY                                          DATE: 12 May 1987 11:07:

HENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001   RUN#


                                 UNREDUCED DATA (volts)
HRUST     THRUST     <-------            THRUST CALIBRATION                    ------->
RUN       ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
3.801     +1.324     +2.547     +3.773     +4.986     +3.793     +2.565     +1.324

f(run)      Pf(O)            Ps(run)      Ps(O)           Palt(run)      Palt(O)
--------    --------         --------     --------        --------       --------
.013720     +.000010         +.016953     -.000223        -.000048       -.00005


                          RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv             Tm

-------       -------        -------        -------        -------        -------
 +80.8        +1188.1        +1688.8        +1221.4        +225.3         +701.

 Th            Tspare         Tspare         Tspare         Tspare         Tspare

-------       -------        -------        -------        -------        -------
1558.7          +32.0          +32.0          +32.0          +0.0          +0.


                                  REDUCED DATA
(exit)     A(throat)  A(throat)    Pf         Ps                      Palt
           COLD       COR.
s. in.     sq. in.    sq. in.      psia       psia                    psia
-------    --------   --------   --------   --------   --------    --------
 .06228    .000633    .000641     169.8      64.5        0.0         .0019

HEATER     HEATER     HEATER     HEATER     HEATER     HEATER       Pf
                                                       WIRE         DELTA
volts      amps       watts      ohms       temp       dia          psia
-------    --------   --------   --------   --------   --------    --------
 34.16     23.406     799.5      1.4594     4795.6     .00000        0.0


IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------   --------   --------    --------
0.00000     .64082    60.419     60.535


 CD          Cf          C*       REYNOLDS     GAS         PSF          ISP
                                  NUMBER       TEMP.
                       ft/sec                  deg. f                   sec.
 -----    ---------   --------    --------   --------   --------    --------
 .9096     1.50e6      7261.5     2074.2      4287.5     13.207       340.1
```

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OCKET RESEARCH COMPANY                                      DATE: 12 May 1987 11:4[illegible]:50

HELIUM HEAT EXCHANGER - BASELINE HEATER                                 SN# 001   RUN# 2
/

                              UNREDUCED DATA (volts)
HRUST    THRUST   <-------          THRUST CALIBRATION                 -------
RUN      ZERO     STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
-----    ------   ------    ------    ------    ------    ------    ------
3.690    +1.335   +2.557    +3.777    +5.004    +3.800    +2.574    +1.320

f(run)      Pf(0)          Pa(run)       Pa(0)        Palt(run)    Palt(0)
-------    --------       --------      --------     --------     --------
.013338    +.000010       +.016000      -.000287     -.000046     -.000061


                      RECORDED TEMPERATURES (degrees F)
Tf          Tc          T16          Tb          Tv          Tm

------     -------     -------     -------     -------     -------
+83.5      +1185.1     +1655.6     +1218.7     +227.2      +680.2

Th          Tspare      Tspare      Tspare      Tspare      Tspare

------     -------     -------     -------     -------     -------
1532.9       +32.0       +32.0       +32.0       +0.0        +0.0


                                REDUCED DATA
(exit)    A(throat)  A(throat)    Pf         Pa                     Palt
           COLD       COR.
s. in.    sq. in.    sq. in.     psia       psia                   psia
-------   --------   --------   --------   --------   --------   --------
 .06228   .000623    .000639    165.4      61.2       0.0        .0025

HEATER    HEATER     HEATER     HEATER     HEATER     HEATER     Pf
                                                      WIRE       DELTA
 volts     amps       watts      ohms       temp       dia        psia
-------   --------   --------   --------   --------   --------   --------
 32.75    22.912     750.4      1.4295     4701.3     .00000      0.0

IGHT      MICRO      THRUST     THRUST
LASS      MOTION     MEAS       VAC
bs/hr     lbs/hr     mlbs       mlbs
-------   --------   --------   --------   --------   --------   --------
0.00000   .65163     57.380     57.538

 CD        Cf         C*       REYNOLDS    GAS        PSF        ISP
                                NUMBER     TEMP.
                     ft/sec                deg. f                sec.
 -----    --------   --------   --------   --------   --------   --------
 .9111    1.5104     6985.7     2150.3     3923.6     13.042     327.9
```

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OCKET RESEARCH COMPANY                                          DATE: 12 May 1987 13:18
HENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001   RUN#

                                UNREDUCED DATA (volts)
HRUST    THRUST    <-------             THRUST CALIBRATION                       -------
RUN      ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------   ------    ------     ------     ------     ------     ------     ------
3.954    +1.430    +2.641     +3.847     +5.077     +3.880     +2.666     +1.406

f(run)        Pf(0)          Ps(run)        Ps(0)          Palt(run)      Palt(0)
--------      ---------      ---------      ---------      ---------      --------
.014310       +.000010       +.017000       -.000205       -.000041       -.00005

                        RECORDED TEMPERATURES (degrees F)
 Tf            Tc            T16            Tb             Tv             Tm

-------       -------       -------        -------        -------        -------
 +82.7        +1190.0       +1725.7        +1224.6        +222.8         +713.

 Th            Tspare        Tspare         Tspare         Tspare         Tspare

-------       -------       -------        -------        -------        -------
1586.2          +32.0         +32.0          +32.0           +0.0           +0.

                                REDUCED DATA
(exit)     A(throat)  A(throat)    Pf          Ps                      Palt
             COLD       COR.
s. in.     sq. in.    sq. in.      psia        psia                    psia
--------   --------   --------   --------    --------    --------    --------
 .06225     .000623    .000639    176.4       64.6         0.0        .0029

HEATER     HEATER     HEATER     HEATER      HEATER      HEATER       Pf
                                                          WIRE        DELTA
 volts      amps       watts      ohms        temp        dia         psia
--------   --------   --------   --------    --------    --------    --------
 35.16     24.326     855.3      1.4453      4751.2      .00000       0.0

IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
--------   --------   --------   --------    --------    --------    --------
0.00000    .86045     81.924     62.104

 CD         Cf         C*        REYNOLDS    GAS         PSP          ISP
                                 NUMBER      TEMP.
                      ft/sec                 deg. f                   sec.
 -----     --------   --------   --------    --------    --------    --------
 .9123     1.5433     7057.4     2213.8      4032.0      13.772      338.5
```

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OCKET RESEARCH COMPANY                                       DATE: 12 May 1987 14:05:23

HENIUM HEAT EXCHANGER - BASELINE HEATER                               SN# 001   RUN# 2?


                                 UNREDUCED DATA (volts)
HRUST     THRUST     <--------              THRUST CALIBRATION                     -------->
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-----     ------     ------     ------     ------     ------     ------     ------
3.879     +1.381     +2.588     +3.810     +5.039     +3.834     +2.610     +1.354

f(run)       Pf(0)           Ps(run)         Ps(0)            Palt(run)        Palt(0)
--------   ---------        ---------       ---------        ---------        ---------
.014308    +.000010         +.017000        -.000317         -.000041         -.000058


                           RECORDED TEMPERATURES (degrees F)
 Tf             Tc              T16             Tb              Tv              Tm

------        -------         -------         -------         -------         -------
 +86.5        +1200.5         +1730.2         +1236.7          +244.0          +775.8

 Th           Tspare          Tspare          Tspare          Tspare          Tspare

------        -------         -------         -------         -------         -------
1594.5          +32.0           +32.0           +32.0            +0.0            +0.0


                                      REDUCED DATA
(exit)     A(throat)   A(throat)     Pf            Ps                          Palt
            COLD        COR.
s. in.     sq. in.     sq. in.       psia          psia                        psia
-------    --------    --------    --------      --------      --------      --------
 .06228    .000623     .000640      176.4          65.0           0.0          .0005

HEATER     HEATER      HEATER      HEATER        HEATER        HEATER          Pf
                                                               WIRE          DELTA
 volts      amps        watts       ohms          temp          dia           psia
-------    --------    --------    --------      --------      --------      --------
 35.20     24.156       850.2      1.4570        4788.2        .00000          0.0


IGHT       MICRO       THRUST      THRUST
LASS       MOTION      MEAS        VAC
bs/hr      lbs/hr      mlbs        mlbs
--------   --------    --------    --------      --------      --------      --------
0.00000    -.65265     61.064      61.244


 CD          Cf          C*        REYNOLDS        GAS           PSP           ISP
                                    NUMBER         TEMP.
                       ft/sec                     deg. f                       sec.
 -----     --------    --------    --------      --------      --------      --------
 .9109      1.5121      7188.3      2138.9        4196.3        13.882        337.8
```

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OCKET RESEARCH COMPANY                                                  DATE: 12 May 1987 14:3
HENIUM HEAT EXCHANGER - BASELINE HEATER                                      SN# 001   RUN

                                  UNREDUCED DATA (volts)
HRUST     THRUST     <-------               THRUST CALIBRATION                       -------
 RUN       ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
------    ------     ------     ------     ------     ------     ------     -----
2.886     +1.285     +2.519     +3.744     +4.947     +3.756     +2.528     +1.29

f(run)      Pf(0)           Ps(run)        Ps(0)           Palt(run)      Palt(0
--------   --------        --------       --------         --------       -------
+.007088   +.000010        +.011000       -.000303         -.000050       -.0000


                       RECORDED TEMPERATURES (degrees F)
  Tf           Tc            T16           Tb            Tv           Tm

-------      -------       -------       -------       -------      -----
 +87.7       +1158.4       +1533.4       +1184.8       +277.4       +588

 Th          Tspare        Tspare        Tspare        Tspare       Tspar

-------      -------       -------       -------       -------      -----
1437.8        +32.0         +32.0         +32.0         +0.0         +0


                                    REDUCED DATA
(exit)     A(throat)  A(throat)     Pf         Ps                    Palt
             COLD       COR.
s. in.     sq. in.    sq. in.      psia       psia                   psia
--------   --------   --------   --------   --------   --------   --------
 .06228    .000623    .000435      94.8       42.4       0.0        .0020

HEATER     HEATER     HEATER     HEATER     HEATER     HEATER       Pf
                                                        WIRE        DELTA
 volts      amps      watts       ohms       temp       dia         psia
--------   --------   --------   --------   --------   --------   --------
 25.28     19.774     499.9      1.2786     4225.3     .00000       0.0


IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     lbs        lbs
--------   --------   --------   --------   --------   --------   --------
0.00000     .46559     38.966     39.093


 CD          Cf          C*       REYNOLDS      GAS         PSP         ISP
                                   NUMBER      TEMP.
                       ft/sec                  deg. f                   sec.
--------   --------   --------   --------   --------   --------   --------
 .9019      1.4767     6576.9     1745.7     3323.4     12.788      302.7
```

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ROCKET RESEARCH COMPANY                                        DATE: 12 May 1987 15:17:47

HENIUM HEAT EXCHANGER - BASELINE HEATER                                    SN# 001  RUN# 30


                                   UNREDUCED DATA (volts)
HRUST     THRUST     <-------               THRUST CALIBRATION                  ------->
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
3.365     +1.334     +2.550     +3.773     +4.994     +3.786     +2.560     +1.308

f(run)       Pf(0)              Ps(run)       Ps(0)              Palt(run)      Palt(0)
-------    --------            --------     --------             --------       --------
.010221    +.000010            +.014000     -.000319             -.000050       -.000063


                           RECORDED TEMPERATURES (degrees F)
 Tf             Tc             T16            Tb             Tv             Tn

------        -------        -------        -------        -------        -------
 +88.3        +1206.0        +1715.9        +1225.3        +246.7         +717.8

 Th           Tspare         Tspare         Tspare         Tspare         Tspare

------        -------        -------        -------        -------        -------
1582.8          +32.0          +32.0          +32.0          +0.0           +0.0


                                     REDUCED DATA
(exit)      A(throat)   A(throat)     Pf          Ps                       Palt
             COLD        COR.
s. in.      sq. in.     sq. in.      psia        psia                      psia
-------     --------    --------    --------    --------    --------    --------
 .06228      .000623     .000639     130.2        53.8         0.0        .0022

HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                             WIRE        DELTA
 volts       amps        watts       ohms        temp         dia         psia
--------    --------    --------    --------    --------    --------    --------
 32.82       22.846      749.9       1.4367      4723.9      .00000        0.0

IGHT        MICRO       THRUST      THRUST
LASS        MOTION      MEAS        VAC
bs/hr       lbs/hr      mlbs        mlbs
--------    --------    --------    --------    --------    --------    --------
0.00000     .54147      49.525      49.683

 CD          Cf          C*         REYNOLDS      GAS         PSP         ISP
                                    NUMBER       TEMP.
                        ft/sec                   deg. f                   sec.
 -----      --------    --------    --------    --------    --------    --------
 .9034       1.4828      7164.2      1802.3      4082.3      15.099      330.2
```

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[illegible] RESEARCH COMPANY                                   DATE: 13 May 1987 15:39

[illegible]HENIUM HEAT EXCHANGER - BASELINE HEATER                          SN# 001   RUN#

                              UNREDUCED DATA (volts)
THRUST   THRUST   --------             THRUST CALIBRATION                     -------
 RUN      ZERO     STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
------   ------   ------    ------    ------    ------    ------    ------
+3.550   +1.891   +3.111    +4.320    +5.526    +4.332    +3.116    +1.87(

Pf(run)        Pf(0)            Ps(run)        Ps(0)          Palt(run)        Palt(0
--------      --------          --------       --------       --------         --------
.007140      +.000007          +.011983       -.000031       -.000009         -.0000

                       RECORDED TEMPERATURES (degrees F)
 Tf            Tc            T16            Tb             Tv             Tp

------       --------      --------       --------       --------       -----
+78.4        +1144.6       +1521.3        +1172.5        +207.5         +574

 Th           Tspare        Tspare         Tspare         Tspare         Tspar

------       --------      --------       --------       --------       -----
1440.1       +32.0         +32.0          +32.0          -0.0           +[illegible]

                                   REDUCED DATA
A(exit)    A(throat)   A(throat)     Pf         Ps                         Palt
             COLD        [illegible]
sq. in.    sq. in.     sq. in.       psia       psia                       psia
--------   --------    --------    --------   --------    --------       --------
.0621[illegible]    .000[illegible]     .000[illegible]      95.4       45.1         0.0            .00[illegible]

HEATER     HEATER      HEATER      HEATER     HEATER      HEATER          Pf
                                                           WIRE           DELTA
volts      amps        watts       ohms       temp        dia             psia
--------   --------    --------    --------   --------    --------       --------
25.37      19.696      499.6       1.2880     4255.0      .00000          0.0

[illegible]GHT     MICRO       THRUST      THRUST
[illegible]LASS    MOTION      MEAS        VAC
[illegible]bs/hr   lbs/hr      mlbs        mlbs
--------   --------    --------    --------   --------    --------       --------
0.00000    [illegible]         40.529      40.677

CD          Cf          C*        REYNOLDS    GAS         PSF             ISP
                                   NUMBER     TEMP.
                        ft/sec                deg. f                      sec.
-----      --------    --------    --------   --------    --------       --------
.899[illegible]      1.4475      6930.9      1646.1     3731.3      [illegible]            311.8
```

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OCKET RESEARCH COMPANY                                          DATE: 13 May 1987 16:17:33
ENIUM HEAT EXCHANGER - BASELINE HEATER                          SN# 001  RUN# 3

                              UNREDUCED DATA (volts)
HRUST     THRUST    <-------                THRUST CALIBRATION                   --------
RUN       ZERO      STEP 1    STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------    ------    ------     ------     ------     ------     ------
4.029     +1.882    +3.094    +4.345     +5.562     +4.364     +3.153     +1.894

f(run)       Pf(0)          Ps(run)         Ps(0)         Palt(run)       Palt(0)
------     --------        --------       --------        --------       --------
.010371    +.000007        +.014373       -.000208        -.000005       -.000016


                         RECORDED TEMPERATURES (degrees F)
Tf           Tc           T16           Tb            Tv            Tm

------     -------      -------       -------       -------       -------
+84.2      +1193.9      +1807.7       +1235.1       +251.7        +765.8

Th         Tspare       Tspare        Tspare        Tspare        Tspare

------     -------      -------       -------       -------       -------
1672.7       +32.0        +32.0         +32.0         +0.0          +0.0


                                  REDUCED DATA
(exit)     A(throat)   A(throat)     Pf          Ps                          Palt
           COLI        COR.
s. in.     sq. in.     sq. in.       psia        psia                        psia
-------    --------    --------    --------    --------    --------    --------
.06228     .000623     .000640      131.9        54.8         0.0         .0019

HEATER     HEATER      HEATER      HEATER      HEATER      HEATER         Pf
                                                           WIRE          DELTA
volts      amps        watts       ohms        temp        dia           psia
-------    --------    --------    --------    --------    --------    --------
35.85      23.644      847.6       1.5163      4975.0      .00000          0.0


IGHT       MICRO       THRUST      THRUST
LASS       MOTION      MEAS        VAC
bs/hr      lbs/hr      mlbs        mlbs
-------    --------    --------    --------    --------    --------    --------
0.00000    .54251      52.189      52.305


CD          Cf          C*         REYNOLDS    GAS          PSF          ISP
                                   NUMBER      TEMP.
                        ft/sec                 deg. f                    sec.
 -----    --------    --------    --------    --------    --------    --------
.9025      1.5336      7281.5      1769.0      4233.8      16.206       347.1
```

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OCKET RESEARCH COMPANY                                          DATE: 14 May 1987 05:37

HENIUM HEAT EXCHANGER - BASELINE HEATER                                   SN# 001  RUN#


                                  UNREDUCED DATA (volts)
HRUST     THRUST     <-------              THRUST CALIBRATION                   -------
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------    ------     ------     ------     ------     ------     ------     ------
4.226     +2.065     +3.264     +4.488     +5.720     +4.527     +3.309     +2.066

f(run)      Pf(0)            Ps(run)       Pd(0)           Palt(run)      Palt(0)
-------   ---------         ---------    ---------         ---------      -------
.010610    +.000007          +.014997     -.000023         -.000024       -.00003



                          RECORDED TEMPERATURES (degrees F)
 Tf              Tc              T16             Tb              Tv             Tm

------         -------         -------         -------         -------        ------
 +75.9         +1170.5         +1712.4         +1207.8         +214.8         +689.

 Th            Tspare          Tspare          Tspare          Tspare         Tspare

------         -------         -------         -------         -------        ------
1596.1           +32.0           +32.0           +32.0            +0.0          +0.



                                      REDUCED DATA
(exit)    A(throat)  A(throat)     Pf         Ps                         Palt
             COLD       COR.
s. in.    sq. in.    sq. in.      psia       psia                        psia
-------   --------   --------   --------   --------   --------   --------
 .06229   .000623    .000635     134.6       56.4        0.0       .0070

HEATER    HEATER     HEATER     HEATER     HEATER     HEATER       Pf
                                                       WIRE       DELTA
 volts     amps       watts      ohms       temp       dia        psia
-------   --------   --------   --------   --------   --------   --------
 32.91    22.688     746.7      1.4506     4767.9     .00000       0.0


IGHT      MICRO      THRUST     THRUST
LASS      MOTION      MEAS       VAC
bs/hr     lbs/hr      mlbs       mlbs
-------   --------   --------   --------   --------   --------   --------
0.00000   1.56864    53.068     53.195


 CD         Cf         C*      REYNOLDS     GAS        PSP        ISP
                                NUMBER      TEMP.
                     ft/sec                deg. f                 sec.
 -----    --------   --------   --------   --------   --------   --------
 .9055    1.5142     7155.7      1889.8     4093.6     14.037     336.8
```

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APPENDIX B

Sealed Cavity Data

```
ROCKET RESEARCH COMPANY                                      DATE: 31 Aug 1987 15:

RHENIUM HEAT EXCHANGER - BASELINE HEATER                               SN# 001  RL


                              UNREDUCED DATA (volts)
THRUST    THRUST    <-------            THRUST CALIBRATION              -----
 RUN       ZERO     STEP 1    STEP 2    STEP 3    STEP 4    STEP 5     STEP
------    ------    ------    ------    ------    ------    ------     ----
 +.460     +.331    +0.000    +0.000    +0.000    +0.000    +0.000     +0.

Pf(run)          Pf(0)          Ps(run)        Ps(0)          Palt(run)       Palt(
--------        --------        --------      --------        --------        -----
+.002082        -.000650        +.008187      +.001019        -.002019        -.00


                         RECORDED TEMPERATURES (degrees F)
  Tc             T16             Tb             Tv             Thb             Ts

-------        -------        -------        -------        -------         ----
+1104.1         +439.9        +1107.8         +128.8         +562.2          +6

  Ts1            Ts2            Ts3           Tcon            Th1             Th

-------        -------        -------        -------        -------         ----
 +248.9         +282.6         +327.2         +489.3         +269.2          +27


                                    REDUCED DATA
A(exit)    A(throat)  A(throat)    Pf        Ps                  Palt
             COLD       COR.
sq. in.    sq. in.    sq. in.     psia      psia                 psia
--------   --------   --------   --------  --------  --------  --------
 .06228    .000623    .000626     88.5      28.8       0.0       .0004

 HEATER     HEATER     HEATER    HEATER    HEATER     HEATER       Pf
                                                       WIRE       DELTA
  volts      amps       watts     ohms      temp       dia        psia
--------   --------   --------   --------  --------  --------  --------
  -0.00      -.004       0.0     0.0000      0.0     .00000       0.0

SIGHT      MICRO      THRUST     THRUST
GLASS      MOTION     MEAS       VAC
lbs/hr     lbs/hr     mlbs       mlbs
--------   --------   --------   --------  --------  --------  --------
0.00000     .51260     25.872    25.899

  CD         Cf         C*      REYNOLDS     GAS        PSP        ISP
                                 NUMBER     TEMP.
                      ft/sec               deg. f                  sec.
--------   --------   --------   --------  --------  --------  --------
 .9296      1.4463     4046.3     3550.6    1076.2     0.000      181.9
```

```
ROCKET RESEARCH COMPANY                                         DATE: 31 Aug 1987 15:52:19

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                    SN# 001   RUN#   3


                                  UNREDUCED DATA (volts)
THRUST      THRUST     <-------             THRUST CALIBRATION                         ------->
 RUN         ZERO      STEP 1      STEP 2     STEP 3      STEP 4      STEP 5      STEP 6
------      ------     ------      ------     ------      ------      ------      ------
 +.502       +.329     +0.000      +0.000     +0.000      +0.000      +0.000      +0.000

Pf(run)        Pf(0)              Ps(run)          Ps(0)           Palt(run)       Palt(0)
--------     --------             --------       --------          --------       --------
+.002080     -.000650             +.010623       +.000962          -.002024       -.002041


                              RECORDED TEMPERATURES (degrees F)
  Tc              T16              Tb               Tv               Thb              Ts

-------         -------          -------          -------          -------          -------
+1119.4         +1006.0          +1135.8          +156.6           +1310.0          +1424.6

  Ts1             Ts2              Ts3             Tcon              Th1              Th2

-------         -------          -------          -------          -------          -------
 +785.0          +650.7           +792.6          +1020.1          +1270.7          +2956.0


                                       REDUCED DATA
A(exit)      A(throat)    A(throat)      Pf           Ps                         Palt
               COLD         COR.
sq. in.      sq. in.      sq. in.       psia         psia                        psia
--------     --------     --------    --------     --------     --------      --------
 .06228      .000623      .000632       88.4         38.8          0.0          .0004

 HEATER       HEATER       HEATER      HEATER       HEATER       HEATER          Pf
                                                                  WIRE          DELTA
  volts        amps         watts       ohms         temp          dia          psia
--------     --------     --------    --------     --------     --------      --------
  13.83       21.340       295.2       .6482        3376.7       .00000         0.0

 SIGHT        MICRO        THRUST      THRUST
 GLASS        MOTION        MEAS        VAC
 lbs/hr       lbs/hr        mlbs        mlbs
--------     --------     --------    --------     --------     --------      --------
 0.00000      .46796       34.659      34.682

   CD           Cf           C*       REYNOLDS       GAS          PSP           ISP
                                       NUMBER       TEMP.
                           ft/sec                  deg. f                      sec.
--------     --------     --------    --------     --------     --------      --------
  .9075       1.4369       5974.0      1978.9       2699.4        8.512         266.8
```

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ROCKET RESEARCH COMPANY DATE: ~~STORAGE ERROR~~

RHENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 R

```
                               UNREDUCED DATA (volts)
THRUST     THRUST     <-------           THRUST CALIBRATION                   ----
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STE
------     ------     ------     ------     ------     ------     ------     ---
 +.557      +.338     +0.000     +0.000     +0.000     +0.000     +0.000     +0.

Pf(run)        Pf(0)            Ps(run)          Ps(0)           Palt(run)       Palt
---------    ---------        ---------        ---------        ---------       ----
+.003418     -.000640         +.013054         +.000908         -.002051        -.00


                          RECORDED TEMPERATURES (desrees F)
  Tc               T16              Tb               Tv               Thb            T

-------          -------          -------          -------          -------        ---
+1179.7           +672.7          +1173.0           +173.0          +1539.3        +16

  Ts1              Ts2              Ts3              Tcon             Th1            T

-------          -------          -------          -------          -------        ---
+1025.5           +836.1          +1014.9          +1140.4          +1719.5        +34


                                     REDUCED DATA
A(exit)     A(throat)   A(throat)     Pf          Ps                      Palt
              COLD        COR.
ss. in.     sq. in.     sq. in.      psia        psia                    psia
---------   ---------   ---------   ---------   ---------   ---------   -------
 .06228      .000623     .000635     124.3       48.7        0.0        .0004

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER      Pf
                                                             WIRE        DELTA
  volts       amps        watts       ohms        temp       dia         psia
---------   ---------   ---------   ---------   ---------   ---------   -------
  19.54      25.568      499.6       .7643       3988.4      .00000      0.0

SIGHT       MICRO       THRUST      THRUST
GLASS       MOTION      MEAS        VAC
lbs/hr      lbs/hr      mlbs        mlbs
---------   ---------   ---------   ---------   ---------   ---------   -------
 0.00000     .54212      44.032      44.055
  .5474

  CD          Cf          C*        REYNOLDS      GAS        PSP         ISP
                                     NUMBER      TEMP.
                        ft/sec                  des. f                   sec.
---------   ---------   ---------   ---------   ---------   ---------   -------
  .9091      1.4518      6483.5      2050.2      3274.3      11.341     292.
                                                                        289.
```

```
ROCKET RESEARCH COMPANY                                        DATE: STORAGE ERROR

RHENIUM HEAT EXCHANGER - BASELINE HEATER                            SN# 001   RUN#  6


                                UNREDUCED DATA (volts)
THRUST      THRUST     <-------              THRUST CALIBRATION                  ------->
 RUN         ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
------      ------     ------     ------     ------     ------     ------     ------
 +.600       +.343     +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

Pf(run)        Pf(0)           Ps(run)          Ps(0)           Palt(run)      Palt(0)
--------     --------          --------       --------          --------       --------
+.004828     -.000640          +.014890       +.000922          -.002019       -.002042


                          RECORDED TEMPERATURES (degrees F)
  Tc               T16               Tb               Tv               Thb              Ts

-------          -------          -------          -------          -------          -------
+1190.1           +633.5          +1183.1           +160.5          +1496.4          +1627.8
  Ts1              Ts2              Ts3              Tcon             Th1              Th2

-------          -------          -------          -------          -------          -------
 +965.7           +783.8           +952.8          +1114.0          +2055.9             +0.0


                                     REDUCED DATA
A(exit)      A(throat)    A(throat)      Pf           Ps                         Palt
               COLD         COR.
sq. in.      sq. in.      sq. in.       psia         psia                        psia
--------     --------     --------     --------     --------     --------     --------
  .06228      .000623      .000635     162.3         56.0          0.0          .0005

 HEATER       HEATER       HEATER       HEATER       HEATER       HEATER        Pf
                                                                   WIRE        DELTA
  volts        amps         watts        ohms         temp          dia         psia
--------     --------     --------     --------     --------     --------     --------
  19.42       25.732        499.8        .7549       3938.9        .00000        0.0

SIGHT         MICRO        THRUST       THRUST
GLASS         MOTION       MEAS         VAC
lbs/hr        lbs/hr       mlbs         mlbs
--------     --------     --------     --------     --------     --------     --------
 0.00000       .62444       51.567       51.597
  .6957

  CD            Cf           C*        REYNOLDS       GAS          PSP          ISP
                                        NUMBER       TEMP.
                          ft/sec                    deg. f                     sec.
--------     --------     --------     --------     --------     --------     --------
  .9146       1.4786       6472.8       2347.5       3308.3        9.687        297.5
                                                                               287.7
```

```
ROCKET RESEARCH COMPANY                                          DATE: STORAGE ERROR

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                    SN# 001   RU


                                 UNREDUCED DATA (volts)
THRUST     THRUST     <-------              THRUST CALIBRATION                    -----
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
-------    -------    -------    -------    -------    -------    -------    ----
 +.543      +.321     +0.000     +0.000     +0.000     +0.000     +0.000     +0.0

Pf(run)         Pf(0)           Ps(run)         Ps(0)           Palt(run)       Palt(
---------       ---------       ---------       ---------       ---------       -----
+.003384        -.000633        +.013139        +.000980        -.002140        -.002


                            RECORDED TEMPERATURES (degrees F)
  Tc             T16            Tb             Tv             Thb            Ts

--------       --------       --------       --------       --------       ----
+1180.7         +665.6        +1175.4        +1327.2        +1539.0        +166
  Ts1            Ts2            Ts3            Tcon           Th1            Th

--------       --------       --------       --------       --------       ----
+1026.7         +834.6        +1017.9        +1137.4        +1962.9        +39


                                        REDUCED DATA
A(exit)      A(throat)    A(throat)      Pf           Ps                         Palt
               COLD         COR.
sq. in.      sq. in.      sq. in.       psia         psia                        psia
---------    ---------    ---------    ---------    ---------    ---------    ---------
  .06228      .000623      .000633      123.2         48.8          0.0         .0013

 HEATER       HEATER       HEATER       HEATER       HEATER       HEATER         Pf
                                                                   WIRE         DELTA
  volts        amps         watts        ohms         temp         dia          psia
---------    ---------    ---------    ---------    ---------    ---------    ---------
  19.56       25.536        499.4        .7659       3997.0       .00000         0.0

SIGHT        MICRO        THRUST       THRUST
GLASS        MOTION        MEAS         VAC
lbs/hr       lbs/hr        mlbs         mlbs
---------    ---------    ---------    ---------    ---------    ---------    ---------
 0.00000      .58569       44.513       44.596
  .5541

  CD           Cf            C*        REYNOLDS        GAS          PSP          ISP
                                        NUMBER        TEMP.
                           ft/sec                    deg. f                     sec.
---------    ---------    ---------    ---------    ---------    ---------    ---------
  .9160       1.4680       6007.6       2427.8       2794.2       11.199       ~~274.1~~
                                                                                289.7
```

```
OCKET RESEARCH COMPANY                                         DATE:  2 Sep 1987 11:18:33

HENIUM HEAT EXCHANGER - BASELINE HEATER                                 SN# 001  RUN#  8


                                  UNREDUCED DATA (volts)
HRUST      THRUST     <-------            THRUST CALIBRATION                     -------->
RUN        ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-------    -------    -------    -------    -------    -------    -------    -------
+.563      +.335      +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

f(run)        Pf(0)          Pg(run)        Pg(0)          Palt(run)      Palt(0)
---------     ---------      ---------      ---------      ---------      ---------
.003413       -.000642       +.013467       +.000925       -.002116       -.002132


                         RECORDED TEMPERATURES (degrees F)
Tc            T16            Tb             Tv             Thb            Ts

---------     ---------      ---------      ---------      ---------      ---------
1166.8        +774.5         +1185.2        +185.0         +1695.0        +1823.7

Ts1           Ts2            Ts3            Tcon           Th1            Th2

---------     ---------      ---------      ---------      ---------      ---------
1171.9        +958.8         +1173.2        +1209.1        +0.0           +2460.8


                                  REDUCED DATA
(exit)     A(throat)  A(throat)  Pf         Pg                    Palt
           COLD       COR.
g. in.     sq. in.    sq. in.    psia       psia                  psia
---------  ---------  ---------  ---------  ---------  ---------  ---------
.06228     .000623    .000635    124.2      50.3       0.0        .0004

HEATER     HEATER     HEATER     HEATER     HEATER     HEATER     Pf
                                                       WIRE       DELTA
volts      amps       watts      ohms       temp       dia        psia
---------  ---------  ---------  ---------  ---------  ---------  ---------
23.50      27.678     650.4      .8490      4434.9     .00000     0.0

IGHT       MICRO      THRUST     THRUST
LASS       MOTION     MEAS       VAC
bs/hr      lbs/hr     mlbs       mlbs
---------  ---------  ---------  ---------  ---------  ---------  ---------
0.00000    .56702     45.728     45.751
.5419

CD         Cf         C*         REYNOLDS   GAS        PSP        ISP
                                 NUMBER     TEMP.
                      ft/sec                deg. f                sec.
---------  ---------  ---------  ---------  ---------  ---------  ---------
.9115      1.4601     6400.5     2173.7     3198.3     14.215     290.5
                                                                  304.0
```

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ROCKET RESEARCH COMPANY                                                  DATE:  2 Sep 1987 13:2

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                          SN# 001  RU


                                    UNREDUCED DATA (volts)
THRUST     THRUST      <--------             THRUST CALIBRATION
 RUN        ZERO       STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
-------    -------     -------    -------    -------    -------    -------    -----
 +.521      +.336      +0.000     +0.000     +0.000     +0.000     +0.000     +0.0

Pf(run)         Pf(0)           Pg(run)         Pg(0)           Palt(run)      Palt(
---------       ---------       ---------       ---------       ---------      -----
+.002102        -.000642        +.011362        +.000933        -.002132       -.0021


                              RECORDED TEMPERATURES (degrees F)
  Tc              T16             Tb              Tv              Thb             Ts

--------        --------        --------        --------        --------        -----
+1198.1          +824.2         +1191.9          +203.1         +1767.7         +181
  Ts1             Ts2             Ts3            Tcon             Th1             Th

--------        --------        --------        --------        --------        -----
+1224.3         +1015.0         +1232.8         +1248.9            +0.0         +280


                                       REDUCED DATA
A(exit)      A(throat)    A(throat)     Pf           Pg                         Palt
               COLD         COR.
sq. in.      sq. in.      sq. in.      psia         psia                        psia
---------    ---------    ---------    ---------    ---------    ---------    ---------
 .06228       .000623      .000633      88.8         41.8          0.0         .0004

 HEATER       HEATER       HEATER       HEATER       HEATER       HEATER        Pf
                                                                   WIRE        DELTA
  volts        amps         watts        ohms         temp         dia         psia
---------    ---------    ---------    ---------    ---------    ---------    ---------
  23.69       27.460        650.5        .8627       4507.4       .00000        0.0


SIGHT        MICRO        THRUST       THRUST
GLASS        MOTION        MEAS         VAC
lbs/hr       lbs/hr        mlbs         mlbs
---------    ---------    ---------    ---------    ---------    ---------    ---------
 0.00000      .49462       37.081       37.104
 .4456

  CD            Cf           C*        REYNOLDS        GAS          PSP           ISP
                                        NUMBER        TEMP.
                           ft/sec                     deg. f                     sec.
---------    ---------    ---------    ---------    ---------    ---------    ---------
 .9086        1.4241       6101.1       2028.4       2844.4       17.532        270.1
                                                                                299.8
```

```
OCKET RESEARCH COMPANY                                      DATE:  2 Sep 1987 14:11:21
HENIUM HEAT EXCHANGER - BASELINE HEATER                           SN# 001   RUN# 10

                              UNREDUCED DATA (volts)
HRUST      THRUST    <---------          THRUST CALIBRATION                 --------->
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-------    -------   --------   --------   --------   --------   --------   --------
+.589      +.321     +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

f(run)       Pf(0)          Pg(run)          Pg(0)            Palt(run)        Palt(0)
--------     ---------      ---------        ---------        ---------        ---------
.004862      -.000642       +.015421         +.000905         -.002119         -.002147


                        RECORDED TEMPERATURES (degrees F)
Tc             T16             Tb              Tv              Thb             Ts
--------       --------        --------        --------        --------        --------
1180.7         +750.5          +1199.1         +182.0          +1679.6         +1737.5
Ts1            Ts2             Ts3             Tcon            Th1             Th2
--------       --------        --------        --------        --------        --------
1136.1         +929.2          +1127.8         +1205.3         +0.0            +3030.0


                                     REDUCED DATA
(exit)      A(throat)   A(throat)   Pf          Pg                      Palt
            COLD        COR.
g. in.      sq. in.     sq. in.     psia        psia                    psia
--------    --------    --------    --------    --------    --------    --------
.06228      .000623     .000634     163.3       58.2        0.0         .0006
HEATER      HEATER      HEATER      HEATER      HEATER      HEATER      Pf
                                                            WIRE        DELTA
volts       amps        watts       ohms        temp        dia         psia
--------    --------    --------    --------    --------    --------    --------
23.30       27.864      649.3       .8363       4367.9      .00000      0.0

IGHT        MICRO       THRUST      THRUST
LASS        MOTION      MEAS        VAC
bs/hr       lbs/hr      mlbs        mlbs
--------    --------    --------    --------    --------    --------    --------
0.00000     .68211      53.823      53.862
,6408

CD          Cf          C*          REYNOLDS    GAS         PSP         ISP
                                    NUMBER      TEMP.
                        ft/sec                  deg. f                  sec.
--------    --------    --------    --------    --------    --------    --------
.9202       1.4852      6158.1      2713.6      2995.2      12.054      284.3
                                                                        302.6
```

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ROCKET RESEARCH COMPANY                                              DATE:   3 Sep 1987 11:1

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                         SN# 001   RUN


                              UNREDUCED DATA (volts)
THRUST    THRUST    <--------             THRUST CALIBRATION                      --------
 RUN       ZERO      STEP 1    STEP 2     STEP 3     STEP 4     STEP 5     STEP
-------   -------   -------   -------    -------    -------    -------    ------
 +.483     +.327    +0.000    +0.000     +0.000     +0.000     +0.000     +0.00

Pf(run)        Pf(0)          Pg(run)        Pg(0)          Palt(run)      Palt(0
---------      ---------      ---------      ---------      ---------      ------
+.003353       -.000658       +.009568       +.001050       -.002103       -.0021


                      RECORDED TEMPERATURES (degrees F)
  Tc             T16            Tb             Tv             Thb            Ts

--------       --------       --------       --------       --------       ------
+1122.9         +239.2        +1118.2         +121.0         +584.8         +616

  Ts1            Ts2            Ts3            Tcon           Th1            Th2

--------       --------       --------       --------       --------       ------
 +266.0         +305.0         +345:8         +495.6         +163.2         +150


                                  REDUCED DATA
A(exit)     A(throat)   A(throat)     Pf          Pg                      Palt
              COLD        COR.
sq. in.     sq. in.     sq. in.      psia        psia                    psia
--------    --------    --------    --------    --------    --------    --------
 .06228      .000623     .000623     123.0        34.2         0.0       .0005

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                              WIRE        DELTA
  volts       amps        watts       ohms        temp        dia         psia
--------    --------    --------    --------    --------    --------    --------
 -0.00       0.000         0.0       0.0000        0.0       .00000        0.0

SIGHT       MICRO       THRUST      THRUST
GLASS       MOTION      MEAS        VAC
lbs/hr      lbs/hr      mlbs        mlbs
--------    --------    --------    --------    --------    --------    --------
 0.00000     1.01067     31.300      31.330
 ,6110
  CD          Cf          C*        REYNOLDS      GAS         PSP         ISP
                                     NUMBER      TEMP.
                        ft/sec                   deg. f                   sec.
--------    --------    --------    --------    --------    --------    --------
 .9592       1.4723      2438.8      12063.2      147.3       0.000       111.6
                                                                          185.7
```

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ROCKET RESEARCH COMPANY                                      DATE:  3 Sep 1987 11:54:40

RHENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001  RUN# 12


                                UNREDUCED DATA (volts)
THRUST     THRUST     <-------          THRUST CALIBRATION                    -------->
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-------    -------    -------    -------    -------    -------    -------    -------
 +.599      +.329     +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

Pf(run)       Pf(0)            Pg(run)        Pg(0)            Palt(run)       Palt(0)
--------     --------         --------       --------          --------       --------
+.004910     -.000658         +.014430       +.000948          -.002111       -.002133


                          RECORDED TEMPERATURES (degrees F)
 Tc             T16            Tb             Tv              Thb             Ts

-------       -------        -------        -------         -------         -------
+1171.2        +738.5        +1193.1         +175.5         +1673.1         +1745.6

 Ts1            Ts2            Ts3           Tcon             Th1             Th2

-------       -------        -------        -------         -------         -------
-1125.6        +918.6        +1113.2        +1199.0            +0.0         +2493.3


                                    REDUCED DATA
(exit)      A(throat)   A(throat)     Pf          Pg                       Palt
              COLD        COR.
g. in.      sq. in.     sq. in.      psia        psia                      psia
-------     -------     -------     -------     -------     -------      -------
 .06228     .000623     .000625      165.0        54.1         0.0        .0005

HEATER      HEATER      HEATER      HEATER      HEATER      HEATER         Pf
                                                            WIRE          DELTA
 volts       amps        watts       ohms        temp        dia          psia
-------     -------     -------     -------     -------     -------      -------
 23.37      27.810       649.9       .8403      4389.4      .00000         0.0

IGHT        MICRO       THRUST      THRUST
LASS        MOTION      MEAS         VAC
bs/hr       lbs/hr      mlbs        mlbs
-------     -------     -------     -------     -------     -------      -------
0.00000     1.05466      54.210      54.241
 .643

 CD           Cf          C*       REYNOLDS      GAS         PSP           ISP
                                    NUMBER      TEMP.
                        ft/sec                  deg. f                     sec.
-------     -------     -------     -------     -------     -------      -------
 .9511      1.6104      3699.1      7953.6       888.4      11.982        185.1
                                                                          303.6
```

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ROCKET RESEARCH COMPANY                                                     DATE:   3 Sep 1987 14:20

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                           SN# 001   RUN#


                                        UNREDUCED DATA (volts)
THRUST     THRUST     <--------               THRUST CALIBRATION                           -------
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-------    -------    -------    -------    -------    -------    -------    -------
 +.554      +.324     +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

Pf(run)          Pf(0)            Pg(run)          Pg(0)            Palt(run)        Palt(0)
--------         --------         --------         --------         --------         --------
+.003388         -.000662         +.012927         +.000887         -.002086         -.00210


                              RECORDED TEMPERATURES (degrees F)
  Tc               T16              Tb               Tv               Thb              Ts

--------         --------         --------         --------         --------         --------
+1184.8           +848.6          +1209.1           +201.5          +1817.6          +1857.
  Ts1              Ts2              Ts3              Tcon             Th1              Th2

--------         --------         --------         --------         --------         --------
+1273.1          +1051.5          +1265.8          +1269.5            +0.0           +2537.


                                        REDUCED DATA
A(exit)     A(throat)   A(throat)     Pf          Pg                          Palt
              COLD        COR.
sq. in.     sq. in.     sq. in.      psia        psia                         psia
--------    --------    --------    --------    --------    --------    --------
 .06228     .000623     .000626      124.1        48.3         0.0        .0004

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                              WIRE        DELTA
  volts       amps        watts       ohms        temp        dia         psia
--------    --------    --------    --------    --------    --------    --------
  25.86      29.026       750.5      .8908       4655.3      .00000        0.0


SIGHT       MICRO        THRUST      THRUST
GLASS       MOTION        MEAS        VAC
lbs/hr      lbs/hr        mlbs        mlbs
--------    --------    --------    --------    --------    --------    --------
 0.00000     .85389      46.132      46.156
  .5324.

  CD          Cf           C*        REYNOLDS      GAS         PSP          ISP
                                      NUMBER       TEMP.
                         ft/sec                   deg. f                   sec.
--------    --------    --------    --------    --------    --------    --------
 .9434       1.5344      4080.4      5738.7      1147.6      16.260       194.6
                                                                          312.1
```

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ROCKET RESEARCH COMPANY DATE: 4 Sep 1987 08:32:38

RHENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RUN# 14

UNREDUCED DATA (volts)

THRUST RUN	THRUST ZERO	THRUST CALIBRATION STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP 6
+.521	+.331	+0.000	+0.000	+0.000	+0.000	+0.000	+0.000

Pf(run)	Pf(0)	Pg(run)	Pg(0)	Palt(run)	Palt(0)
+.002129	-.000650	+.011471	+.000937	-.002158	-.002174

RECORDED TEMPERATURES (degrees F)

Tc	T16	Tb	Tv	Thb	Ts
+1206.1	+876.3	+1205.7	+205.3	+1852.7	+1897.2

Ts1	Ts2	Ts3	Tcon	Tm	Tf
+1313.3	+1092.1	+1265.1	+1284.8	+645.3	+96.8

REDUCED DATA

A(exit) sq. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Pg psia		Palt psia
.06228	.000623	.000626	89.7	42.3	0.0	.0004

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
26.15	28.688	750.3	.9116	4765.3	.00000	0.0

SIGHT GLASS lbs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000 .4438	.77662	38.043	38.065			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9423	1.4463	3925.2	5496.3	1026.8	19.710	176.5 308.9

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ROCKET RESEARCH COMPANY                                          DATE:  4 Sep 1987 09:3

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                     SNH 001  RUN


                                 UNREDUCED DATA (volts)
THRUST     THRUST     <--------            THRUST CALIBRATION
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
-------    -------    -------    -------    -------    -------    -------    ------
 +.604      +.332     +0.000     +0.000     +0.000     +0.000     +0.000     +0.00

Pf(run)          Pf(O)            Pg(run)          Pg(O)            Palt(run)       Palt(0
--------         --------         --------         --------         --------        ------
+.004837         -.000650         +.014525         +.000898         -.002133        -.0021


                          RECORDED TEMPERATURES (degrees F)
  Tc              T16             Tb              Tv              Thb             Ts

--------        --------        --------        --------        --------        ------
+1185.5          +798.7         +1206.2          +188.8         +1758.8         +181

  Ts1             Ts2             Ts3             Tcon            Tm              Tf

--------        --------        --------        --------        --------        ------
+1229.1         +1005.7         +1144.0         +1243.9          +591.9          +9


                                      REDUCED DATA
A(exit)     A(throat)   A(throat)     Pf          Pg                        Palt
              COLD        COR.
sg. in.     sq. in.     sq. in.      psia        psia                      psia
--------    --------    --------    --------    --------    --------    --------
 .06228     .000623     .000625      162.9       54.7         0.0        .0005

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                              WIRE        DELTA
  volts       amps        watts       ohms        temp        dia         psia
--------    --------    --------    --------    --------    --------    --------
  25.81      29.086       750.8       .8875      4638.0      .00000        0.0


SIGHT       MICRO       THRUST      .THRUST
GLASS       MOTION      MEAS         VAC
lbs/hr      lbs/hr      mlbs         mlbs
--------    --------    --------    --------    --------    --------    --------
 0.00000    1.07209      54.532      54.561
 ,6293

  CD          Cf          C*        REYNOLDS      GAS         PSP         ISP
                                     NUMBER       TEMP.
                        ft/sec                   deg. f                   sec.
--------    --------    --------    --------    --------    --------    --------
 .9516       1.6026      3678.1      8137.8      874.9       13.761      183.2
                                                                         312.1
```

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OCKET RESEARCH COMPANY                                 DATE:  4 Sep 1987 10:19:38

HENIUM HEAT EXCHANGER - BASELINE HEATER                         SN# 001   RUN# 16


                          UNREDUCED DATA (volts)
HRUST    THRUST    <---------        THRUST CALIBRATION                ------->
RUN      ZERO      STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
------   ------    ------    ------    ------    ------    ------    ------
+.549    +.320     +0.000    +0.000    +0.000    +0.000    +0.000    +0.000

f(run)       Pf(0)          Pg(run)       Pg(0)         Palt(run)     Palt(0)
--------     --------       --------      --------      --------      --------
.003395      -.000650       +.012910      +.000863      -.002110      -.002126


                     RECORDED TEMPERATURES (degrees F)
Tc           T16           Tb            Tv            Thb           Ts
-------      -------       -------       -------       -------       -------
1179.7       +840.4        +1208.9       +204.6        +1804.0       +1861.9

Ts1          Ts2           Ts3           Tcon          Tm            Tf
-------      -------       -------       -------       -------       -------
1285.9       +1056.5       +1174.9       +1258.7       +610.2        +93.2


                              REDUCED DATA
(exit)    A(throat)  A(throat)   Pf         Pg                     Palt
          COLD       COR.
sq. in.   sq. in.    sq. in.     psia       psia                   psia
-------   -------    -------     -------    -------    -------     -------
.06228    .000623    .000626     123.9      48.3       0.0         .0003

HEATER    HEATER     HEATER      HEATER     HEATER     HEATER      Pf
                                                       WIRE        DELTA
volts     amps       watts       ohms       temp       dia         psia
-------   -------    -------     -------    -------    -------     -------
25.89     29.010     751.1       .8925      4664.2     .00000      0.0

IGHT      MICRO      THRUST      THRUST
LASS      MOTION     MEAS        VAC
lbs/hr    lbs/hr     mlbs        mlbs
-------   -------    -------     -------    -------    -------     -------
0.00000   .88388     46.005      46.026
.5295

CD        Cf         C*          REYNOLDS   GAS        PSP         ISP
                                 NUMBER     TEMP.
                     ft/sec                 deg. f                 sec.
-------   -------    -------     -------    -------    -------     -------
.9453     1.5292     3944.1      6191.1     1050.3     16.319      187.5
                                                                   313.0
```

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ROCKET RESEARCH COMPANY                                          DATE: STORAGE ERROR

RHENIUM HEAT EXCHANGER - BASELINE HEATER                              SN# 001   RU


                                UNREDUCED DATA (volts)
THRUST     THRUST     <-------              THRUST CALIBRATION                ----
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP
------     ------     ------     ------     ------     ------     ------     ----
 +.609      +.331     +0.000     +0.000     +0.000     +0.000     +0.000     +0.0

Pf(run)         Pf(0)            Ps(run)         Ps(0)            Palt(run)      Palt(
--------      --------           --------       --------          --------       -----
+.004886      -.000650           +.014670       +.000863          -.002088       -.002


                         RECORDED TEMPERATURES (degrees F)
  Tc              T16             Tb              Tv              Thb            Ts

-------         -------         -------         -------         -------         ----
+1191.2          +858.0         +1216.6          +202.1         +1826.0         +18
  Ts1             Ts2             Ts3            Tcon             Tm             Tf

-------         -------         -------         -------         -------         ----
+1310.7         +1071.6         +1184.2         +1268.8          +626.0          +


                                    REDUCED DATA
A(exit)     A(throat)   A(throat)     Pf          Ps                         Palt
              COLD        COR.
sq. in.     sq. in.     sq. in.      psia        psia                        psia
--------    --------    --------    --------    --------    --------    --------
 .06228      .000623     .000626     164.2       55.4         0.0         .0006

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER        Pf
                                                              WIRE        DELTA
  volts       amps        watts       ohms        temp        dia         psia
--------    --------    --------    --------    --------    --------    --------
  27.97      30.388       849.8       .9203      4811.0      .00000        0.0


SIGHT        MICRO       THRUST      THRUST
GLASS        MOTION       MEAS        VAC
lbs/hr       lbs/hr       mlbs        mlbs
--------    --------    --------    --------    --------    --------    --------
 0.00000     1.01524      55.881      55.915
  .6253

  CD           Cf           C*       REYNOLDS      GAS          PSF         ISP
                                      NUMBER      TEMP.
                          ft/sec                  deg. f                    sec.
--------    --------    --------    --------    --------    --------    --------
  .9485      1.6210      3935.5      7099.6      1054.0      15.199       198.3
                                                                          322.
```

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CKET RESEARCH COMPANY                                         DATE:  4 Sep 1987 12:16:29

ENIUM HEAT EXCHANGER - BASELINE HEATER                                SN# 001   RUN# 18


                              UNREDUCED DATA (volts)
RUST     THRUST    <--------          THRUST CALIBRATION                    -------->
UN       ZERO      STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
------   ------    ------    ------    ------    ------    ------    ------
.553     +.322     +0.000    +0.000    +0.000    +0.000    +0.000    +0.000

 (run)       Pf(0)          Pg(run)        Pg(0)           Palt(run)      Palt(0)
--------    ---------      ---------      ---------       ---------      ---------
.003355     -.000659       +.013074       +.000921        -.002097       -.002113


                         RECORDED TEMPERATURES (degrees F)
 Tc          T16          Tb            Tv            Thb           Ts
--------    --------     --------      --------      --------      --------
1188.4      +898.3       +1223.2       +206.8        +1884.1       +1938.9

 Ts1         Ts2          Ts3           Tcon          Tm            Tf
--------    --------     --------      --------      --------      --------
1370.8      +1135.0      +1245.0       +1298.1       +655.1        +95.2


                                 REDUCED DATA
(exit)     A(throat)   A(throat)    Pf          Pg                       Palt
            COLD        COR.
g. in.     sq. in.     sq. in.      psia        psia                     psia
--------   --------    --------     --------    --------    --------     --------
 .06228    .000623     .000626      123.1       48.8        0.0          .0004

HEATER     HEATER      HEATER       HEATER      HEATER      HEATER       Pf
                                                            WIRE         DELTA
 volts      amps        watts       ohms        temp        dia          psia
--------   --------    --------     --------    --------    --------     --------
 28.13     30.232      850.3        .9303       4863.8      .00000       0.0

IGHT       MICRO       THRUST       THRUST
LASS       MOTION      MEAS         VAC
bs/hr      lbs/hr      mlbs         mlbs
--------   --------    --------     --------    --------    --------     --------
0.00000     .84353     46.440       46.462
,5267

 CD         Cf          C*          REYNOLDS    GAS         PSP          ISP
                                     NUMBER     TEMP.
                        ft/sec                  deg. f                   sec.
--------   --------    --------     --------    --------    --------     --------
 .9424     1.5302      4169.2       5519.7      1213.2      18.301       198.3
                                                                         317.6
```

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ROCKET RESEARCH COMPANY DATE: 8 Sep 1987 08:25

RHENIUM HEAT EXCHANGER - BASELINE HEATER SN# 001 RJN#

UNREDUCED DATA (volts)

THRUST RUN	THRUST ZERO	THRUST CALIBRATION STEP 1	STEP 2	STEP 3	STEP 4	STEP 5	STEP
+.502	+.281	+0.000	+0.000	+0.000	+0.000	+0.000	+0.00

Pf(run)	Pf(0)	Pg(run)	Pg(0)	Palt(run)	Palt(0
+.003384	-.000647	+.012642	+.001002	-.002124	-.0021

RECORDED TEMPERATURES (degrees F)

Tc	T16	Tb	Tv	Thb	Ts
+1158.5	+649.2	+1166.7	+165.1	+1557.1	+1645

Ts1	Ts2	Ts3	Tcon	Tm	Tf
+1011.5	+821.5	+903.9	+1149.1	+494.7	+84

REDUCED DATA

A(exit) sq. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Pg psia		Palt psia
.06228	.000623	.000625	123.5	46.7	0.0	.0004

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
19.44	25.718	499.8	.7557	3943.4	.00000	0.0

SIGHT GLASS lbs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000 .5534	.91349	44.496	44.522			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9480	1.5310	3687.2	6945.2	871.5	11.227	175.5 289.7

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OCKET RESEARCH COMPANY                                          DATE:   8 Sep 1987 09:15:01

HENIUM HEAT EXCHANGER - BASELINE HEATER                                    SN# 001   RUN# 20


                                      UNREDUCED DATA (volts)
HRUST      THRUST      <-----------                THRUST CALIBRATION                  ------------>
RUN        ZERO        STEP 1      STEP 2      STEP 3      STEP 4      STEP 5      STEP 6
-------    -------     -------     -------     -------     -------     -------     -------
+.452      +.268       +0.000      +0.000      +0.000      +0.000      +0.000      +0.000

f(run)         Pf(0)             Pg(run)          Pg(0)               Palt(run)        Palt(0).
--------       ---------         ---------        ---------           ---------        ---------
.002136        -.000647          +.011145         +.000907            -.002138         -.002151


                                RECORDED TEMPERATURES (degrees F)
 Tc              T16              Tb               Tv                 Thb              Ts

--------         --------         --------         --------           --------         --------
1153.9           +695.6           +1171.7          +184.5             +1609.1          +1701.9

 Ts1             Ts2              Ts3              Tcon               Tm               Tf

--------         --------         --------         --------           --------         --------
1081.5           +881.9           +955.2           +1176.1            +524.0           +85.4



                                           REDUCED DATA
(exit)         A(throat)      A(throat)      Pf             Pg                            Palt
               COLD           COR.
g. in.         sq. in.        sq. in.        psia           psia                          psia
---------      ---------      ---------      ---------      ---------      ---------      ---------
 .06228        .000623        .000626        89.9           41.1           0.0            .0003

HEATER         HEATER         HEATER         HEATER         HEATER         HEATER         Pf
                                                                           WIRE           DELTA
 volts          amps           watts          ohms           temp          dia            psia
---------      ---------      ---------      ---------      ---------      ---------      ---------
 19.54         25.606         500.3          .7630          3981.9         .00000         0.0

IGHT           MICRO          THRUST         THRUST
LASS           MOTION         MEAS           VAC
bs/hr          lbs/hr         mlbs           mlbs
---------      ---------      ---------      ---------      ---------      ---------      ---------
 0.00000        .76561        36.803         36.820
 .4572

 CD             Cf             C*            REYNOLDS       GAS            PSP            ISP
                                             NUMBER         TEMP.
                               ft/sec                       deg. f                        sec.
---------      ---------      ---------      ---------      ---------      ---------      ---------
 .9424         1.4396         3869.4         5517.8         986.1          13.587         173.1
                                                                                          289.9
```

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ROCKET RESEARCH COMPANY DATE: 8 Sep 1987 10:0

RHENIUM HEAT EXCHANGER – BASELINE HEATER SN# 001 RUN

UNREDUCED DATA (volts)

THRUST RUN	THRUST ZERO	<------- STEP 1	STEP 2	THRUST CALIBRATION STEP 3	STEP 4	STEP 5	STEP
+.539	+.280	+0.000	+0.000	+0.000	+0.000	+0.000	+0.00

Pf(run)	Pf(O)	Pg(run)	Pg(O)	Palt(run)	Palt(O
+.004858	-.000647	+.013961	+.000888	-.002107	-.0021

RECORDED TEMPERATURES (degrees F)

Tc	T16	Tb	Tv	Thb	Ts
+1167.3	+619.0	+1173.8	+165.5	+1502.4	+1586

Ts1	Ts2	Ts3	Tcon	Tm	Tf
+953.3	+771.4	+853.1	+1117.5	+463.4	+84

REDUCED DATA

A(exit) sq. in.	A(throat) COLD sq. in.	A(throat) COR. sq. in.	Pf psia	Pg psia		Palt psia
.06228	.000623	.000625	163.3	52.4	0.0	.0005

HEATER volts	HEATER amps	HEATER watts	HEATER ohms	HEATER temp	HEATER WIRE dia	Pf DELTA psia
19.17	26.084	500.0	.7348	3833.3	.00000	0.0

SIGHT GLASS lbs/hr	MICRO MOTION lbs/hr	THRUST MEAS mlbs	THRUST VAC mlbs			
0.00000 .6466	1.06396	51.967	51.996			

CD	Cf	C* ft/sec	REYNOLDS NUMBER	GAS TEMP. deg. f	PSP	ISP sec.
.9523	1.5920	3555.6	8416.8	791.2	9.616	175.9 289.4

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OCKET RESEARCH COMPANY                                    DATE:  8 Sep 1987 10:48:04

HENIUM HEAT EXCHANGER - BASELINE HEATER                         SN# 001   RUN# 22


                           UNREDUCED DATA (volts)
HRUST     THRUST     <-------          THRUST CALIBRATION                    ------->
RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-----     ------     ------     ------     ------     ------     ------     ------
+.499     +.271      +0.000     +0.000     +0.000     +0.000     +0.000     +0.000

f(run)       Pf(O)         Pg(run)        Pg(O)          Palt(run)     Palt(O)
-------    ---------     ---------     ---------       ---------     ---------
.003360    -.000647      +.012890      +.000844        -.002100      -.002117


                      RECORDED TEMPERATURES (degrees F)
 Tc           T16           Tb            Tv            Thb           Ts
------      -------       -------       -------       -------       -------
1181.8       +841.1       +1207.9       +202.8        +1785.9       +1659.3

 Ts1          Ts2           Ts3          Tcon           Tm            Tf
------      -------       -------       -------       -------       -------
1291.9      +1051.6       +1135.7       +1249.7        +614.0        +91.3


                                 REDUCED DATA
A(exit)    A(throat)    A(throat)      Pf           Pg                       Palt
             COLD          COR.
sg. in.     sq. in.      sq. in.      psia         psia                      psia
-------    ---------    ---------    -------      -------      -------     -------
 .06228     .000623      .000626      122.9         48.3          0.0        .0004

 HEATER     HEATER       HEATER       HEATER       HEATER       HEATER        Pf
                                                                 WIRE        DELTA
  volts      amps         watts        ohms         temp          dia         psia
-------    -------      -------      -------      -------      -------     -------
  24.73     30.326        749.9       .8154        4257.8       .00000        0.0

SIGHT       MICRO        THRUST       THRUST
GLASS       MOTION        MEAS         VAC
lbs/hr      lbs/hr        mlbs         mlbs
-------    -------      -------      -------      -------      -------     -------
 0.00000     .86439       45.886       45.908
 .5290

  CD          Cf           C*         REYNOLDS      GAS           PSP         ISP
                                       NUMBER       TEMP.
                          ft/sec                    deg. f                    sec.
-------    -------      -------      -------      -------      -------     -------
  .9441     1.5254       4032.8       5892.9       1113.3       16.334      191.2
                                                                            312.4
```

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ROCKET RESEARCH COMPANY                                    DATE:  8 Sep 1987 13:23

RHENIUM HEAT EXCHANGER - BASELINE HEATER                        SN# 001   RUN#


                              UNREDUCED DATA (volts)
THRUST     THRUST     <---------          THRUST CALIBRATION                    ------
 RUN        ZERO      STEP 1     STEP 2     STEP 3     STEP 4     STEP 5     STEP 6
-------    -------    -------    -------    -------    -------    -------    -------
 +.474      +.287     +0.000     +0.000     +0.000     +0.000     +0.000     +0.00

Pf(run)         Pf(0)           Pg(run)         Pg(0)           Palt(run)       Palt(0)
---------       ---------       ---------       ---------       ---------       ------
+.002109        -.000656        +.011513        +.000930        -.002092        -.0021


                         RECORDED TEMPERATURES (degrees F)
  Tc             T16            Tb             Tv             Thb            Ts

---------      ---------      ---------      ---------      ---------      ------
+1193.8         +880.2        +1212.2         +212.6        +1832.1        +1911.
  Ts1            Ts2            Ts3            Tcon           Tm             Tf

---------      ---------      ---------      ---------      ---------      ------
+1319.2        +1083.0        +1170.6        +1270.6         +646.7         +101.


                                   REDUCED DATA
A(exit)     A(throat)   A(throat)      Pf          Pg                         Palt
              COLD        COR.
sq. in.     sq. in.     sq. in.       psia        psia                        psia
---------   ---------   ---------   ---------   ---------   ---------   ---------
 .06228      .000623     .000627      89.4        42.5         0.0         .0003

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER         Pf
                                                              WIRE         DELTA
  volts       amps        watts       ohms        temp         dia          psia
---------   ---------   ---------   ---------   ---------   ---------   ---------
  24.62      30.474       750.2       .8079      4218.2       .00000         0.0


SIGHT       MICRO       THRUST      THRUST
GLASS       MOTION       MEAS        VAC
lbs/hr      lbs/hr       mlbs       . mlbs
---------   ---------   ---------   ---------   ---------   ---------   ---------
 0.00000     .69227      37.440      37.458
 .4350

  CD          Cf           C*       REYNOLDS       GAS          PSP          ISP
                                     NUMBER       TEMP.
                         ft/sec                  deg. f                     sec.
---------   ---------   ---------   ---------   ---------   ---------   ---------
  .9350      1.4167      4423.7      4226.2      1392.1      20.028        194.8
                                                                           310.0
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OCKET RESEARCH COMPANY                                DATE:  8 Sep 1987 14:13:07
HENIUM HEAT EXCHANGER - BASELINE HEATER                      SN# 001   RUN# 24


                            UNREDUCED DATA (volts)
HRUST     THRUST     <-------         THRUST CALIBRATION                  ------->
RUN       ZERO       STEP 1    STEP 2    STEP 3    STEP 4    STEP 5    STEP 6
-------   -------    -------   -------   -------   -------   -------   -------
+.544     +.273      +0.000    +0.000    +0.000    +0.000    +0.000    +0.000

f(run)       Pf(0)          Fg(run)       Pg(0)          Palt(run)     Palt(0)
---------    ---------      ---------     ---------      ---------     ---------
.004830      -.000656       +.015679      +.000869       -.002087      -.002109


                       RECORDED TEMPERATURES (degrees F)
 Tc            T16           Tb            Tv            Thb           Ts
-------      -------       -------       -------       -------       -------
1182.2       +801.5        +1209.3       +191.3        +1739.4       +1841.7
 Ts1           Ts2           Ts3           Tcon          Tm            Tf
-------      -------       -------       -------       -------       -------
1241.3       +1007.5       +1070.9       +1236.1       +590.7        +89.0


                                REDUCED DATA
A(exit)    A(throat)   A(throat)   Pf         Pg                     Palt
           COLD        COR.
sq. in.    sq. in.     sq. in.     psia       psia                   psia
-------    -------     -------     -------    -------    -------     -------
 .06228    .000623     .000627     162.8      59.4       0.0         .0005
HEATER     HEATER      HEATER      HEATER     HEATER     HEATER      Pf
                                                         WIRE        DELTA
 volts     amps        watts       ohms       temp       dia         psia
-------    -------     -------     -------    -------    -------     -------
 24.66     30.422      750.3       .8107      4233.4     .00000      0.0

SIGHT      MICRO       THRUST      THRUST
GLASS      MOTION      MEAS        VAC
lbs/hr     lbs/hr      mlbs        mlbs
-------    -------     -------     -------    -------    -------     -------
0.00000    1.00179     54.476      54.505
 .6285

 CD         Cf          C*         REYNOLDS   GAS        PSP         ISP
                                   NUMBER     TEMP.
                        ft/sec                deg. f                 sec.
-------    -------     -------     -------    -------    -------     -------
 .9457     1.4731      4277.9      6295.3     1314.2     13.766      195.9
                                                                     312.3
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ROCKET RESEARCH COMPANY                                          DATE:   9 Sep 1987  14:3

RHENIUM HEAT EXCHANGER - BASELINE HEATER                                    SN# 001   RUN


                                  UNREDUCED DATA (volts)
THRUST      THRUST      <--------           THRUST CALIBRATION                        ------
 RUN         ZERO       STEP 1      STEP 2      STEP 3      STEP 4      STEP 5     STEP
------      ------      ------      ------      ------      ------      ------     ------
 +.518      +.288      +0.000      +0.000      +0.000      +0.000      +0.000     +0.00

Pf(run)          Pf(O)             Pg(run)          Pg(O)            Palt(run)        Palt(O
--------        --------          --------         --------          --------         ------
+.003338        -.000652          +.013580         +.000959          -.002057         -.0020


                            RECORDED TEMPERATURES (degrees F)
  Tc               T16              Tb               Tv               Thb              Ts

-------          -------          -------          -------          -------          ------
+1183.8           +838.9          +1216.2           +213.4          +1820.3          +1939

  Ts1              Ts2              Ts3              Tcon             Tm               Tf

-------          -------          -------          -------          -------          ------
+1276.0          +1039.4          +1260.1          +1277.9           +631.5           +99


                                     REDUCED DATA
A(exit)     A(throat)   A(throat)    Pf          Pg                          Palt
              COLD        COR.
sq. in.     sq. in.     sq. in.     psia        psia                        psia
-------     -------     -------     -------     -------     -------     -------
 .06228     .000623     .000627     122.4       50.6         0.0         .0005

 HEATER      HEATER      HEATER      HEATER      HEATER      HEATER       Pf
                                                             WIRE        DELTA
 volts       amps        watts       ohms        temp        dia         psia
-------     -------     -------     -------     -------     -------     -------
 26.39       28.468      751.4       .9271       4847.1      .00000       0.0

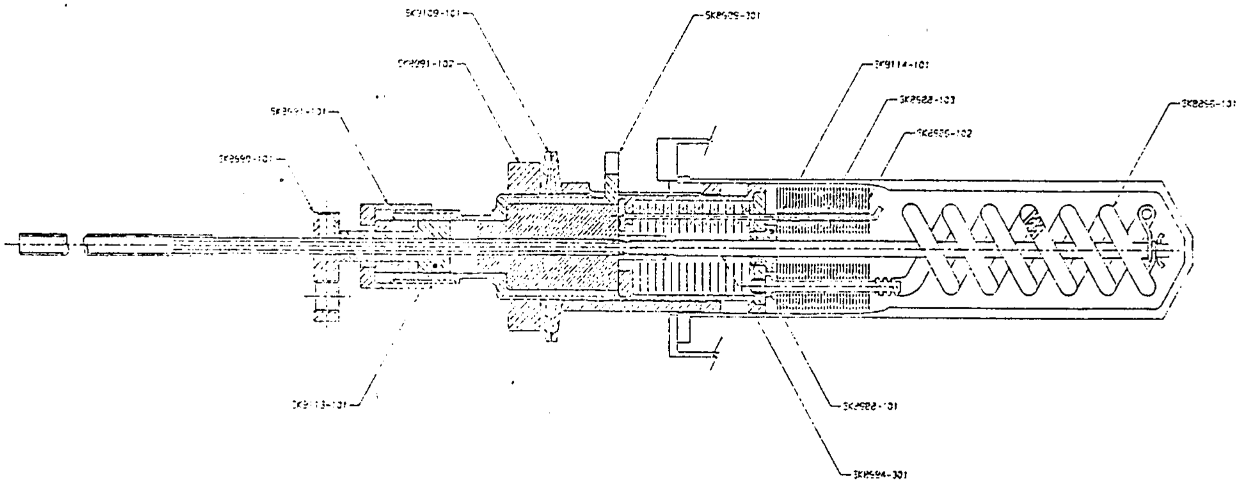

SIGHT       MICRO       THRUST      THRUST
GLASS       MOTION      MEAS        VAC
lbs/hr      lbs/hr      mlbs        mlbs
-------     -------     -------     -------     -------     -------     -------
 0.00000     .83735      46.159      46.189
 ,5282

  CD          Cf          C*        REYNOLDS     GAS         PSP         ISP
                                     NUMBER      TEMP.
                        ft/sec                   deg. f                  sec.
-------     -------     -------     -------     -------     -------     -------
 .9406      1.4649      4361.6      5166.3      1363.2      16.268      198.6
                                                                        319.8
```

ORIGINAL PAGE IS
OF POOR QUALITY

APPENDIX C

Sealed Cavity Design



1			SK9114-101	ISOLATOR, ELECTRICAL			
1			SK9113-101	CONAX, MODIFIED			
2			SK9109-101	BELLEVILLE WASHER			
1			SK8591-102	TORQUE NUT			
1			SK8591-101	NUT			
1			SK8250-101	CONNECTOR, ELECTRICAL			
29			SK8922-103	SPACER			
3			SK8928-101	COIL SUPPORT			
30			SK8926-102	HEAT SHIELD			
1			SK8256-101	HEATER COIL			
1			SK8594-301	SUB ASSY INLET TUBE			
1			SK8585-301	SUB ASSY UPPER BODY			
			-301-11	—	—		

PARTS LIST

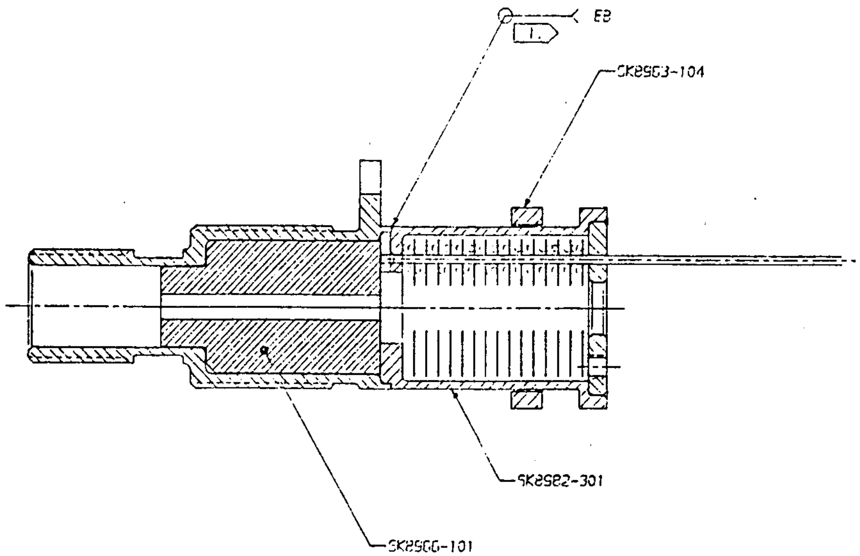
ROCKET RESEARCH COMPANY

ASSEMBLY, RESISTOJET

21562 SK9119

ORIGINAL PAGE IS
OF POOR QUALITY

1. MACHINE FLUSH TO DIAMETER AFTER WELDMENT.



C-3

QTY REQD -301-11	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO
1			SK8966-101	SUPPORT			
1			SK8963-104	RING			
1			SK8982-301	SUB-ASSEMBLY, LOWER BODY			
			301-11	——	——		

PARTS LIST

PART NO	NEXT ASSY	USED ON
–	–	–

APPLICATION

CONTRACT NO.
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCES
.XX ±.03 | .XXX ±.010 | ANGLES ± –°
DO NOT SCALE DRAWING
INTERPRET PER DOD-STD-100.
PART MARK PER [illegible]
REMOVE BURRS & SHARP EDGES
PER [illegible]
SURFACE FINISH √

DRAWN N. THUN 2?-3 ?1

ROCKET RESEARCH COMPANY
ROCKCOR

SUB-ASSEMBLY,
UPPER BODY

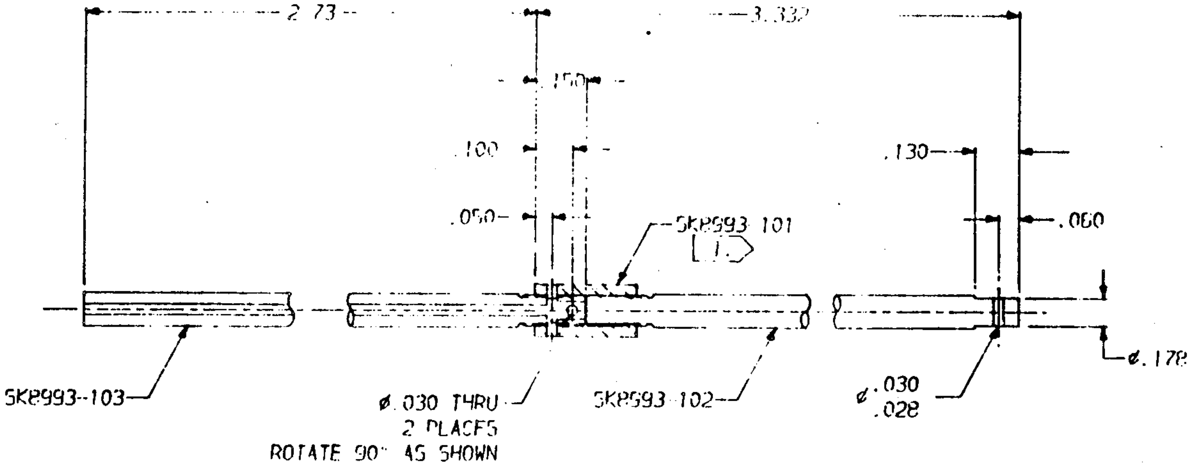
SIZE D | FSCM NO 21562 | DWG NO SK8989 | REV –
SCALE 4/1 | RELEASE | SHEET 1 OF 1

REVISIONS
REV	DESCRIPTION	DATE	APPROVED

4 3 1

REV	DESCRIPTION	DATE	APPROVED

[1.> STAKE SK8993-101 TO SK8993-102 & -103 USING CENTER PUNCH.



C-4

QTY REQD -301	[illegible]	[illegible]	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	[illegible]	ITEM
1			SK8993-103	GAS INLET TUBE			
1			SK8993-102	SUPPORT POST			
1			SK8993-101	SLEEVE			
			301-11	——	——		

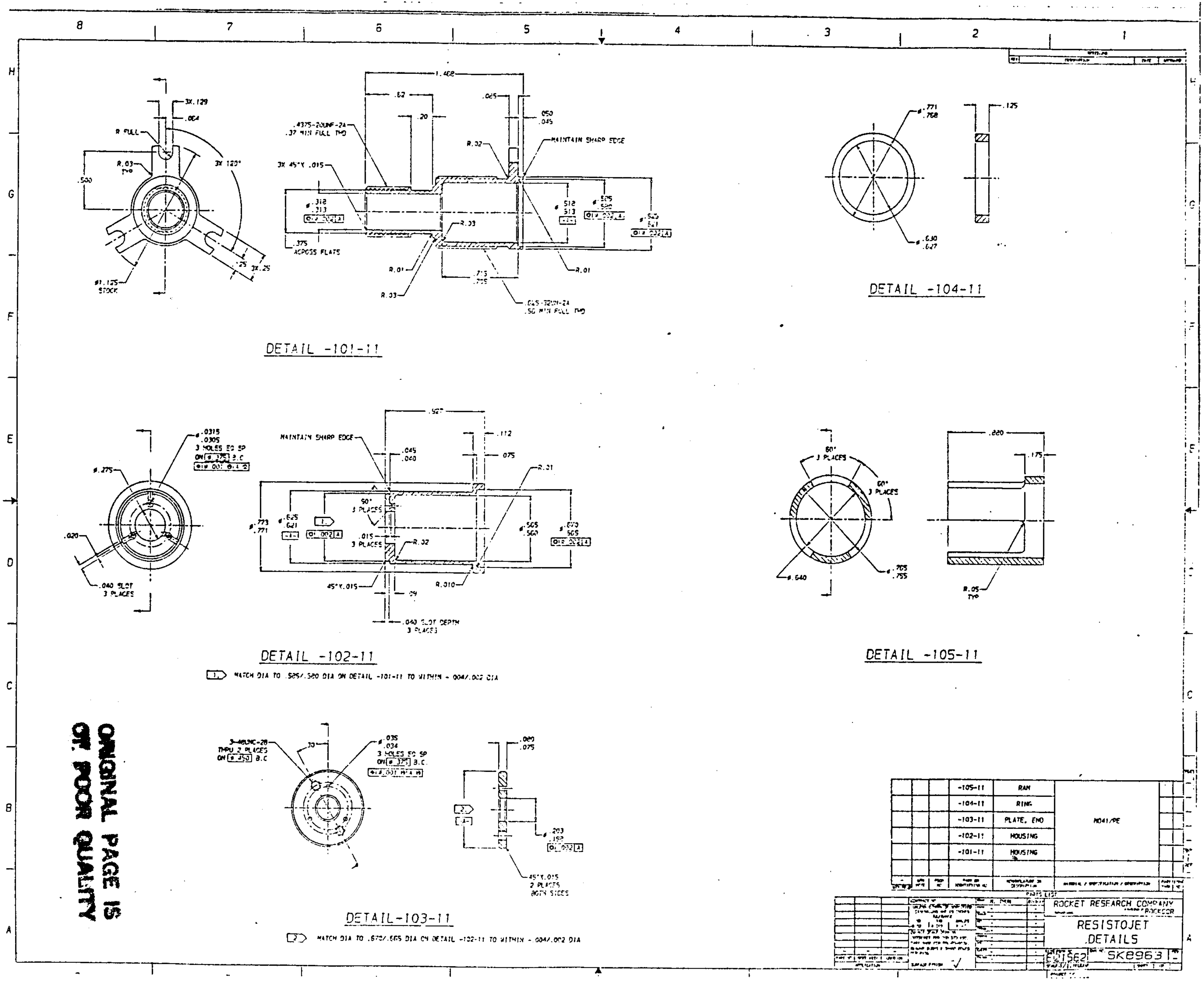
PARTS LIST

H. THUN

ROCKET RESEARCH COMPANY

ROCKCOR

SUB-ASSEMBLY,
INLET TUBE



DETAIL -101-11

DETAIL -104-11

DETAIL -102-11

DETAIL -105-11

1 MATCH DIA TO .525/.520 DIA ON DETAIL -101-11 TO WITHIN -.004/.002 DIA

DETAIL-103-11

2 MATCH DIA TO .670/.665 DIA ON DETAIL -102-11 TO WITHIN -.004/.002 DIA

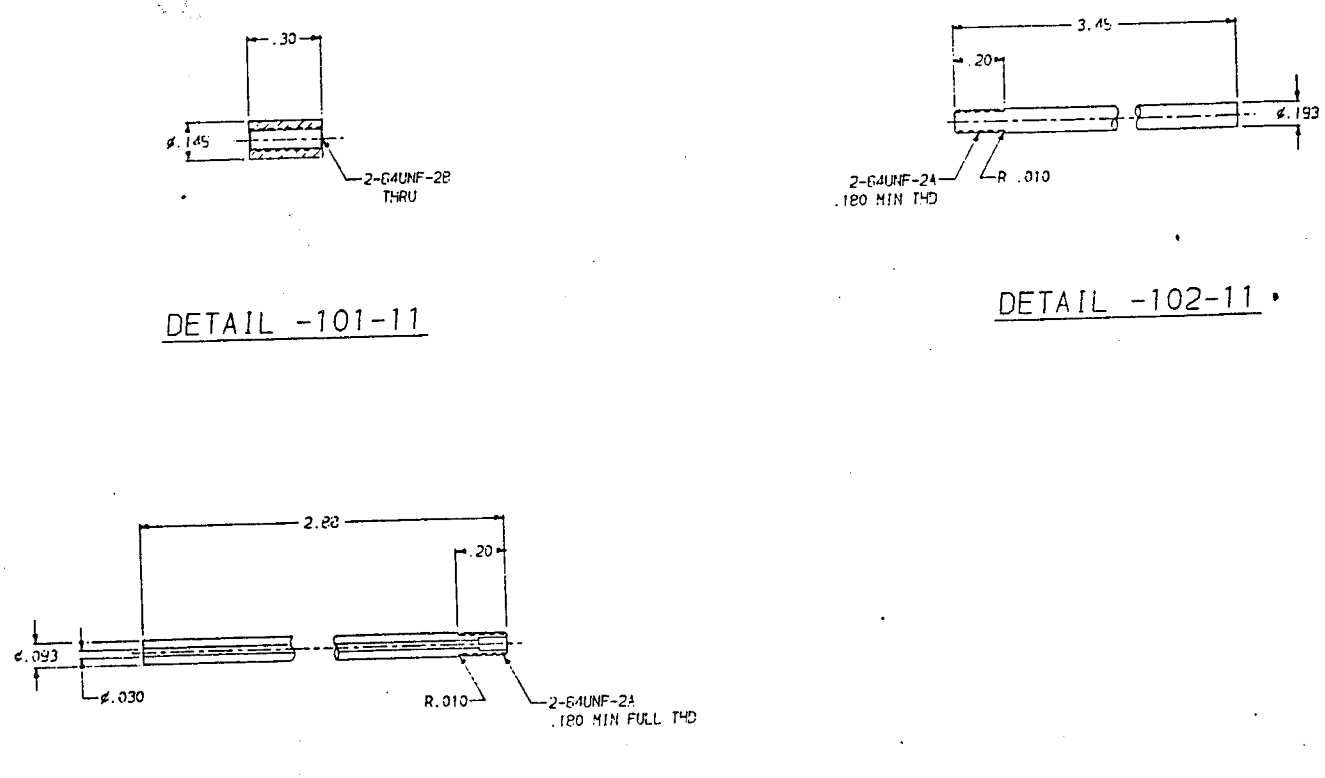
			-105-11	RAM		
			-104-11	RING		
			-103-11	PLATE, END	N041/PE	
			-102-11	HOUSING		
			-101-11	HOUSING		

PARTS LIST

ROCKET RESEARCH COMPANY
ROCKCOR

RESISTOJET
DETAILS

E21562 SK8963



DETAIL -101-11

DETAIL -102-11

DETAIL -103-11

C-11

ORIGINAL PAGE IS OF POOR QUALITY

			-103-11	INLET TUBE			
			-102-11	SUPPORT	INCONEL 625		
			-101-11	SLEEVE			
-							
QTY REQD	UPN NOTE	FSCN NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO

PARTS LIST

PART NO	NEXT ASSY	USED ON
-	-	-

APPLICATION

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± -°

DO NOT SCALE DRAWING.
INTERPRET PER DOD STD-100.
PART MARK PER PDC-PS-0002
REMOVE BURRS & SHARP EDGES
PER R150.

SURFACE FINISH √

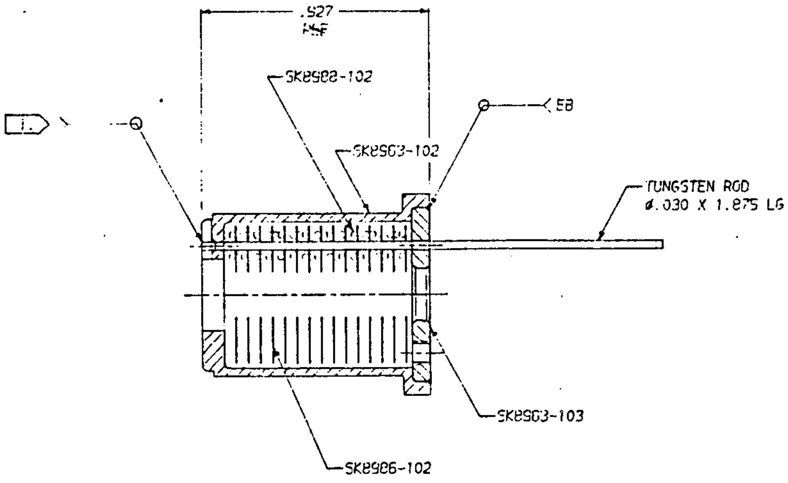
N. THUN 87-3-25

ROCKET RESEARCH COMPANY
ROCKCOR

DETAILS, (INCONEL)
RESISTOJET

SIZE D
FSCM NO. 21562
DWG NO. SK8993
REV -
SCALE 1/1
RELEASE
SHEET 1 OF 1

REVISIONS
REV | DESCRIPTION | DATE | APPROVED



3			——	——	TUNGSTEN ROD ⌀.030 X 1.875 LG		
15			SK8988-102	SPACER			
15			SK8986-102	SHIELD, HEAT			
1			SK8963-103	PLATE, END			
1			SK8963-102	HOUSING			
			301-11	——	——		
-301-11 QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO

PARTS LIST

PART NO.	NEXT ASSY	USED ON
-	-	-

APPLICATION

CONTRACT NO.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± -°
DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER PRC-PS-0226.
REMOVE BURRS & SHARP EDGES PER P156.
SURFACE FINISH √

DRAWN N. THUN 27-3-21

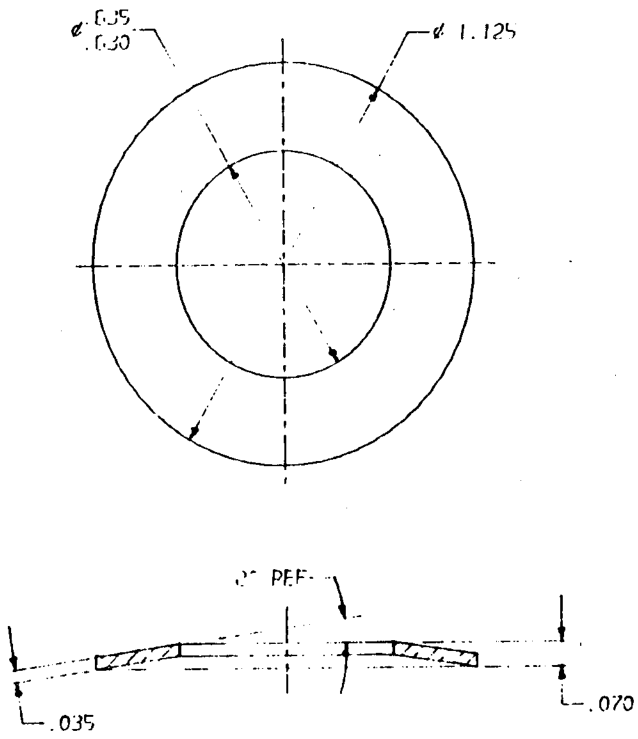
ROCKET RESEARCH COMPANY
ROCKCOR

SUB-ASSEMBLY,
LOWER BODY

SIZE D FSCM NO. 21562 DWG NO. SK8982 REV -
SCALE 4/1 RELEASE SHEET 1 OF 1
PROJECT. SK

REVISIONS
REV | DESCRIPTION | DATE | APPROVED

ORIGINAL PAGE IS
OF POOR QUALITY



QTY REQD	NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION		ITEM NO
-			-101-11	——	TZM		

PARTS LIST

-	-	-
NEXT ASSY	USED ON	
APPLICATION		

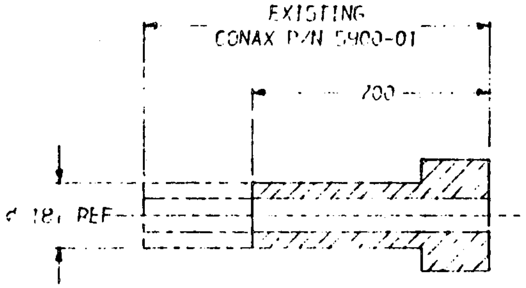
H. THUN

ROCKET RESEARCH COMPANY
ROCKCOR

WASHER,
BELLEVILLE

SIZE C 21562 SK9109

SCALE 4/1 SHEET 1 OF 1



PARTS LIST

QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	REF DESIG	ITEM NO
			-101-11	——	CONAX P/N 5900-01		

N. THUN

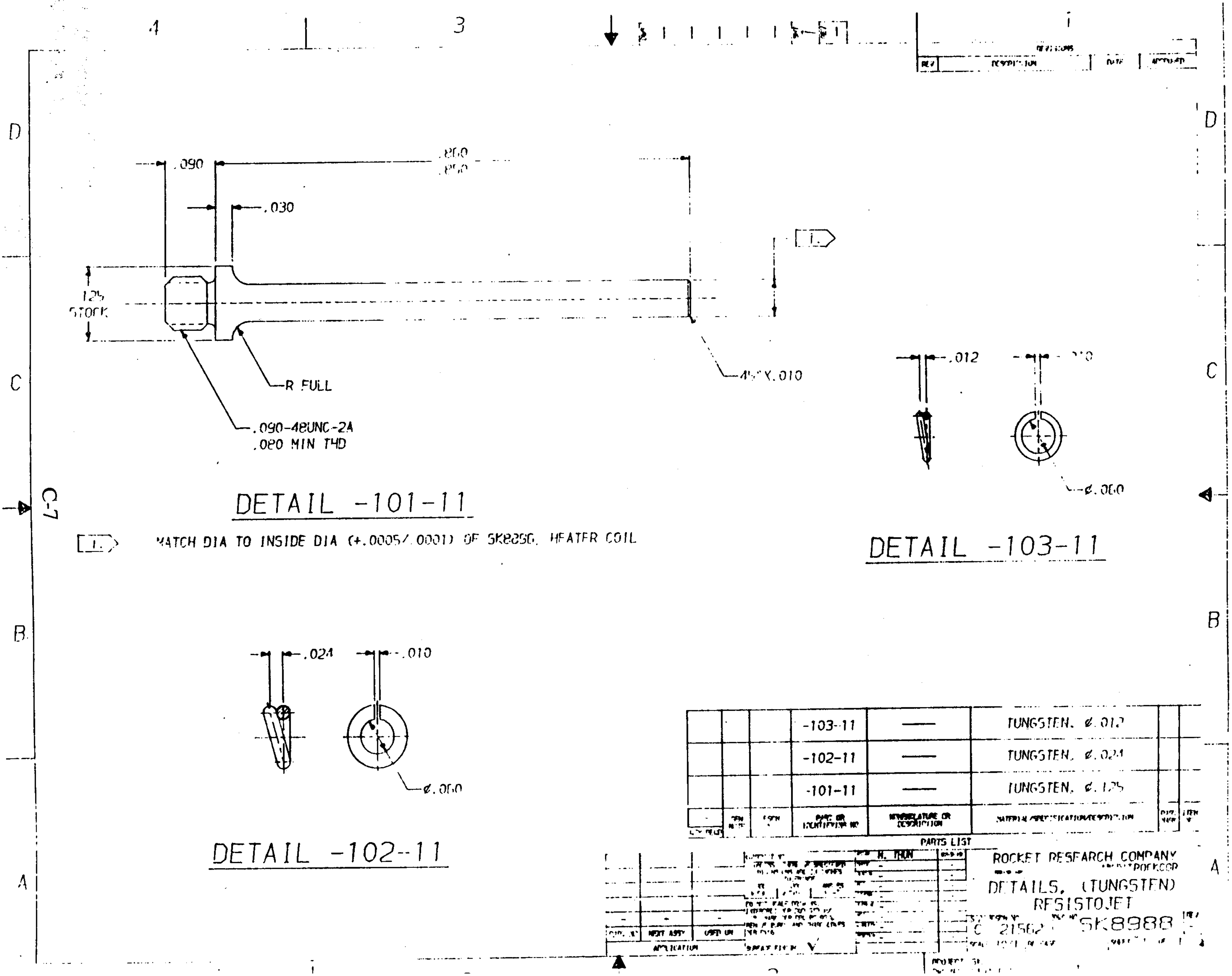
ROCKET RESEARCH COMPANY

CONAX,
MODIFIED

SK9113

C-3

C-7



DETAIL -101-11

[1] MATCH DIA TO INSIDE DIA (+.0005/.0001) OF SK8250, HEATER COIL

DETAIL -103-11

DETAIL -102-11

			PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION		ITEM NO
			-103-11	——	TUNGSTEN, ø.012		
			-102-11	——	TUNGSTEN, ø.024		
			-101-11	——	TUNGSTEN, ø.125		

PARTS LIST

H. THUN

ROCKET RESEARCH COMPANY

ROCKCOR

DETAILS, (TUNGSTEN)
RESISTOJET

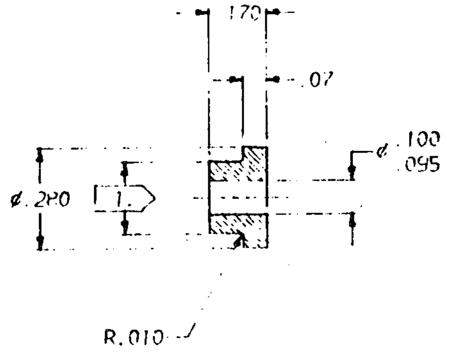
C 21562 SK8988

NEXT ASSY USED ON

APPLICATION

ORIGINAL PAGE IS
OF POOR QUALITY

[1] MATCH DIA TO .203/.198 DIA ON SK8963-103-11 TO WITHIN -.005/.002 DIA



PARTS LIST

QTY REQD	[illegible]	[illegible]	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	[illegible]	ITEM NO
-			-101-11	——	PN		

ROCKET RESEARCH COMPANY

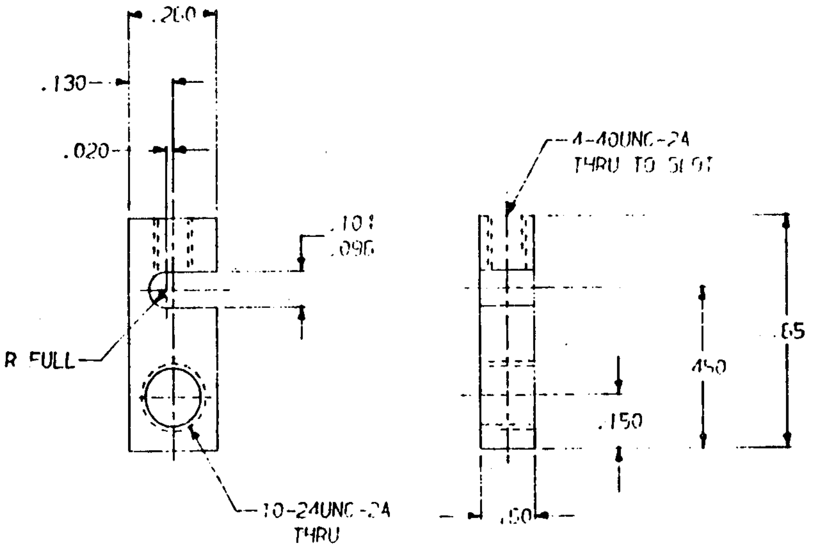
SPACER

C 21562 SK9114

H. THUN

REVISIONS

REV	DESCRIPTION	DATE	APPROVED



QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	FIND NO	ITEM NO
-			-101-11	——	COPPER		

PARTS LIST

DRAWN N. THAN

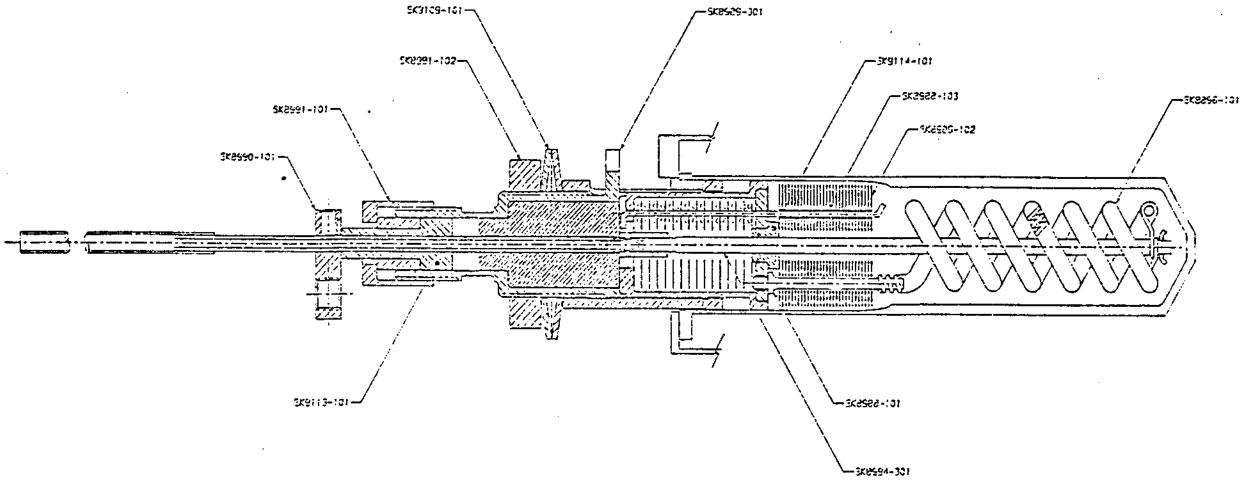
ROCKET RESEARCH COMPANY
ROCKCOR

CONNECTOR,
ELECTRICAL

C 21562 SK8[illegible]

PART NO	NEXT ASSY	USED ON
-	-	-

APPLICATION



-301-11	[illegible]	[illegible]	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	[illegible]	[illegible]
1			SK9114-101	ISOLATOR, ELECTRICAL			
1			SK9113-101	CONAX, MODIFIED			
2			SK3109-101	BELLEVILLE WASHER			
1			SK8591-102	TORQUE NUT			
1			SK8591-101	NUT			
1			SK8290-101	CONNECTOR, ELECTRICAL			
23			SK8922-103	SPACER			
3			SK8922-101	COIL SUPPORT			
30			SK8929-102	HEAT SHIELD			
1			SK8395-101	HEATER COIL			
1			SK8594-301	SUB ASSY INLET TUBE			
1			SK8989-301	SUB ASSY UPPER BODY			
			-301-11	—	—		

PARTS LIST

ROCKET RESEARCH COMPANY

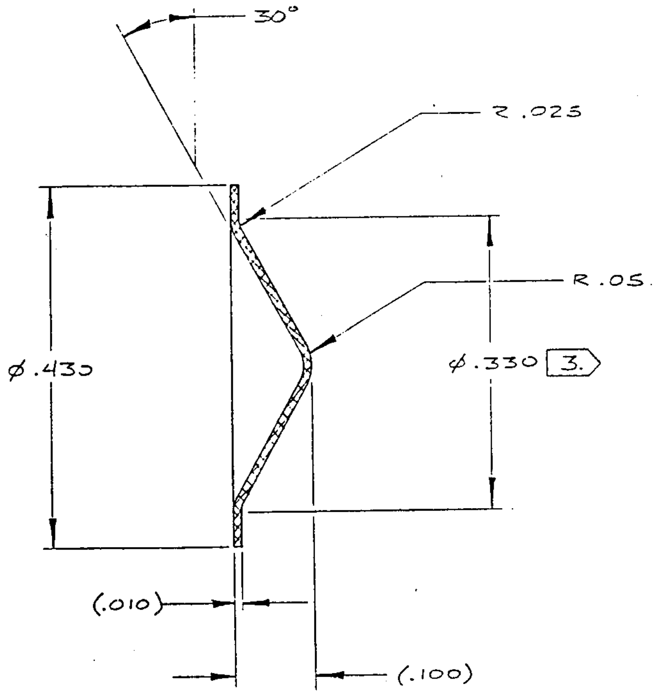
ASSEMBLY,
RESISTOJET

21562 SK9119

REV	DESCRIPTION	DATE	APPROVED

1. INTERPRET DRAWING PER ANSI Y14.5M-1982.

2. MATERIAL: 100 X 100 MESH, .004 DIA. WIRE, PLAIN SQUARE WEAVE HAYNES 25, TYPE 1, CLASS 1, PER AMS 5796.



3. DIAMETER MEASURED TO TANGENT POINT OF FILLET RADIUS.

4. REMOVE ALL HANGING STRANDS.

5. SOLVENT DEGREASE PER RRC-PS-0205 USING M.E.K.

6. VISUALLY INSPECT UNDER 10X MAGNIFICATION. NONE OF THE FOLLOWING CONDITIONS ARE ALLOWED:
   - A.) TWO PARALLEL WIRES TOUCHING.
   - B.) BROKEN WIRES.
   - C.) DELAMINATION OR FRAYED EDGES.

PARTS LIST

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
—			-101-11	———	2.		

APPLICATION

PART NO	NEXT ASSY	USED ON
-101	SK10231	IRAD

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
XX ±.03 | XXX ±.010 | ANGLES ± 5°

DO NOT SCALE DRAWING.
INTERPRET PER DOD STD 100
PART MARK PER RRC PS 0008
REMOVE BURRS & SHARP EDGES PER R100.

SURFACE FINISH ✓

DRAWN S. RICHARDS
DESIGN S. Richards
CHECK
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

SCREEN

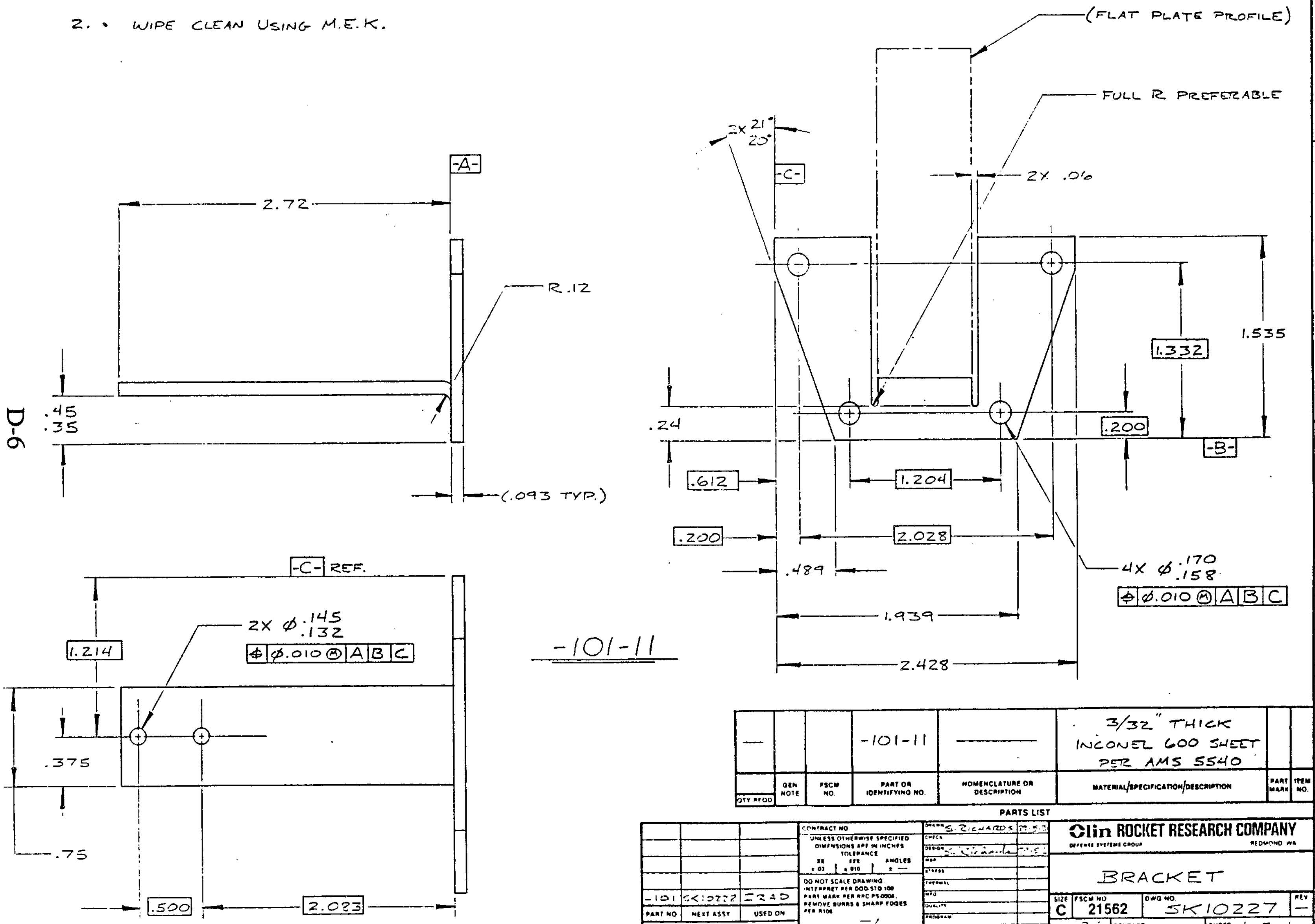
SIZE C | FSCM NO. 21562 | DWG NO. SK10232 | REV —
SCALE 10/1 | RELEASE | SHEET 1 OF 1

REV	DESCRIPTION	DATE	APPROVED

REVISIONS

1. INTERPRET DRAWING PER ANSI Y14.5M-1982.

2. • WIPE CLEAN USING M.E.K.



PARTS LIST

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
—			-101-11	———	3/32" THICK INCONEL 600 SHEET PER AMS 5540		

PART NO	NEXT ASSY	USED ON
-101	SK10222	IRAD

APPLICATION

CONTRACT NO

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± —

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100
PART MARK PER RRC PS-0006.
REMOVE BURRS & SHARP EDGES PER R106

SURFACE FINISH √

DRAWN S. RICHARDS
CHECK
DESIGN S. Richards
MSP
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND WA

BRACKET

SIZE	FSCM NO	DWG NO.	REV
C	21562	SK10227	—

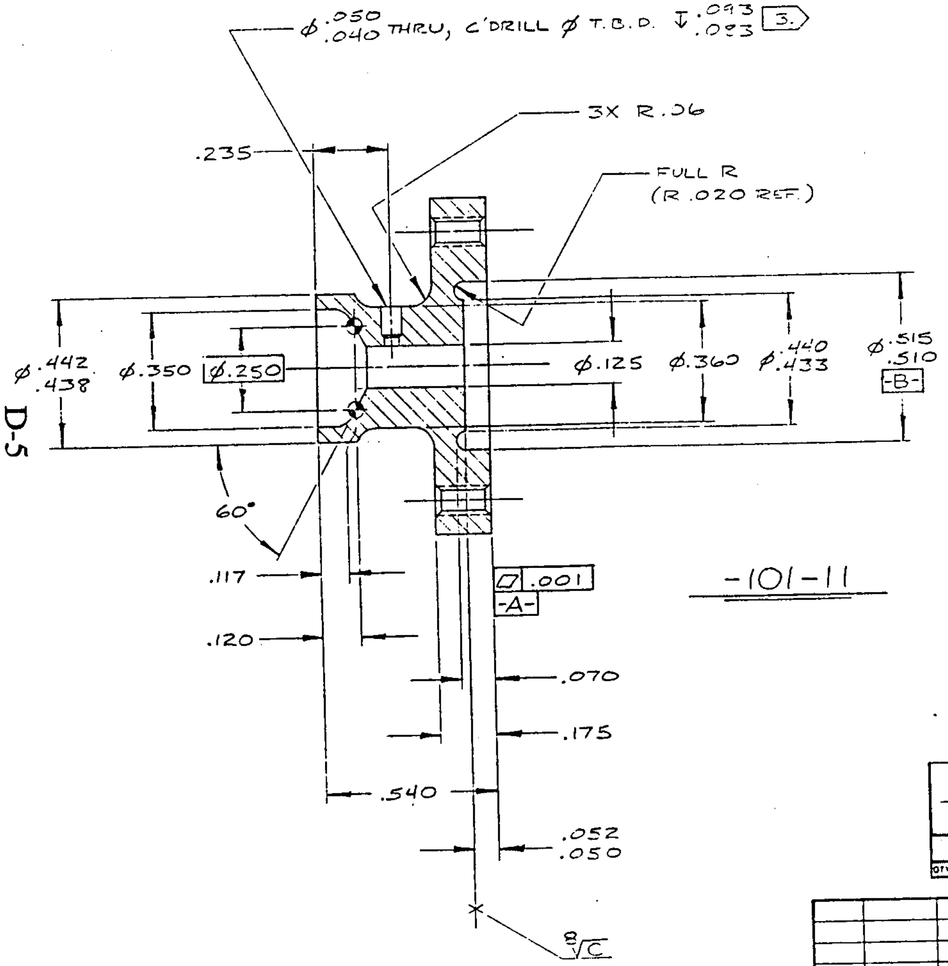
SCALE 2/1 RELEASE SHEET 1 OF 1

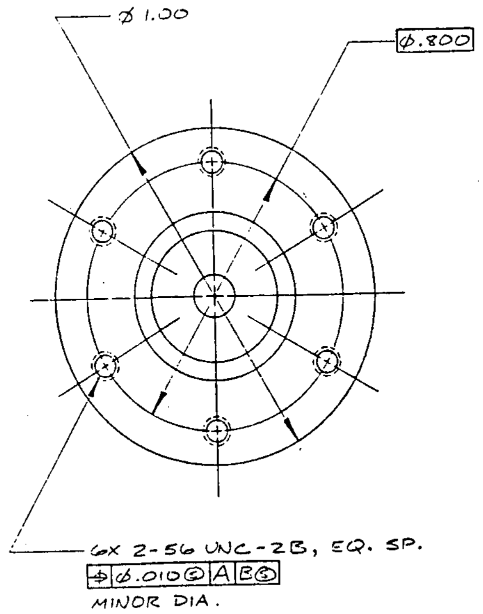
REVISIONS			
REV	DESCRIPTION	DATE	APPROVED

1. INTERPRET DIMENSIONS & TOLERANCES PER ANSI Y14.5M-1982.

2. SOLVENT CLEAN PER RRC-PS-0205.

3.> ORIENT APPROXIMATELY AS SHOWN.





—			-101-11	————	HASTELLOY 'B' PER RRC-MS-0135		
QTY REQD	DEP NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO

PARTS LIST

-101	SK10231	IRAD
PART NO	NEXT ASSY	USED ON
APPLICATION		

CONTRACT NO

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ±3°

DO NOT SCALE DRAWING
INTERPRET PER DOD-STD-100
PART MARK PER RRC PS-0108.
REMOVE BURRS & SHARP EDGES
PER 8108.

SURFACE FINISH 125√

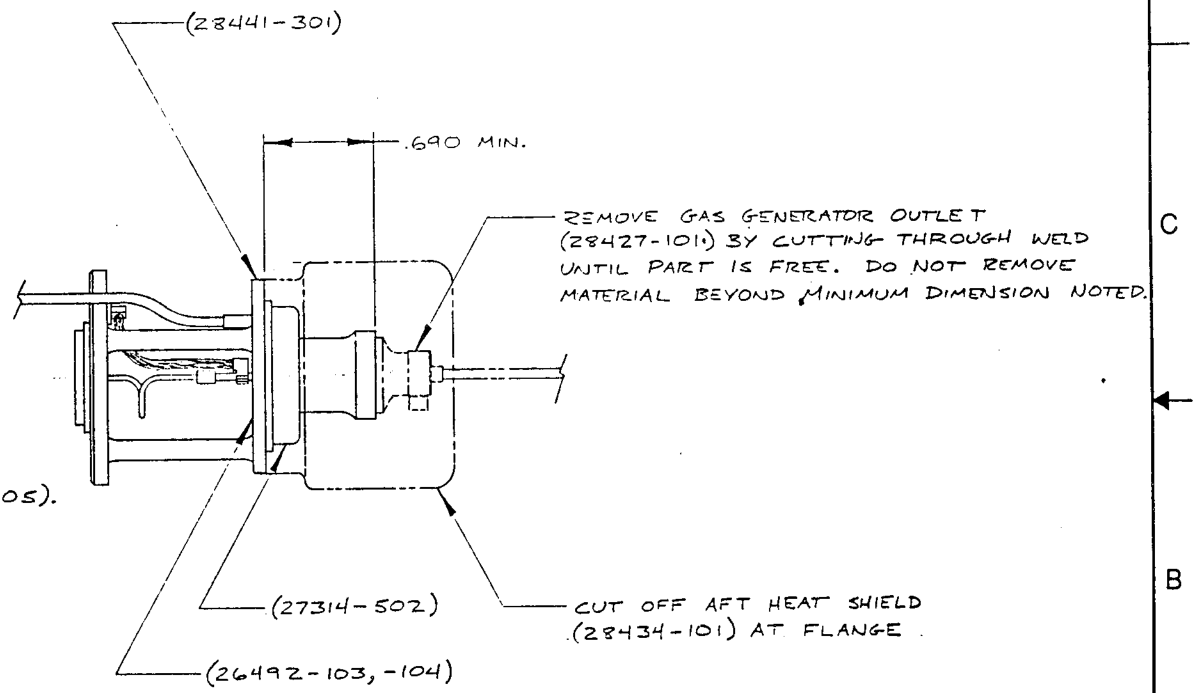
DRAWN	S. Richards	[illegible]
CHECK		
DESIGN	Richards	[illegible]
M&P		
STRESS		
THERMAL		
MFG		
QUALITY		
PROGRAM		

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND WA

OUTLET / ADAPTER

SIZE	FSCM NO	DWG NO	REV
C	21562	SK10226	—
SCALE 4/1	RELEASE	SHEET 1 OF 1	

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



-101-11

MAKE FROM ASSEMBLY OBTAINED BY REMOVING GAS GENERATOR FROM EHT ASSEMBLY (28420-305).

ORIGINAL PAGE IS
OF POOR QUALITY

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.

PARTS LIST

CONTRACT NO
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
XX ±.03 | XXX ±.010 | ANGLES ±

DO NOT SCALE DRAWING
INTERPRET PER DOD STD-100
PART MARK PER RRC PS 0006
REMOVE BURRS & SHARP EDGES PER R106

SURFACE FINISH ✓

PART NO	NEXT ASSY	USED ON

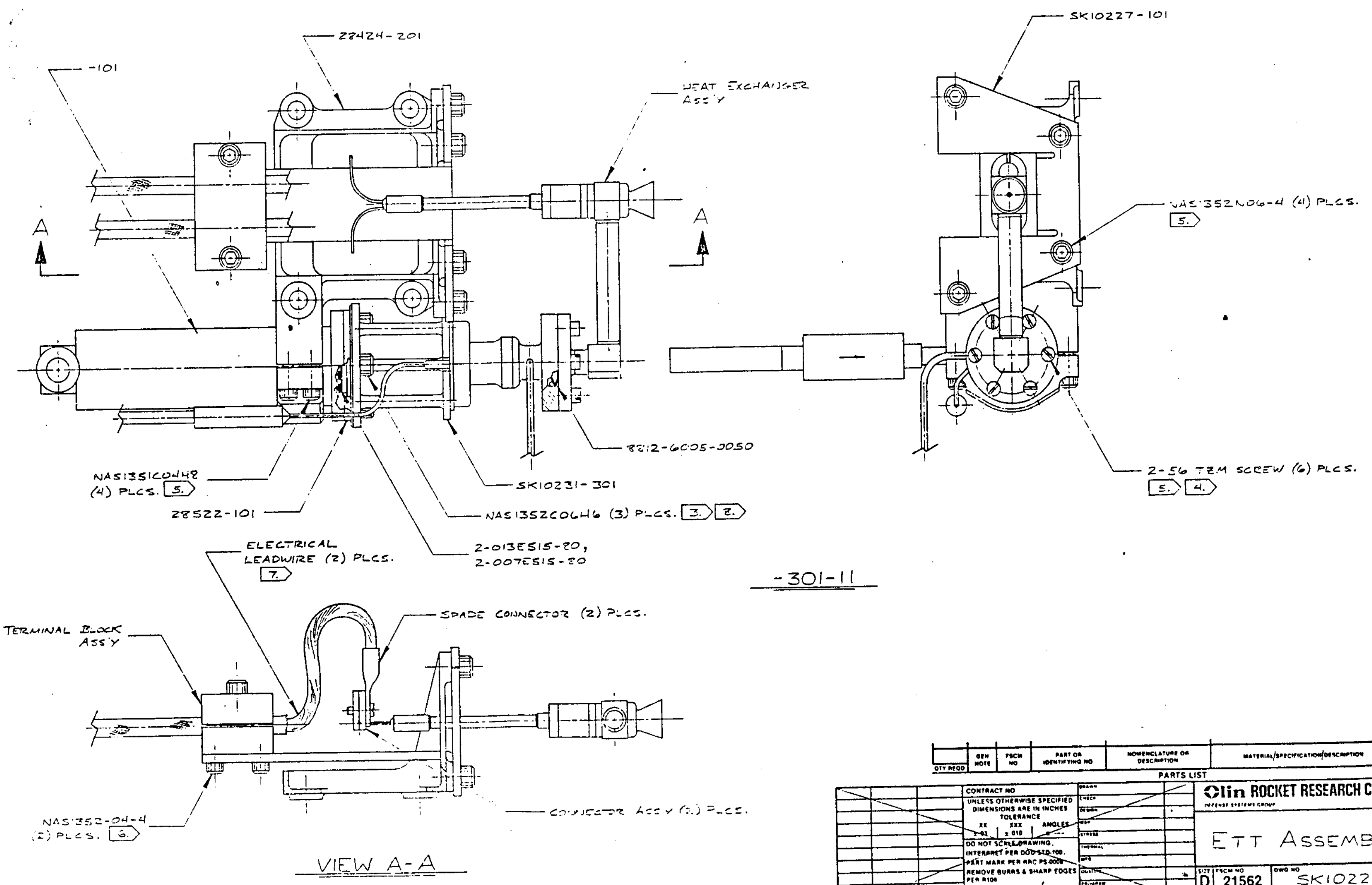
APPLICATION

DRAWN
CHECK
DESIGN
MAP
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

GAS GENERATOR ASS'Y

SIZE C | FSCM NO 21562 | DWG NO. SK10231 | REV —
SCALE 2/1 | RELEASE | SHEET 2 OF 2



D-3

REV	DESCRIPTION	DATE	APPROVED

REVISIONS

QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO

PARTS LIST

CONTRACT NO

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCE

.XX	.XXX	ANGLES
±.03	±.010	±

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RRC PS-0008
REMOVE BURRS & SHARP EDGES PER R106

SURFACE FINISH √

PART NO	NEXT ASSY	USED ON

APPLICATION

DRAWN
CHECK
DESIGN
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY

DEFENSE SYSTEMS GROUP REDMOND WA

ETT ASSEMBLY

SIZE	FSCM NO	DWG NO	REV
D	21562	SK10228	–

SCALE RELEASE SHEET OF

REVISIONS

REV	DESCRIPTION	DATE	APPROVED

1. INTERPRET DIMENSIONS & TOLERANCES PER ANSI Y14.5M-1982.

2. THIS PART IS THE ASSEMBLY OBTAINED BY REMOVING PROPELLANT VALVE/FLUID RESISTOR FROM EHT ASSEMBLY (28420-305).

3. TORQUE TO 8-9 IN-LBS.

4. TORQUE TO T.B.D. IN-LBS.

5. APPLY BORON NITRIDE AEROSOL SPRAY TO THREADS PRIOR TO INSTALLATION. APPLY GENEROUSLY.

6. AN EQUIVALENT SCREW MAY BE SUBSTITUTED.

7. STRIP WIRE AND BEND APPROXIMATELY AS SHOWN ON ASSEMBLY.

8. TRIM SCREW AS REQUIRED TO LIMIT PROTRUSION.

-301-11 QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO
AR			———	BORON NITRIDE	AEROSOL SPRAY STANDARD OIL		
2			———	CONNECTOR ASS'Y			
2			———	SPADE CONNECTOR			
AR			———	ELECTRICAL LEADWIRE	AWG 10, HIGH TEMP.		
1		17506	2-013 E515-80	O-RING	PARKER		
1			2-007 E515-80				
4			NAS1352 NO6-4	SOCKET HEAD CAP SCREW			
3			NAS1352 CO6H6				
2			NAS1352 -04-4				
4			NAS 1351 CO4H8				
6			———	2-56 TZM SCREW			
1		83259	2812-6005 -0050	V-SEAL	PARKER		
1			———	TERMINAL BLOCK ASS'Y			
1			———	HEAT EXCHANGER ASS'Y			
1			SK10227 -101	BRACKET			
1			SK10231 -301	GAS GENERATOR ASS'Y			
1			28522 -101	VALVE SPACER			
1			28424 -201	MOUNTING STRUCTURE			
1			-101-11	VALVE/ FLUID RESISTOR	2.		
—			-301-11	———			

PARTS LIST

PART NO	NEXT ASSY	USED ON
-301	END ITEM	ERAD

APPLICATION

CONTRACT NO

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCE

.XX	.XXX	ANGLES
± .03	± .010	± —

DO NOT SCALE DRAWING.
INTERPRET PER DOD STD 100
PART MARK PER RRC PS-0008
REMOVE BURRS & SHARP EDGES PER R106

SURFACE FINISH √

DRAWN RICHARDS
CHECK
DESIGN
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

ETT ASSEMBLY

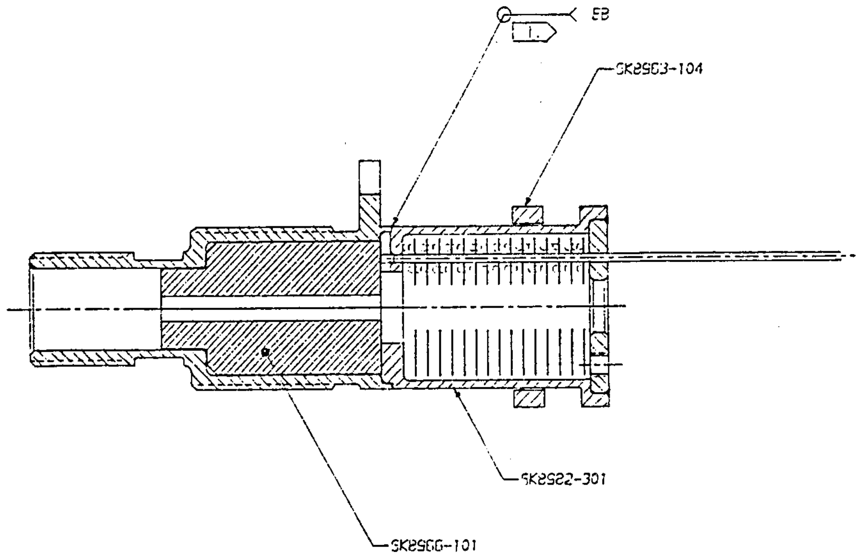
SIZE	FSCM NO	DWG NO.	REV
D	21562	SK10228	—

SCALE 2/1 RELEASE SHEET 1 OF 2

APPENDIX D

Immersed Heater Design

1. MACHINE FLUSH TO DIAMETER AFTER WELDMENT.



PARTS LIST

-301-11 QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO
1			SK8966-101	SUPPORT			
1			SK8963-104	RING			
1			SK8982-301	SUB-ASSEMBLY, LOWER-BODY			
			301-11	——	——		

PART NO	NEXT ASSY	USED ON
–	–	–

APPLICATION

CONTRACT NO.
UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 .XXX ±.010 ANGLES ± –°
DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RPC-PS-0002.
REMOVE BURRS & SHARP EDGES
PER FIG.
SURFACE FINISH √

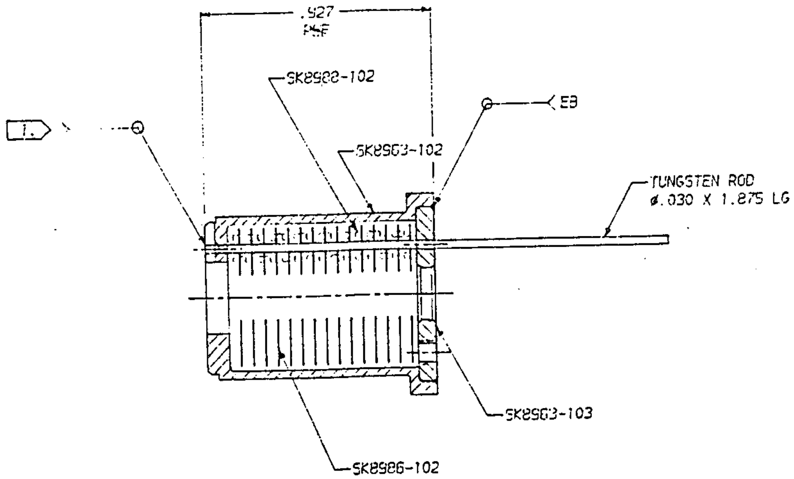
N. THUN 8/-3 22

ROCKET RESEARCH COMPANY
ROCKCOR

SUB-ASSEMBLY,
UPPER BODY

SIZE D FSCM NO. 21562 DWG NO SK8989 REV –
SCALE 4/1 RELEASE SHEET 1 OF 1

D-9



-301-11 QTY REQD	GEN NOTE	FSCN NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO
3			——	——	TUNGSTEN ROD ø.030 X 1.875 LG		
15			SK8928-102	SPACER			
15			SK8986-102	SHIELD, HEAT			
1			SK8963-103	PLATE, END			
1			SK8963-102	HOUSING			
			301-11	——	——		

PARTS LIST

PART NO.	NEXT ASSY	USED ON
-	-	-

APPLICATION

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± -°

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER PRL-PS-0006.
REMOVE BURRS & SHARP EDGES PER R156.

SURFACE FINISH √

M. THUN 27-3-29

ROCKET RESEARCH COMPANY
ROCKCOR

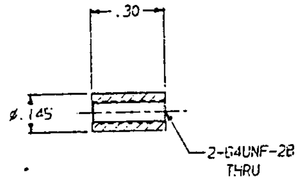
SUB-ASSEMBLY,
LOWER BODY

SIZE D | FSCM NO. 21562 | DWG NO. SK8982 | REV -

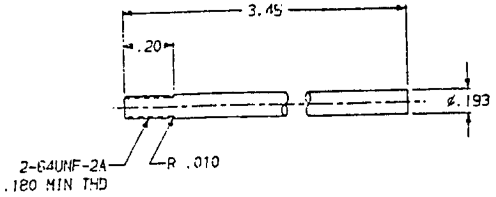
SCALE 4/1 | RELEASE | SHEET 1 OF 1

PROJECT. SK 1

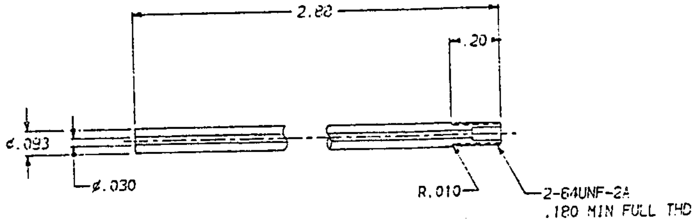
D-10



DETAIL -101-11



DETAIL -102-11



DETAIL -103-11

QTY REQD	LFN NOTE	FSCM NO	PART OR IDENTIFYING NO	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION	PART MARK	ITEM NO
			-103-11	INLET TUBE			
			-102-11	SUPPORT	INCONEL 625		
			-101-11	SLEEVE			
-							

PARTS LIST

CONTRACT NO.
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± -°
DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER PRC-PS-0202
REMOVE BURRS & SHARP EDGES PER P150.
SURFACE FINISH √

PART NO.	NEXT ASSY	USED ON
-	-	-

APPLICATION

DRWN N. THUN 12-3-21

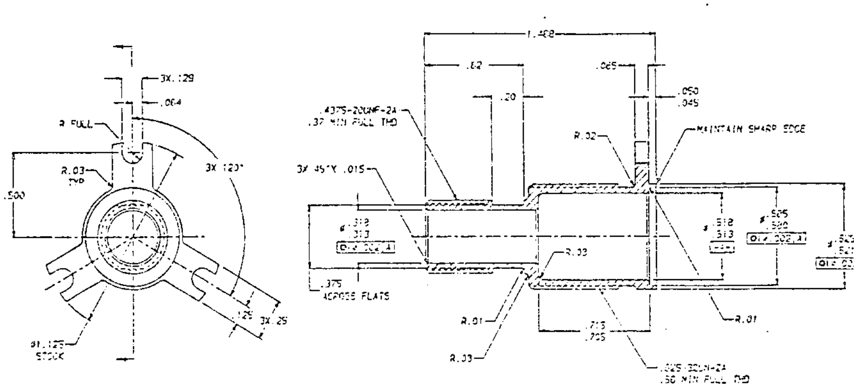
ROCKET RESEARCH COMPANY
ROCKCOR

DETAILS, (INCONEL)
RESISTOJET

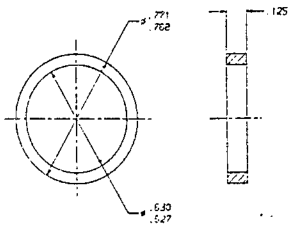
SIZE D FSCM NO. 21562 DWG NO. SK8993 REV -
SCALE 4/1 RELEASE SHEET 1 OF 1

REVISIONS

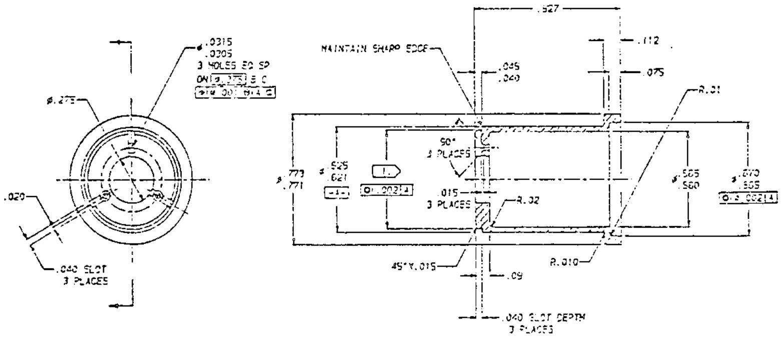
REV	DESCRIPTION	DATE	APPROVED



DETAIL -101-11

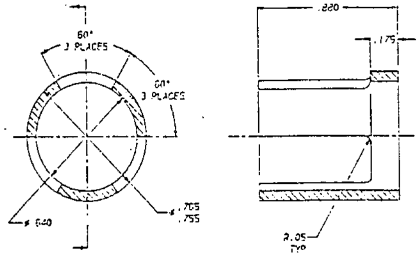


DETAIL -104-11

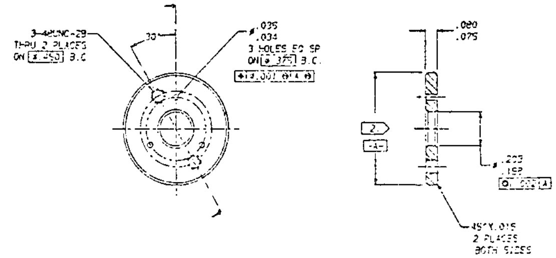


DETAIL -102-11

1. MATCH DIA TO .585/.580 DIA ON DETAIL -101-11 TO WITHIN -.004/.002 DIA



DETAIL -105-11



DETAIL-103-11

2. MATCH DIA TO .570/.565 DIA ON DETAIL -102-11 TO WITHIN -.004/.002 DIA

			-105-11	RAM	M041/PE
			-104-11	RING	
			-103-11	PLATE, END	
			-102-11	HOUSING	
			-101-11	HOUSING	
[illegible]	[illegible]	[illegible]	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL / SPECIFICATION / DESCRIPTION

PARTS LIST

ROCKET RESEARCH COM

RESISTOJET
DETAILS

SK896

D-12

1. INTERPRET DIMENSIONS & TOLERANCES PER ANSI Y14.5M-1982.

2. THIS PART IS THE ASSEMBLY OBTAINED BY REMOVING PROPELLANT VALVE/FLUID RESISTOR FROM EHT ASSEMBLY (28420-305).

3. TORQUE TO 8-9 IN-LBS.

4. TORQUE TO T.B.D. IN-LBS.

5. APPLY BORON NITRIDE AEROSOL SPRAY TO THREADS PRIOR TO INSTALLATION. APPLY GENEROUSLY.

6. AN EQUIVALENT SCREW MAY BE SUBSTITUTED.

7. STRIP WIRE AND BEND APPROXIMATELY AS SHOWN ON ASSEMBLY.

8. TRIM SCREW AS REQUIRED TO LIMIT PROTRUSION.

-301-11 QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
AR			———	BORON NITRIDE	AEROSOL SPRAY STANDARD OIL		
2			———	CONNECTOR ASS'Y			
2			———	SPADE CONNECTOR			
AR			———	ELECTRICAL LEADWIRE	AWG 10, HIGH TEMP.		
1		17506	2-013 E515-80	O-RING	PARKER		
1			2-007 E515-80				
4			NAS1352 N06-4	SOCKET HEAD CAP SCREW			
3			NAS1352 C06H6				
2			NAS1352 -04-4				
4			NAS 1351 C04H8				
6			———	2-56 TEM SCREW			
1		83259	8812-6005 -0050	V-SEAL	PARKER		
1			———	TERMINAL BLOCK ASS'Y			
1			———	HEAT EXCHANGER ASS'Y			
1			SK10227 -101	BRACKET			
1			SK10231 -301	GAS GENERATOR ASS'Y			
1			28522 -101	VALVE SPACER			
1			28424 -201	MOUNTING STRUCTURE			
1			-101-11	VALVE / FLUID RESISTOR	2.		
—			-301-11	———			

PARTS LIST

-301	EHT ITEM	[illegible]
PART NO	NEXT ASSY	USED ON
APPLICATION		

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED
DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ± .03 | .XXX ± .010 | ANGLES ± —
DO NOT SCALE DRAWING.
INTERPRET PER DOD STD 100
PART MARK PER RRC PS-0008.
REMOVE BURRS & SHARP EDGES PER 9106
SURFACE FINISH √

DRAWN C. RICHARDS
CHECK
DESIGN
MAP
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND WA

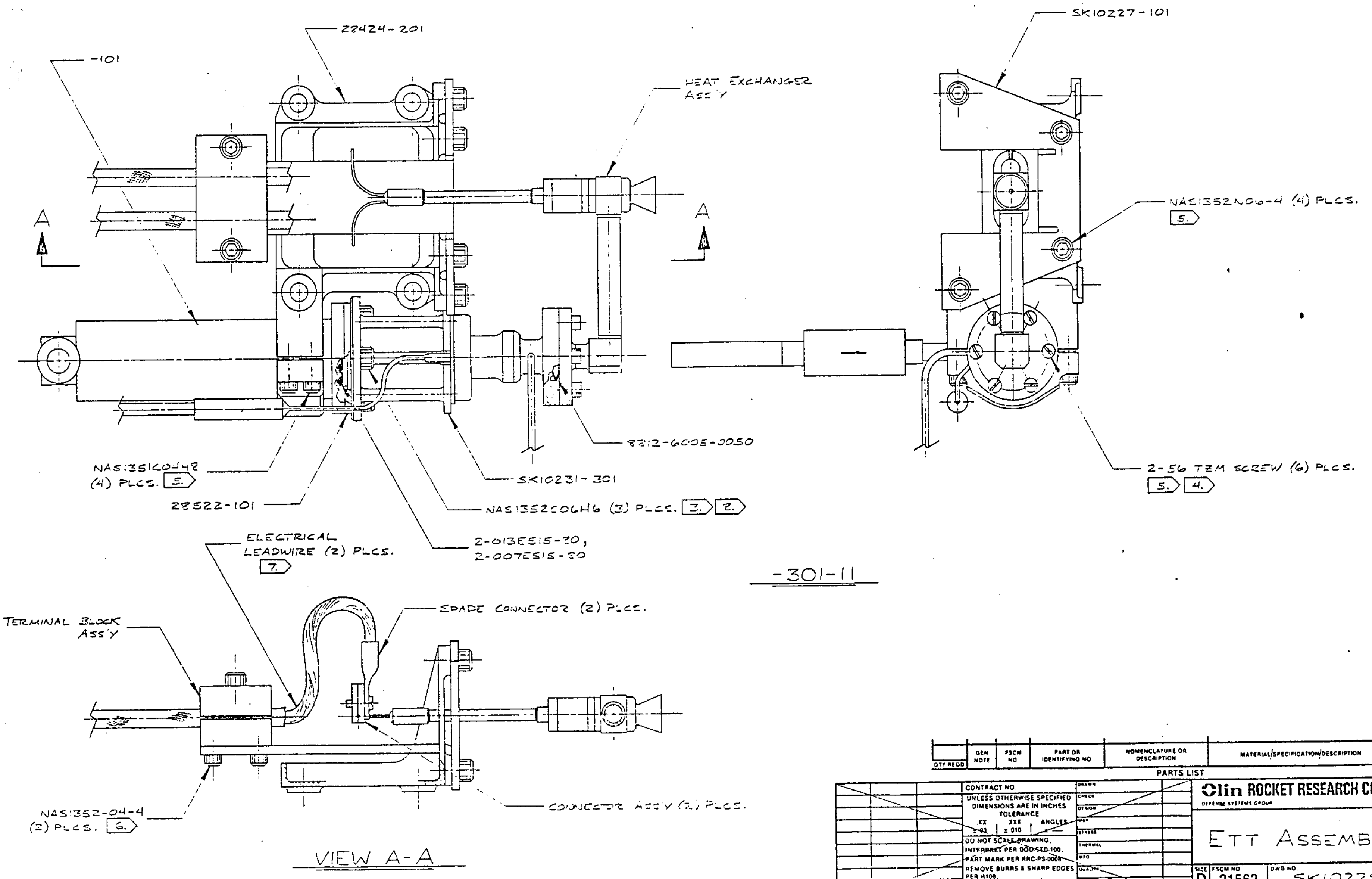
ETT ASSEMBLY

SIZE D | FSCM NO 21562 | DWG NO. SK10228 | REV. —
SCALE 2/1 | RELEASE | SHEET 1 OF 2

REVISIONS
REV	DESCRIPTION	DATE	APPROVED

ORIGINAL PAGE IS OF POOR QUALITY

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED



VIEW A-A

QTY REQD	GEN NOTE	FSCM NO	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.

PARTS LIST

PART NO	NEXT ASSY	USED ON
APPLICATION		

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± —

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RRC-PS-0008
REMOVE BURRS & SHARP EDGES PER H106.

SURFACE FINISH √

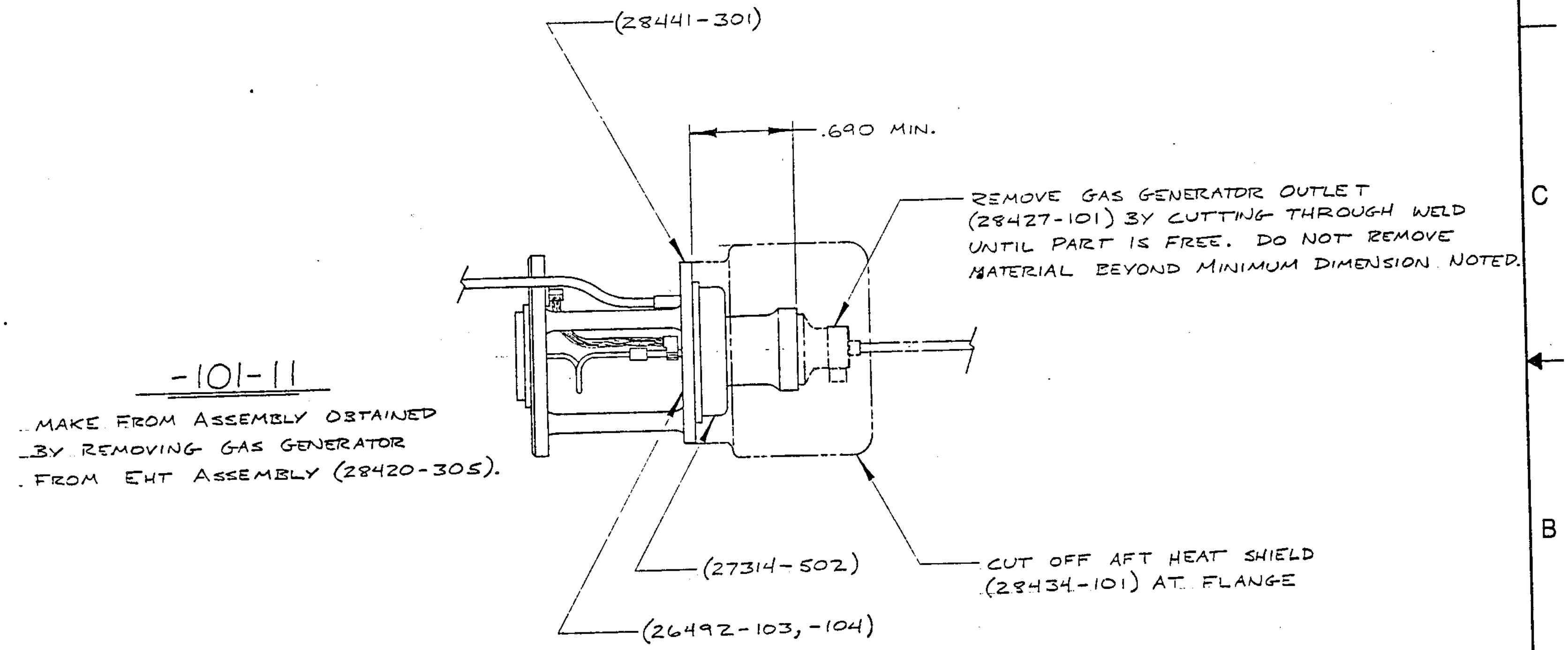
DRAWN
CHECK
DESIGN
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND WA

ETT ASSEMBLY

SIZE D | FSCM NO 21562 | DWG NO. SK10228 | REV. —
SCALE ~/1 | RELEASE | SHEET 1 OF 1

REV	DESCRIPTION	DATE	APPROVED



PARTS LIST

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.

PART NO.	NEXT ASSY	USED ON

APPLICATION

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ±

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RRC PS-0006.
REMOVE BURRS & SHARP EDGES PER R106.

SURFACE FINISH ✓

DRAWN
CHECK
DESIGN
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

GAS GENERATOR ASS'Y

SIZE C | FSCM NO. 21562 | DWG NO. SK10231 | REV. —
SCALE 2/1 | RELEASE | SHEET 2 OF 2

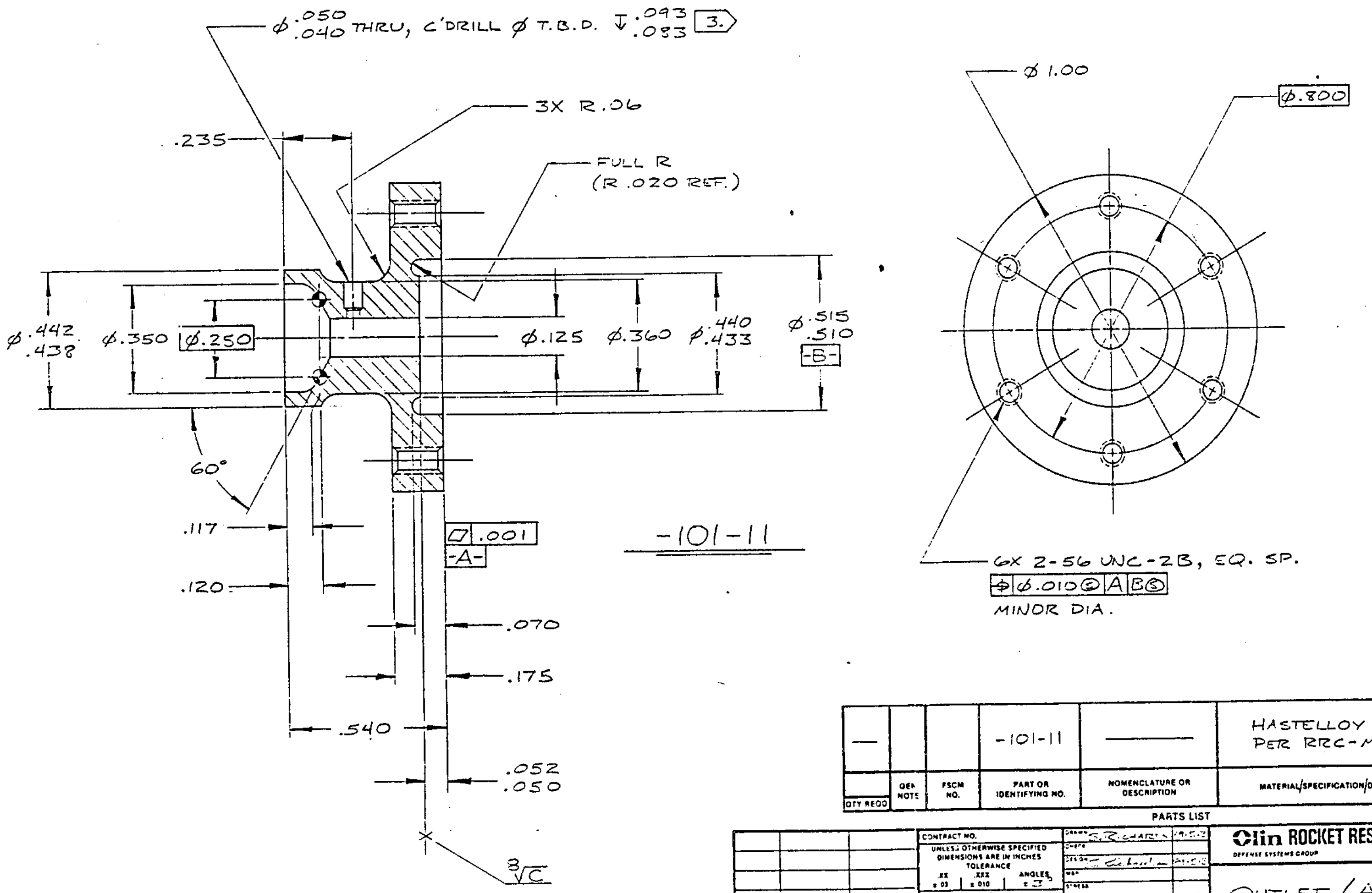
DWG | SHT | REV

THE COMPLETE LINE/ 123028

REV	DESCRIPTION	DATE	APPROVED

REVISIONS

1. INTERPRET DIMENSIONS ＆ TOLERANCES PER ANSI. Y14.5M-1982.
2. SOLVENT CLEAN PER RRC-PS-0205.
3. ORIENT APPROXIMATELY AS SHOWN.



QTY REQD	GEN NOTES	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
—			-101-11	———	HASTELLOY 'B' PER RRC-MS-0135		

PARTS LIST

PART NO.	NEXT ASSY	USED ON
-101	SK10231	IRAD

APPLICATION

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ±3°

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD 100.
PART MARK PER RRC-PS-0008.
REMOVE BURRS & SHARP EDGES PER R106.

SURFACE FINISH 125√

DRAWN S. Richards 4-5-2
CHECK
DESIGN S. Richards 4-5-2
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

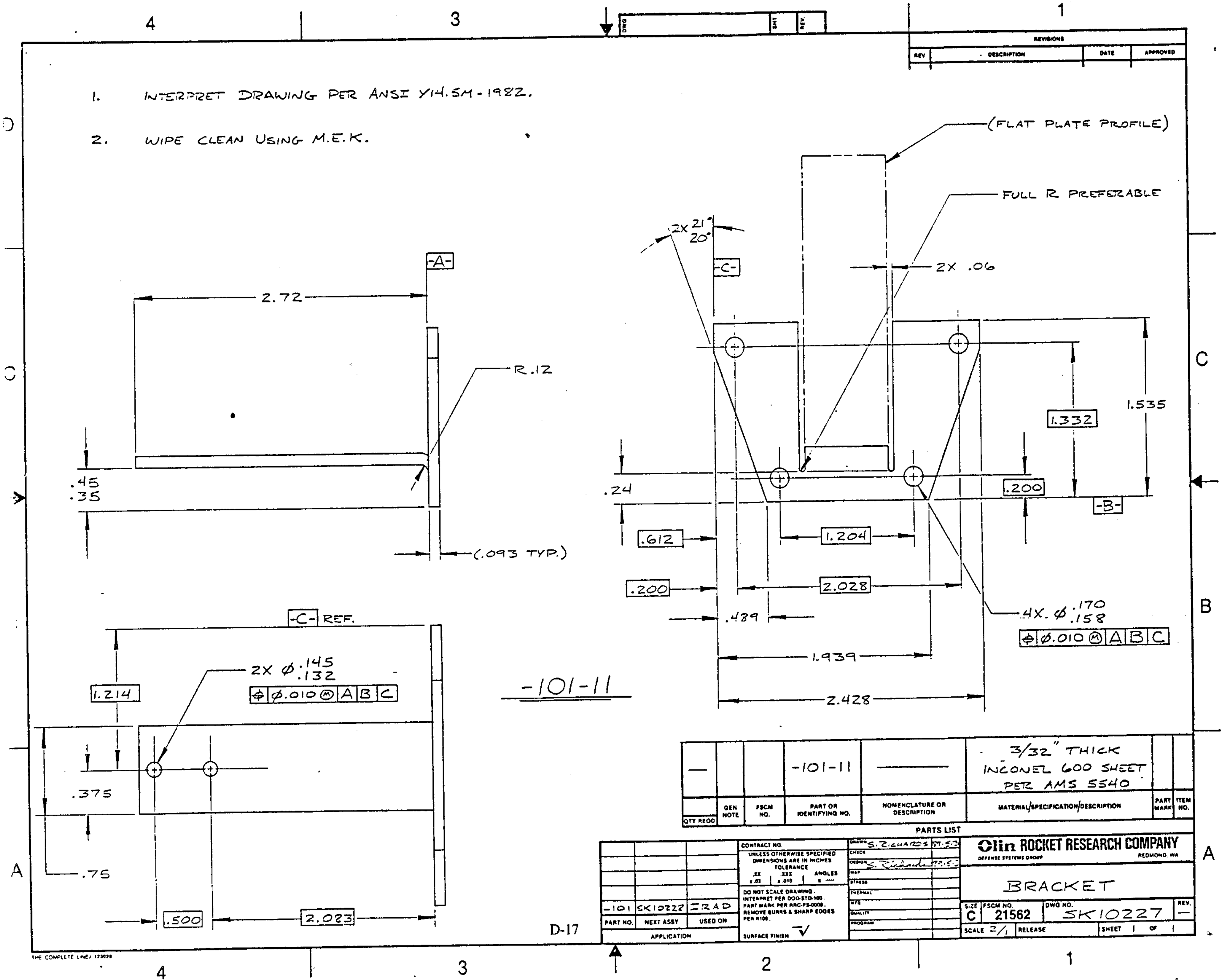
Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

OUTLET / ADAPTER.

SIZE C | FSCM NO. 21562 | DWG NO. SK10226 | REV. —
SCALE 4/1 | RELEASE | SHEET 1 OF 1

DWG | SHT | REV

THE COMPLETE LINE/ 133026



1. INTERPRET DRAWING PER ANSI Y14.5M-1982.

2. WIPE CLEAN USING M.E.K.

PARTS LIST

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
—			-101-11	———	3/32" THICK INCONEL 600 SHEET PER AMS 5540		

APPLICATION

PART NO.	NEXT ASSY	USED ON
-101	SK10222	IRAD

CONTRACT NO.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES

TOLERANCE
.XX ±.03 | .XXX ±.010 | ANGLES ± —

DO NOT SCALE DRAWING.
INTERPRET PER DOD-STD-100.
PART MARK PER RRC-PS-0000.
REMOVE BURRS & SHARP EDGES PER R100.

SURFACE FINISH √

DRAWN S. RICHARDS
CHECK
DESIGN S. Richards
M&P
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

BRACKET

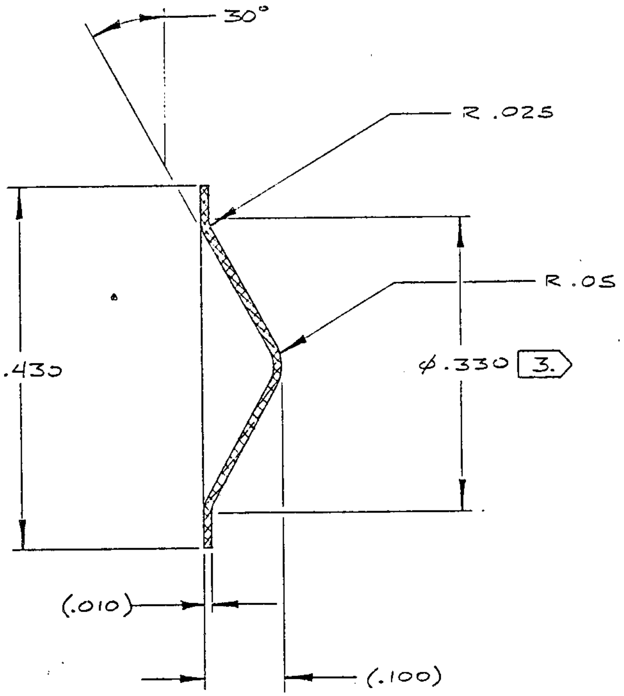
SIZE C | FSCM NO. 21562 | DWG NO. SK10227 | REV. —

SCALE 2/1 | RELEASE | SHEET 1 OF 1

REVISIONS			
REV	DESCRIPTION	DATE	APPROVED

1. INTERPRET DRAWING PER ANSI Y14.5M-1982.

2.) MATERIAL: 100 X 100 MESH, .004 DIA. WIRE, PLAIN SQUARE WEAVE HAYNES 25, TYPE 1, CLASS 1, PER AMS 5796.



3.) DIAMETER MEASURED TO TANGENT POINT OF FILLET RADIUS.

4. REMOVE ALL HANGING STRANDS.

5. SOLVENT DEGREASE PER RRC-PS-0205 USING M.E.K.

6. VISUALLY INSPECT UNDER 10X MAGNIFICATION.
NONE OF THE FOLLOWING CONDITIONS ARE ALLOWED:
A.) TWO PARALLEL WIRES TOUCHING.
B.) BROKEN WIRES.
C.) DELAMINATION OR FRAYED EDGES.

D-18

QTY REQD	GEN NOTE	FSCM NO.	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL/SPECIFICATION/DESCRIPTION	PART MARK	ITEM NO.
—			-101-11	—	2.)		

PARTS LIST

APPLICATION		
PART NO	NEXT ASSY	USED ON
-101	SK10231	IRAD

CONTRACT NO
UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOLERANCE .XX ±.03 .XXX ±.010 ANGLES ± 5°
DO NOT SCALE DRAWING.
INTERPRET PER DOD STD-100.
PART MARK PER RRC-PS-0006.
REMOVE BURRS & SHARP EDGES PER R106.
SURFACE FINISH ✓

DRAWN S. RICHARDSON 9-5-0
CHECK
DESIGN S. Richardson 24.5.
MAP
STRESS
THERMAL
MFG
QUALITY
PROGRAM

Olin ROCKET RESEARCH COMPANY
DEFENSE SYSTEMS GROUP
REDMOND, WA

SCREEN

SIZE C | FSCM NO. 21562 | DWG NO. SK10232 | REV. —
SCALE 10/1 | RELEASE | SHEET 1 OF 1

APPENDIX E

Immersed Heater Data

OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 10:46

CONTRACT NUMBER 121587-4330

5=2 1

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-01 Sample Number 6

Parameter	Data	Units	Parameter	Data	Un
Flow	1.5278	Lbm/Hr	Tc	1251.9	De
Thrust (meas)	87.071	MlbF	Tv	117.4	De
Thrust (corr)	87.071	MlbF	Tf	67.7	De
Fuel Pressure	322.62	Psia	T1	1232.1	De
Chamber Pressure	177.26	Psia	T2	1287.4	De
Alt. Pressure	210.30	Mtorr	T3	1124.8	De
E ht.	0.002	Volts	T4	1174.2	De
I ht.	0.011	Amps	T5	1096.6	De
Ht. Power	0.000	Watts	T6	149.8	De
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.34510	
Gas Temperature	0.0	Degs.	C*	4924.4	Ft
PSP	0.00000		Reynolds#	0	
ISP	205.9	Secs.			

Remarks

End of run Data

ORIGINAL PAGE IS OF POOR QUALITY

OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 11:18:59

CONTRACT NUMBER 121587-4330

SEQ 2

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-01 Sample Number 12

Parameter	Data	Units	Parameter	Data	Units
Flow	1.3216	Lbm/Hr	Tc	1252.7	Degs F
Thrust (meas)	74.258	MlbF	Tv	121.8	Degs F
Thrust (corr)	74.258	MlbF	Tf	68.4	Degs F
Fuel Pressure	259.00	Psia	T1	1215.7	Degs F
Chamber Pressure	152.75	Psia	T2	1268.2	Degs F
Alt. Pressure	173.60	Mtorr	T3	1104.3	Degs F
E ht.	0.002	Volts	T4	1149.3	Degs F
I ht.	0.011	Amps	T5	1073.3	Degs F
Ht. Power	0.000	Watts	T6	156.6	Degs F
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.33103	
Gas Temperature	0.0	Degs.	C*	4905.8	Ft/Sec
PSP	0.00000		Reynolds#	0	
ISP	203.0	Secs.			

Remarks ____________________

End of run Data ____________________

OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 11:49

CONTRACT NUMBER 121587-4330 SEQ 3

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-01 Sample Number 18

Parameter	Data	Units	Parameter	Data	Un
Flow	0.7584	Lbm/Hr	Tc	1188.1	De
Thrust (meas)	40.743	MlbF	Tv	137.6	De
Thrust (corr)	40.743	MlbF	Tf	69.6	De
Fuel Pressure	119.78	Psia	T1	1144.6	De
Chamber Pressure	86.74	Psia	T2	1189.1	De
Alt. Pressure	111.62	Mtorr	T3	1015.4	De
E ht.	0.002	Volts	T4	1046.3	De
I ht.	0.014	Amps	T5	977.0	De
Ht. Power	0.000	Watts	T6	150.6	De
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.28682	
Gas Temperature	0.0	Degs.	C*	4854.5	Ft
PSP	0.00000		Reynolds#	0	
ISP	194.2	Secs.			

Remarks

End of run Data

```
OLIN/ROCKET RESEARCH CO.                          DATE: 01-15-1990    12:57:05

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

                     Run Number 102-01     Sample Number  24


Parameter               Data       Units     Parameter            Data      Units
----------------      --------    -------    ---------------    -------    -------

Flow                   0.6636     Lbm/Hr     Tc                  1174.9    Degs F

Thrust (meas)          45.993     MlbF       Tv                   144.6    Degs F

Thrust (corr)          45.993     MlbF       Tf                    71.3    Degs F

Fuel Pressure          118.70     Psia       T1                  1135.8    Degs F

Chamber Pressure        93.72     Psia       T2                  1182.2    Degs F

Alt. Pressure          104.47     Mtorr      T3                  1303.4    Degs F

E ht.                  20.066     Volts      T4                  1257.9    Degs F

I ht.                   8.265     Amps       T5                  1217.7    Degs F

Ht. Power             165.839     Watts      T6                   165.9    Degs F

Ht. Resistance        2.42794     Ohms

Ht Temperature        2404.71     Degs F     CD                 0.00000

P/Mdot                1.98356     MJ/Kg      Cf                 1.34353

Gas Temperature           0.0     Degs.      C*                  5994.8    Ft/Sec

FSP                   3.59416                Reynolds#                0

ISP                     250.3     Secs.



Remarks ________________________________________________________________
End of run Data ________________________________________________________
```

SEG 4

```
OLIN/ROCKET RESEARCH CO.                          DATE: 01-15-1990    13:21:

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

                    Run Number 102-01    Sample Number  29


Parameter            Data      Units     Parameter         Data     Uni
----------------    -------   -------   ---------------   -------   ---

Flow                 0.6156   Lbm/Hr    Tc                 1168.4   Deg

Thrust (meas)        47.881   MlbF      Tv                  153.7   Deg

Thrust (corr)        47.881   MlbF      Tf                   72.5   Deg

Fuel Pressure        118.76   Psia      T1                 1134.8   Deg

Chamber Pressure      97.31   Psia      T2                 1154.1   Deg

Alt. Pressure        100.43   Mtorr     T3                 1572.9   Deg

E ht.                29.943   Volts     T4                 1456.0   Deg

I ht.                 9.057   Amps      T5                 1371.8   Deg

Ht. Power           271.188   Watts     T6                  167.9   Deg

Ht. Resistance      3.30610   Ohms

Ht Temperature      3307.02   Degs F    CD                0.00000

P/Mdot              3.49610   MJ/Kg     Cf                1.34205

Gas Temperature         0.0   Degs.     C*                 6708.4   Ft/

PSP                 5.64698             Reynolds#               0

ISP                   280.8   Secs.



Remarks ____________________________________________________________
End of run Data ____________________________________________________
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SEQ5

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OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 13:42:52

CONTRACT NUMBER 121587-4330

SEQ 6

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-01 Sample Number 34

Parameter	Data	Units	Parameter	Data	Units
Flow	0.5971	Lbm/Hr	Tc	1168.4	Degs F
Thrust (meas)	48.517	MlbF	Tv	154.5	Degs F
Thrust (corr)	48.517	MlbF	Tf	73.6	Degs F
Fuel Pressure	118.84	Psia	T1	1135.6	Degs F
Chamber Pressure	98.83	Psia	T2	1187.6	Degs F
Alt. Pressure	97.94	Mtorr	T3	1690.7	Degs F
E ht.	34.983	Volts	T4	1603.6	Degs F
I ht.	9.236	Amps	T5	1519.0	Degs F
Ht. Power	323.123	Watts	T6	198.0	Degs F
Ht. Resistance	3.78767	Ohms			
Ht Temperature	3801.83	Degs F	CD	0.00000	
P/Mdot	4.29450	MJ/Kg	Cf	1.34350	
Gas Temperature	0.0	Degs.	C*	7024.9	Ft/Sec
PSP	6.64061		Reynolds#	0	
ISP	293.3	Secs.			

Remarks

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 14:00

CONTRACT NUMBER 121587-4330 SEQ7

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 2

Parameter	Data	Units	Parameter	Data	Un
Flow	0.5931	Lbm/Hr	Tc	1143.9	De
Thrust (meas)	50.071	MlbF	Tv	152.3	De
Thrust (corr)	50.071	MlbF	Tf	74.3	De
Fuel Pressure	121.16	Psia	T1	997.8	De
Chamber Pressure	101.30	Psia	T2	1091.6	De
Alt. Pressure	97.62	Mtorr	T3	1772.7	De
E ht.	39.922	Volts	T4	1672.4	De
I ht.	9.590	Amps	T5	1562.4	De
Ht. Power	382.847	Watts	T6	153.3	De
Ht. Resistance	4.16302	Ohms			
Ht Temperature	4187.30	Degs F	CD	0.00000	
P/Mdot	5.12284	MJ/Kg	Cf	1.35261	
Gas Temperature	0.0	Degs.	C*	7248.9	Ft
PSP	7.62496		Reynolds#	0	
ISP	304.7	Secs.			

Remarks 2.4 min RUN Time

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 14:16:20

9EQ 8

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 5

Parameter	Data	Units	Parameter	Data	Units
Flow	0.7612	Lbm/Hr	Tc	1193.9	Degs F
Thrust (meas)	40.966	MlbF	Tv	144.9	Degs F
Thrust (corr)	40.966	MlbF	Tf	73.4	Degs F
Fuel Pressure	120.99	Psia	T1	1140.8	Degs F
Chamber Pressure	87.33	Psia	T2	1162.8	Degs F
Alt. Pressure	110.60	Mtorr	T3	1017.3	Degs F
E ht.	0.002	Volts	T4	1049.3	Degs F
I ht.	0.014	Amps	T5	973.7	Degs F
Ht. Power	0.000	Watts	T6	157.2	Degs F
Ht. Resistance	0.00000	Ohms			
Ht Temperature	4187.50	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.28306	
Gas Temperature	0.0	Degs.	C*	4869.1	Ft/Sec
PSP	0.00000		Reynolds#	0	
ISP	194.5	Secs.			

Remarks

End of run Data

ORIGINAL PAGE IS OF POOR QUALITY

OLIN/ROCKET RESEARCH CO. DATE: 01-15-1990 14:46:2

SEG 9

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 11

Parameter	Data	Units	Parameter	Data	Unit
Flow	1.2411	Lbm/Hr	Tc	1246.7	Degs
Thrust (meas)	83.226	MlbF	Tv	128.8	Degs
Thrust (corr)	83.226	MlbF	Tf	71.3	Degs
Fuel Pressure	258.36	Psia	T1	1215.0	Degs
Chamber Pressure	165.05	Psia	T2	1269.9	Degs
Alt. Pressure	157.23	Mtorr	T3	1300.3	Degs
E ht.	20.056	Volts	T4	1272.7	Degs
I ht.	9.428	Amps	T5	1241.3	Degs
Ht. Power	189.077	Watts	T6	197.8	Degs
Ht. Resistance	2.12739	Ohms			
Ht Temperature	2095.89	Degs F	CD	0.00200	
P/Mdot	1.20914	MJ/Kg	Cf	1.37982	
Gas Temperature	0.0	Degs.	C*	5644.3	Ft/S
FSP	2.26578		Reynolds#	0	
ISP	242.1	Secs.			

Remarks ____________________

End of run Data ____________________

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OLIN/ROCKET RESEARCH CO. .DATE: 01-15-1990 15:06:52

CONTRACT NUMBER 121587-4330

SEG 10'

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 16

Parameter	Data	Units	Parameter	Data	Units
Flow	1.1970	Lbm/Hr	Tc	1244.8	Degs F
Thrust (meas)	87.989	MlbF	Tv	133.9	Degs F
Thrust (corr)	87.989	MlbF	Tf	72.2	Degs F
Fuel Pressure	258.36	Psia	T1	1211.0	Degs F
Chamber Pressure	172.67	Psia	T2	1264.6	Degs F
Alt. Pressure	153.36	Mtorr	T3	1413.9	Degs F
E ht.	29.978	Volts	T4	1339.6	Degs F
I ht.	11.177	Amps	T5	1328.3	Degs F
Ht. Power	335.079	Watts	T6	208.1	Degs F
Ht. Resistance	2.68207	Ohms			
Ht Temperature	2665.83	Degs F	CD	0.00000	
P/Mdot	2.22173	MJ/Kg	Cf	1.39410	
Gas Temperature	0.0	Degs.	C*	6122.4	Ft/Sec
PSP	3.79881		Reynolds#	0	
ISP	265.3	Secs.			

Remarks ________________________________

End of run Data ________________________________

ORIGINAL PAGE IS OF POOR QUALITY

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 07:20:5

CONTRACT NUMBER 121587-4330

SEQ 11

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 22

Parameter	Data	Units	Parameter	Data	Unit
Flow	1.1775	Lbm/Hr	Tc	1252.8	Degs
Thrust (meas)	91.194	MlbF	Tv	126.3	Degs
Thrust (corr)	91.194	MlbF	Tf	67.7	Degs
Fuel Pressure	259.52	Psia	T1	1208.9	Degs
Chamber Pressure	177.09	Psia	T2	1261.7	Degs
Alt. Pressure	133.02	Mtorr	T3	1492.4	Degs
E ht.	35.049	Volts	T4	1389.4	Degs
I ht.	11.723	Amps	T5	1361.7	Degs
Ht. Power	410.882	Watts	T6	193.1	Degs
Ht. Resistance	2.98975	Ohms			
Ht Temperature	2981.97	Degs F	CD	0.00000	
P/Mdot	2.76941	MJ/Kg	Cf	1.40821	
Gas Temperature	0.2	Degs.	C*	6383.2	Ft/S
PSP	4.49628		Reynolds#	0	
ISP	279.4	Secs.			

Remarks

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 07:47:32

CONTRACT NUMBER 121587-4330

SEQ 12

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 28

Parameter	Data	Units	Parameter	Data	Units
Flow	1.1538	Lbm/Hr	Tc	1245.3	Degs F
Thrust (meas)	92.919	MlbF	Tv	131.6	Degs F
Thrust (corr)	92.919	MlbF	Tf	69.7	Degs F
Fuel Pressure	259.83	Psia	T1	1212.8	Degs F
Chamber Pressure	180.91	Psia	T2	1267.3	Degs F
Alt. Pressure	128.46	Mtorr	T3	1587.1	Degs F
E ht.	40.047	Volts	T4	1456.0	Degs F
I ht.	12.083	Amps	T5	1444.3	Degs F
Ht. Power	483.883	Watts	T6	218.3	Degs F
Ht. Resistance	3.31428	Ohms			
Ht Temperature	3315.42	Degs F	CD	0.00000	
P/Mdot	3.32836	MJ/Kg	Cf	1.40439	
Gas Temperature	0.0	Degs.	C*	6654.7	Ft/Sec
PSP	5.19737		Reynolds#	0	
ISP	290.5	Secs.			

Remarks

End of run Data

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OF POOR QUALITY

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OLIN/ROCKET RESEARCH CO.                          DATE: 01-16-1992    06:14:0
CONTRACT NUMBER 121587-4330
HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)
PERFORMANCE MAP ON MODIFIED ETT S/N 001
                     Run Number 102-02    Sample Number  34

Parameter           Data      Units     Parameter           Data      Unit
----------------  --------   --------  ----------------   --------   ----
Flow                1.1330   Lbm/Hr    Tc                   1246.9   Degs
Thrust (meas)       94.765   MlbF      Tv                    137.2   Degs
Thrust (corr)       94.765   MlbF      Tf                     71.2   Degs
Fuel Pressure       260.12   Psia      T1                   1212.0   Degs
Chamber Pressure    184.37   Psia      T2                   1265.9   Degs
Alt. Pressure       124.35   Mtorr     T3                   1684.5   Degs
E ht.               44.985   Volts     T4                   1525.8   Degs
I ht.               12.377   Amps      T5                   1508.4   Degs
Ht. Power          556.769   Watts     T6                    232.0   Degs
Ht. Resistance     3.63469   Ohms
Ht Temperature     3644.64   Degs F    CD                  0.00000
P/Mdot             3.90013   MJ/Kg     Cf                  1.40531
Gas Temperature        0.0   Degs.     C*                   6906.5   Ft/S
FSP                5.86436             Reynolds#                 0
ISP                  301.7   Secs.
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SE913

Remarks ______________________________

End of run Data ______________________________

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 08:21:02

CONTRACT NUMBER 121597-4330 SEQ 14

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 36

Parameter	Data	Units	Parameter	Data	Units
Flow	1.1724	Lbm/Hr	Tc	1227.1	Degs F
Thrust (meas)	91.715	MlbF	Tv	140.8	Degs F
Thrust (corr)	91.715	MlbF	Tf	71.6	Degs F
Fuel Pressure	260.18	Psia	T1	1144.4	Degs F
Chamber Pressure	179.15	Psia	T2	1231.4	Degs F
Alt. Pressure	128.13	Mtorr	T3	1486.6	Degs F
E ht.	39.141	Volts	T4	1356.3	Degs F
I ht.	12.157	Amps	T5	1263.6	Degs F
Ht. Power	475.851	Watts	T6	201.1	Degs F
Ht. Resistance	3.21947	Ohms			
Ht Temperature	3218.01	Degs F	CD	0.00000	
P/Mdot	3.22129	MJ/Kg	Cf	1.39968	
Gas Temperature	0.0	Degs.	C*	6485.4	Ft/Sec
PSP	5.17813		Reynolds#	0	
ISP	282.2	Secs.			

Remarks AT 50V NOT UP TO TEMP

End of run Data

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OLIN/ROCKET RESEARCH CO.                          DATE: 01-16-1990    08:48:5
CONTRACT NUMBER 121387-4300
HI PERF. RESISTO-JET PERFORMANCE MAP   (Ver 1.00)
PERFORMANCE MAP ON MODIFIED ETT S/N 001

                      Run Number 102-02    Sample Number   42

Parameter             Data       Units      Parameter              Data      Unit
---------------      -------    -------    ---------------       -------    ----

Flow                  1.1119    Lbm/Hr     Tc                     1251.2    Degs

Thrust (meas)         96.450    MlbF       Tv                      140.4    Degs

Thrust (corr)         96.450    MlbF       Tf                       72.8    Degs

Fuel Pressure         260.23    Psia       T1                     1212.4    Degs

Chamber Pressure      187.71    Psia       T2                     1266.1    Degs

Alt. Pressure         120.89    Mtorr      T3                     1801.4    Degs

E ht.                 50.073    Volts      T4                     1612.3    Degs

I ht.                 12.626    Amps       T5                     1587.3    Degs

Ht. Power            632.234    Watts      T6                      239.4    Degs

Ht. Resistance       3.96586    Ohms

Ht Temperature       3984.92    Degs F     CD                    0.00000

P/Mdot               4.51287    MJ/Kg      Cf                    1.40472

Gas Temperature          0.0    Degs.      C*                     7165.2    Ft/S

PSP                  6.54345               Reynolds#                   0

ISP                    312.8    Secs.


Remarks
End of run Data
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SEQ15

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OLIN/ROCKET RESEARCH CO.                          DATE: 01-16-1990    09:20:30

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

                    Run Number 102-02    Sample Number  48


Parameter            Data       Units      Parameter              Data       Units
----------------     --------   --------   ----------------       --------   -------

Flow                 1.3860     Lbm/Hr     Tc                     1246.2     Degs F

Thrust (meas)        104.782    MlbF       Tv                      132.3     Degs F

Thrust (corr)        104.782    MlbF       Tf                       71.9     Degs F

Fuel Pressure        322.93     Psia       T1                     1235.6     Degs F

Chamber Pressure     204.86     Psia       T2                     1290.7     Degs F

Alt. Pressure        140.00     Mtorr      T3                     1480.4     Degs F

E ht.                35.123     Volts      T4                     1300.9     Degs F

I ht.                12.278     Amps       T5                     1370.2     Degs F

Ht. Power            431.238    Watts      T6                      231.1     Degs F

Ht. Resistance       2.86061    Ohms

Ht Temperature       2849.27    Degs F     CD                    0.00000

P/Mdot               2.46944    MJ/Kg      Cf                    1.39850

Gas Temperature          0.0    Degs.      C*                     6273.3     Ft/Sec

PSP                  4.10779               Reynolds#                   0

ISP                    272.7    Secs.



Remarks  ________________________________________________________________
End of run Data _________________________________________________________
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SEQ 16

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 09:50:

CONTRACT NUMBER 121587-4330

SEQ 1

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 54

Parameter	Data	Units	Parameter	Data	Unit
Flow	1.3627	Lbm/Hr	Tc	1277.6	Degs
Thrust (meas)	107.849	MlbF	Tv	136.1	Degs
Thrust (corr)	107.849	MlbF	Tf	72.6	Degs
Fuel Pressure	322.98	Psia	T1	1232.6	Degs
Chamber Pressure	208.96	Psia	T2	1237.4	Degs
Alt. Pressure	136.99	Mtorr	T3	1553.3	Degs
E ht.	39.992	Volts	T4	1422.4	Degs
I ht.	12.736	Amps	T5	1433.6	Degs
Ht. Power	509.335	Watts	T6	240.0	Degs
Ht. Resistance	3.14012	Ohms			
Ht Temperature	3136.47	Degs F	CD	0.00000	
P/Mdot	2.96653	MJ/Kg	Cf	1.41102	
Gas Temperature	0.0	Degs.	C*	6508.3	Ft/
FSP	4.71417		Reynolds#	0	
ISP	285.4	Secs.			

Remarks

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 10:16:37

CONTRACT NUMBER 121587-4330

SEQ 18

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 60

Parameter	Data	Units	Parameter	Data	Units
Flow	1.3395	Lbm/Hr	Tc	1246.3	Degs F
Thrust (meas)	110.199	MlbF	Tv	135.7	Degs F
Thrust (corr)	110.199	MlbF	Tf	73.8	Degs F
Fuel Pressure	323.15	Psia	T1	1234.9	Degs F
Chamber Pressure	213.12	Psia	T2	1291.0	Degs F
Alt. Pressure	133.65	Mtorr	T3	1643.7	Degs F
E ht.	44.954	Volts	T4	1482.5	Degs F
I ht.	13.080	Amps	T5	1490.5	Degs F
Ht. Power	588.009	Watts	T6	246.1	Degs F
Ht. Resistance	3.43683	Ohms			
Ht Temperature	3441.34	Degs F	CD	0.00000	
P/Mdot	3.48410	MJ/Kg	Cf	1.41349	
Gas Temperature	0.0	Degs.	C*	6753.2	Ft/Sec
PSP	5.32672		Reynolds#	0	
ISP	296.7	Secs.			

Remarks

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 10:44:

CONTRACT NUMBER 121587-4330

SEG 19

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 66

Parameter	Data	Units	Parameter	Data	Uni
Flow	1.3156	Lbm/Hr	Tc	1276.4	Deg
Thrust (meas)	113.938	MlbF	Tv	137.3	Deg
Thrust (corr)	113.938	MlbF	Tf	74.8	Deg
Fuel Pressure	323.36	Psia	T1	1234.7	Deg
Chamber Pressure	217.11	Psia	T2	1291.9	Deg
Alt. Pressure	130.75	Mtorr	T3	1737.4	Deg
E ht.	49.965	Volts	T4	1545.9	Deg
I ht.	13.370	Amps	T5	1550.2	Deg
Ht. Power	668.046	Watts	T6	251.3	Deg
Ht. Resistance	3.73700	Ohms			
Ht Temperature	3749.77	Degs F	CD	0.00000	
F/Mdot	4.03008	MJ/Kg	Cf	1.43450	
Gas Temperature	0.0	Degs.	C*	7004.1	Ft/
PSP	5.85370		Reynolds#	0	
ISP	312.3	Secs.			

Remarks Post Thrust Calibration error

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 11:19:47

CONTRACT NUMBER 121587-4330

SEQ 2C

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.20)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 72

Parameter	Data	Units	Parameter	Data	Units
Flow	1.2945	Lbm/Hr	Tc	1266.8	Degs F
Thrust (meas)	114.188	MlbF	Tv	140.5	Degs F
Thrust (corr)	114.188	MlbF	Tf	76.0	Degs F
Fuel Pressure	323.55	Psia	T1	1233.6	Degs F
Chamber Pressure	220.69	Psia	T2	1288.8	Degs F
Alt. Pressure	128.68	Mtorr	T3	1836.9	Degs F
E ht.	54.995	Volts	T4	1615.0	Degs F
I ht.	13.628	Amps	T5	1616.0	Degs F
Ht. Power	749.460	Watts	T6	258.0	Degs F
Ht. Resistance	4.03556	Ohms			
Ht Temperature	4056.54	Degs F	CD	0.00000	
P/Mdot	4.59481	MJ/Kg	Cf	1.41424	
Gas Temperature	0.0	Degs.	C*	7235.7	Ft/Sec
PSP	6.55292		Reynolds#	0	
ISP	318.1	Secs.			

Remarks

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 11:28:0

CONTRACT NUMBER 121597-4330

SEQ 21

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 74

Parameter	Data	Units	Parameter	Data	Unit
Flow	1.3337	Lbm/Hr	Tc	1259.3	Degs
Thrust (meas)	110.285	MlbF	Tv	144.6	Degs
Thrust (corr)	110.285	MlbF	Tf	76.3	Degs
Fuel Pressure	323.59	Psia	T1	1149.9	Degs
Chamber Pressure	214.38	Psia	T2	1249.6	Degs
Alt. Pressure	133.39	Mtorr	T3	1625.7	Degs
E ht.	48.597	Volts	T4	1437.5	Degs
I ht.	13.466	Amps	T5	1363.4	Degs
Ht. Power	654.399	Watts	T6	212.8	Degs
Ht. Resistance	3.60889	Ohms			
Ht Temperature	3618.14	Degs F	CD	0.00000	
P/Mdot	3.89431	MJ/Kg	Cf	1.40630	
Gas Temperature	0.0	Degs.	C*	6822.5	Ft/S
PSP	5.92353		Reynolds#	0	
ISP	298.2	Secs.			

Remarks Not steady-state values

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-16-1990 11:57:16

SEQ22

CONTRACT NUMBER 121587-4330

HI PERF. RESISTC-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-02 Sample Number 79

Parameter	Data	Units	Parameter	Data	Units
Flow	1.3158	Lbm/Hr	Tc	1268.1	Degs F
Thrust (meas)	111.995	MlbF	Tv	139.2	Degs F
Thrust (corr)	111.995	MlbF	Tf	75.9	Degs F
Fuel Pressure	323.21	Psia	T1	1233.7	Degs F
Chamber Pressure	217.17	Psia	T2	1288.3	Degs F
Alt. Pressure	130.32	Mtorr	T3	1739.8	Degs F
E ht.	49.956	Volts	T4	1544.2	Degs F
I ht.	13.356	Amps	T5	1553.2	Degs F
Ht. Power	667.230	Watts	T6	249.9	Degs F
Ht. Resistance	3.74018	Ohms			
Ht Temperature	3753.03	Degs F	CD	0.00300	
P/Mcot	4.02449	MJ/Kg	Cf	1.40769	
Gas Temperature	0.0	Degs.	C*	7004.8	Ft/Sec
PSP	5.94787		Reynolds#	0	
ISP	306.9	Secs.			

Remarks ____

End of run Data ____

OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 09:52:

SEQ 24

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 4

Parameter	Data	Units	Parameter	Data	Uni
Flow	0.7506	Lbm/Hr	Tc	1173.8	Deg
Thrust (meas)	40.219	MlbF	Tv	118.5	Deg
Thrust (corr)	40.219	MlbF	Tf	64.6	Deg
Fuel Pressure	119.30	Psia	T1	1132.9	Deg
Chamber Pressure	85.47	Psia	T2	1151.7	Deg
Alt. Pressure	103.64	Mtorr	T3	1049.4	Deg
E ht.	0.002	Volts	T4	1099.3	Deg
I ht.	0.013	Amps	T5	1028.9	Deg
Ht. Power	0.000	Watts	T6	127.4	Deg
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.28371	
Gas Temperature	0.0	Degs.	C*	4332.7	Ft/
PSP	0.00000		Reynolds#	0	
ISP	193.6	Secs.			

Remarks Insulation on

End of run Date 2c its not 2f it is (compare T_2 c [illegible])

OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 10:21:25

CONTRACT NUMBER 121587-4330

SEG25

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 10

Parameter	Data	Units	Parameter	Data	Units
Flow	1.3116	Lbm/Hr	Tc	1259.6	Degs F
Thrust (meas)	73.857	MlbF	Tv	120.5	Degs F
Thrust (corr)	73.857	MlbF	Tf	67.1	Degs F
Fuel Pressure	258.61	Psia	T1	1216.6	Degs F
Chamber Pressure	152.76	Psia	T2	1269.7	Degs F
Alt. Pressure	142.83	Mtorr	T3	1145.6	Degs F
E ht.	0.002	Volts	T4	1212.2	Degs F
I ht.	0.011	Amps	T5	1145.0	Degs F
Ht. Power	0.000	Watts	T6	161.0	Degs F
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.20	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.32304	
Gas Temperature	0.0	Degs.	C*	4943.2	Ft/Sec
FSP	0.00000		Reynolds#	0	
ISP	203.3	Secs.			

Remarks ____________________

End of run Data ____________________

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OLIN/ROCKET RESEARCH CO.                             DATE: 01-17-1990    10:40:

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE  MAP ON MODIFIED ETT S/N 001

                    Run Number 102-04    Sample Number  14


Parameter              Data     Units      Parameter             Data     Uni
---------------      -------   -------    ---------------      -------    ---

Flow                  1.5208   Lbm/Hr     Tc                    1281.3    Deg

Thrust (meas)         86.039   MlbF       Tv                     118.9    Deg

Thrust (corr)         86.039   MlbF       Tf                      67.7    Deg

Fuel Pressure         323.15   Psia       T1                    1235.8    Deg

Chanber Pressure      177.42   Psia       T2                    1292.0    Deg

Alt. Pressure         160.23   Mtorr      T3                    1168.9    Deg

E ht.                  0.002   Volts      T4                    1240.8    Deg

I ht.                  0.010   Amps       T5                    1174.3    Deg

Ht. Power              0.000   Watts      T6                     167.3    Deg

Ht. Resistance       0.00000   Ohms

Ht Temperature          0.00   Degs F     CD                   0.00000

P/Mdot               0.00000   MJ/Kg      Cf                   1.32657

Gas Temperature          0.0   Degs.      C*                    4951.5    Ft/

PSP                  0.00020              Reynolds#                  0

ISP                    204.2   Secs.



Remarks ____________________________________________________________
End of run Data ____________________________________________________
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5E92

OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 11:09:34

SEQ 27

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 19

Parameter	Data	Units	Parameter	Data	Units
Flow	1.0974	Lbm/Hr	Tc	1247.0	Degs F
Thrust (meas)	95.691	MlbF	Tv	132.7	Degs F
Thrust (corr)	95.691	MlbF	Tf	70.8	Degs F
Fuel Pressure	259.19	Psia	T1	1210.2	Degs F
Chamber Pressure	187.18	Psia	T2	1266.8	Degs F
Alt. Pressure	123.71	Mtorr	T3	1891.3	Degs F
E ht.	49.917	Volts	T4	1741.0	Degs F
I ht.	12.445	Amps	T5	1741.9	Degs F
Ht. Power	621.199	Watts	T6	214.1	Degs F
Ht. Resistance	4.01119	Ohms			
Ht Temperature	4031.52	Degs F	CD	2.00000	
P/Mdot	4.49269	MJ/Kg	Cf	1.39770	
Gas Temperature	0.0	Degs.	C*	7239.3	Ft/Sec
PSP	6.47987		Reynolds#	0	
ISP	314.5	Secs.			

Remarks ____

End of run Data ____

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OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 11:41

SEG 2

CONTRACT NUMBER 121387-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 25

Parameter	Data	Units	Parameter	Data	Un
Flow	1.2939	Lbm/Hr	Tc	1282.6	De
Thrust (meas)	114.320	MlbF	Tv	134.8	De
Thrust (corr)	114.320	MlbF	Tf	73.3	De
Fuel Pressure	323.50	Psia	T1	1234.4	De
Chamber Pressure	221.22	Psia	T2	1293.5	De
Alt. Pressure	134.88	Mtorr	T3	1917.7	De
E ht.	54.993	Volts	T4	1736.6	De
I ht.	13.493	Amps	T5	1766.1	De
Ht. Power	742.000	Watts	T6	248.9	De
Ht. Resistance	4.07557	Ohms			
Ht Temperature	4097.64	Degs F	CD	0.00000	
F/Mdot	4.55154	NJ/Kg	Cf	1.41263	
Gas Temperature	0.0	Degs.	C*	7256.5	Ft
PSP	6.47995		Reynolds#	0	
ISP	318.6	Secs.			

Remarks ____

End of run Data __________________________________

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OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 12:35:15

CONTRACT NUMBER 121587-4330

SEQ 29

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 31

Parameter	Data	Units	Parameter	Data	Units
Flow	1.5625	Lbm/Hr	Tc	1294.6	Degs F
Thrust (meas)	126.314	MlbF	Tv	131.4	Degs F
Thrust (corr)	126.314	MlbF	Tf	73.1	Degs F
Fuel Pressure	399.45	Psia	T1	1252.1	Degs F
Chamber Pressure	244.53	Psia	T2	1309.8	Degs F
Alt. Pressure	155.65	Mtorr	T3	1662.0	Degs F
E ht.	45.101	Volts	T4	1535.5	Degs F
I ht.	13.635	Amps	T5	1590.5	Degs F
Ht. Power	614.959	Watts	T6	247.8	Degs F
Ht. Resistance	3.30771	Ohms			
Ht Temperature	3308.67	Degs F	CD	0.00000	
P/Mdot	3.12362	MJ/Kg	Cf	1.41217	
Gas Temperature	0.0	Degs.	C*	6642.3	Ft/Sec
FSP	4.86020		Reynolds#	0	
ISP	291.5	Secs.			

Remarks ______________________________

End of run Data ______________________________

ORIGINAL PAGE IS OF POOR QUALITY

OLIN/ROCKET RESEARCH CO. DATE: 01-17-1992 13:02:

SEQ 3

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 37

Parameter	Data	Units	Parameter	Data	Uni
Flow	1.5442	Lbm/Hr	Tc	1302.0	Deg
Thrust (meas)	128.834	MlbF	Tv	135.9	Deg
Thrust (corr)	128.834	MlbF	Tf	74.4	Deg
Fuel Pressure	399.76	Psia	T1	1252.7	Deg
Chamber Pressure	249.13	Psia	T2	1309.6	Deg
Alt. Pressure	149.94	Mtorr	T3	1746.6	Deg
E ht.	49.946	Volts	T4	1590.3	Deg
I ht.	13.972	Amps	T5	1647.1	Deg
Ht. Power	697.833	Watts	T6	162.9	Deg
Ht. Resistance	3.57479	Ohms			
Ht Temperature	3583.09	Degs F	CD	0.00000	
P/Mdot	3.59669	MJ/Kg	Cf	1.41359	
Gas Temperature	0.0	Degs.	C*	6847.6	Ft/
PSP	5.40760		Reynolds#	0	
ISP	300.9	Secs.			

Remarks

End of run Date

OLIN/ROCKET RESEARCH CO. DATE: 01-17-1990 13:28:52

SEQ 31

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-04 Sample Number 43

Parameter	Data	Units	Parameter	Data	Units
Flow	1.5159	Lbm/Hr	Tc	1283.9	Degs F
Thrust (meas)	131.359	MlbF	Tv	138.8	Degs F
Thrust (corr)	131.359	MlbF	Tf	76.0	Degs F
Fuel Pressure	400.25	Psia	T1	1253.7	Degs F
Chamber Pressure	253.86	Psia	T2	1311.4	Degs F
Alt. Pressure	144.42	Mtorr	T3	1840.1	Degs F
E ht.	54.980	Volts	T4	1655.6	Degs F
I ht.	14.262	Amps	T5	1714.2	Degs F
Ht. Power	784.138	Watts	T6	272.7	Degs F
Ht. Resistance	3.85496	Ohms			
Ht Temperature	3870.97	Degs F	CD	0.00000	
P/Mdot	4.10544	MJ/Kg	Cf	1.41431	
Gas Temperature	0.0	Degs.	C*	7107.6	Ft/Sec
PSP	5.96012		Reynolds#	0	
ISP	312.4	Secs.			

Remarks

End of run Data

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OLIN/ROCKET RESEARCH CO.                           DATE: 01-17-1990     13:55:
CONTRACT NUMBER 121587-4330
HI PERF. RESISTO-JET PERFORMANCE MAP   (Ver 1.00)
PERFORMANCE  MAP ON MODIFIED ETT S/N 001
                       Run Number 102-04    Sample Number   49

Parameter              Data       Units      Parameter              Data      Un
--------------------   --------   --------   ------------------   --------   ---
Flow                    1.4955    Lbm/Hr     Tc                     1301.7   De
Thrust (meas)          133.413    MlbF       Tv                      142.4   De
Thrust (corr)          133.413    MlbF       Tf                       77.3   De
Fuel Pressure           400.40    Psia       T1                     1253.9   De
Chamber Pressure        258.37    Psia       T2                     1309.2   De
Alt. Pressure           140.76    Mtorr      T3                     1936.3   De
E ht.                   59.989    Volts      T4                     1724.5   De
I ht.                   14.514    Amps       T5                     1784.3   De
Ht. Power              870.678    Watts      T6                      280.3   De
Ht. Resistance         4.13315    Ohms
Ht Temperature         4156.81    Degs F     CD                    0.03000
P/Mdot                 4.62079    MJ/Kg      Cf                    1.41127
Gas Temperature            0.0    Degs.      C*                     7332.8   Ft
PSP                    6.51646               Reynolds#                   0
ISP                      321.6    Secs.

Remarks ____________________________________________________________________
End of run Data ____________________________________________________________
```

SEQ32

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OLIN/ROCKET RESEARCH CO.                                DATE: 01-17-1990     14:53:50

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP   (Ver 1.00)

PERFORMANCE  MAP ON MODIFIED ETT S/N 001

                     Run Number 102-04     Sample Number   53


Parameter           Data       Units      Parameter          Data       Units
---------------    -------    -------    ---------------    -------    -------

Flow                1.2766    Lbm/Hr     Tc                  1258.6    Degs F

Thrust (meas)      113.920    MlbF       Tv                   138.4    Degs F

Thrust (corr)      113.920    MlbF       Tf                    78.4    Degs F

Fuel Pressure      323.26     Psia       T1                  1233.0    Degs F

Chamber Pressure   222.38     Psia       T2                  1292.1    Degs F

Alt. Pressure      127.58     Mtorr      T3                  1952.5    Degs F

E ht.               56.474    Volts      T4                  1765.7    Degs F

I ht.               13.520    Amps       T5                  1796.1    Degs F

Ht. Power          763.511    Watts      T6                   217.2    Degs F

Ht. Resistance     4.17723    Ohms

Ht Temperature     4202.10    Degs F     CD                 0.00070

P/Mdot             4.74684    MJ/Kg      Cf                 1.40020

Gas Temperature        0.0    Degs.      C*                  7393.6    Ft/Sec

PSP                6.69156               Reynolds#                0

ISP                  321.8    Secs.



Remarks ____________________________________________________________________
End of run Data ____________________________________________________________
```

SEQ 33

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OF POOR QUALITY

OLIN/ROCKET RESEARCH CO. DATE: 01-18-1990 07:3

SEQ 34

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-05 Sample Number 8

Parameter	Data	Units	Parameter	Data	U
Flow	0.9782	Lbm/Hr	Tc	1232.1	D
Thrust (meas)	82.765	MlbF	Tv	129.4	D
Thrust (corr)	82.765	MlbF	Tf	66.3	D
Fuel Pressure	220.29	Psia	T1	1192.8	D
Chamber Pressure	164.81	Psia	T2	1249.1	D
Alt. Pressure	118.48	Mtorr	T3	1845.0	D
E ht.	44.981	Volts	T4	1710.9	D
I ht.	11.604	Amps	T5	1701.2	D
Ht. Power	521.942	Watts	T6	199.5	D
Ht. Resistance	3.87651	Ohms			
Ht Temperature	3893.11	Degs F	CD	0.00000	
P/Mdot	4.23475	MJ/Kg	Cf	1.37321	
Gas Temperature	0.0	Degs.	C*	7151.0	F
PSP	6.29355		Reynolds#	0	
ISP	305.2	Secs.			

Remarks

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-18-1990 07:58:23

SEQ 35

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-05 Sample Number 13

Parameter	Data	Units	Parameter	Data	Units
Flow	0.9526	Lbm/Hr	Tc	1241.2	Degs F
Thrust (meas)	84.053	MlbF	Tv	137.8	Degs F
Thrust (corr)	84.053	MlbF	Tf	68.1	Degs F
Fuel Pressure	220.44	Psia	T1	1197.7	Degs F
Chamber Pressure	167.49	Psia	T2	1255.0	Degs F
Alt. Pressure	115.38	Mtorr	T3	1988.9	Degs F
E ht.	50.004	Volts	T4	1839.5	Degs F
I ht.	11.805	Amps	T5	1821.5	Degs F
Ht. Power	590.305	Watts	T6	219.9	Degs F
Ht. Resistance	4.23585	Ohms			
Ht Temperature	4262.34	Degs F	CD	0.00000	
P/Mdot	4.91791	MJ/Kg	Cf	1.37223	
Gas Temperature	0.0	Degs.	C*	7461.9	Ft/Sec
PSP	7.00936		Reynolds#	0	
ISP	318.3	Secs.			

Remarks ____________________

End of run Data ____________________

OLIN/ROCKET RESEARCH CO. DATE: 01-18-1990 09:38

SEQ 3

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-06 Sample Number 9

Parameter	Data	Units	Parameter	Data	Un
Flow	0.9585	Lbm/Hr	Tc	1243.5	De
Thrust (meas)	82.812	MlbF	Tv	138.7	De
Thrust (corr)	82.812	MlbF	Tf	69.4	De
Fuel Pressure	220.11	Psia	T1	1194.3	De
Chamber Pressure	166.49	Psia	T2	1249.9	De
Alt. Pressure	115.34	Mtorr	T3	1917.3	De
E ht.	47.473	Volts	T4	1773.4	De
I ht.	11.693	Amps	T5	1760.8	De
Ht. Power	555.117	Watts	T6	214.5	De
Ht. Resistance	4.05992	Ohms			
Ht Temperature	4081.57	Degs F	CD	0.00000	
P/Mdot	4.59630	MJ/Kg	Cf	1.36011	
Gas Temperature	0.0	Degs.	C*	7371.8	Ft
PSP	6.69010		Reynolds#	0	
ISP	311.6	Secs.			

Remarks

End of run Data

```
OLIN/ROCKET RESEARCH CO.                         DATE: 01-22-1990     08:05:15

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

                    Run Number 102-07     Sample Number    7


Parameter             Data       Units      Parameter             Data       Units
---------------      --------   --------   ---------------      --------   ------

Flow                   1.3988   Lbm/Hr     Tc                     1273.1   Degs F

Thrust (meas)          78.737   MlbF       Tv                      116.2   Degs F

Thrust (corr)          78.737   MlbF       Tf                       62.8   Degs F

Fuel Pressure          285.39   Psia       T1                     1221.3   Degs F

Chamber Pressure       164.63   Psia       T2                     1274.7   Degs F

Alt. Pressure          155.88   Mtorr      T3                     1156.2   Degs F

E ht.                   0.004   Volts      T4                     1219.5   Degs F

I ht.                   0.012   Amps       T5                     1155.2   Degs F

Ht. Power               0.000   Watts      T6                      164.3   Degs F

Ht. Resistance        0.00000   Ohms

Ht Temperature           0.00   Degs F     CD                    0.00000

P/Mdot                0.00000   MJ/Kg      Cf                    1.30888

Gas Temperature           0.0   Degs.      C*                     4995.1   Ft/Sec

FSP                   0.00000              Reynolds#                   0

ISP                     203.2   Secs.
```

SEQ 37

Remarks
End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-22-1990 08:32

SEQ 3

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-07 Sample Number 13

Parameter	Data	Units	Parameter	Data	Un
Flow	1.1727	Lbm/Hr	Tc	1249.1	De
Thrust (meas)	102.877	MlbF	Tv	130.5	De
Thrust (corr)	102.877	MlbF	Tf	66.7	De
Fuel Pressure	285.68	Psia	T1	1220.2	De
Chamber Pressure	203.68	Psia	T2	1278.6	De
Alt. Pressure	132.56	Mtorr	T3	1922.1	De
E ht.	52.558	Volts	T4	1746.9	De
I ht.	12.884	Amps	T5	1765.5	De
Ht. Power	677.131	Watts	T6	231.9	De
Ht. Resistance	4.07941	Ohms			
Ht Temperature	4101.60	Degs F	CD	0.00000	
P/Mdot	4.58254	MJ/Kg	Cf	1.38091	
Gas Temperature	0.0	Degs.	C*	7371.4	Ft
PSP	6.56995		Reynolds#	0	
ISP	316.4	Secs.			

Remarks

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-22-1990 09:07:31

CONTRACT NUMBER 121587-4330

SEQ 39

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-07 Sample Number 19

Parameter	Data	Units	Parameter	Data	Units
Flow	1.0936	Lbm/Hr	Tc	1245.9	Degs F
Thrust (meas)	95.558	MlbF	Tv	135.8	Degs F
Thrust (corr)	95.558	MlbF	Tf	68.7	Degs F
Fuel Pressure	262.42	Psia	T1	1210.4	Degs F
Chamber Pressure	191.43	Psia	T2	1267.0	Degs F
Alt. Pressure	124.09	Mtorr	T3	1926.1	Degs F
E ht.	50.981	Volts	T4	1759.3	Degs F
I ht.	12.463	Amps	T5	1767.3	Degs F
Ht. Power	635.366	Watts	T6	232.6	Degs F
Ht. Resistance	4.09057	Ohms			
Ht Temperature	4113.06	Degs F	CD	0.00000	
P/Mdot	4.61124	MJ/Kg	Cf	1.36476	
Gas Temperature	0.0	Degs.	C*	7429.8	Ft/Sec
PSP	6.63680		Reynolds#	0	
ISP	315.2	Secs.			

Remarks
End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 01-22-1990 09:3

SEQ

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-07 Sample Number 25

Parameter	Data	Units	Parameter	Data	U
Flow	1.0201	Lbm/Hr	Tc	1235.2	D
Thrust (meas)	88.701	MlbF	Tv	141.0	D
Thrust (corr)	88.701	MlbF	Tf	70.2	D
Fuel Pressure	240.36	Psia	T1	1205.4	D
Chamber Pressure	179.10	Psia	T2	1262.1	D
Alt. Pressure	117.42	Mtorr	T3	1929.0	D
E ht.	49.285	Volts	T4	1773.4	D
I ht.	12.052	Amps	T5	1770.7	D
Ht. Power	593.986	Watts	T6	234.9	D
Ht. Resistance	4.08934	Ohms			
Ht Temperature	4111.80	Degs F	CD	0.00000	
P/Mdot	4.62131	MJ/Kg	Cf	1.35411	
Gas Temperature	0.0	Degs.	C*	7451.6	F
FSP	6.68392		Reynolds#	0	
ISP	313.6	Secs.			

Remarks ______________________________

End of run Data ______________________________

OLIN/ROCKET RESEARCH CO. DATE: 01-22-1990 10:04:11

CONTRACT NUMBER 121587-4330 SEQ41

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-07 Sample Number 30

Parameter	Data	Units	Parameter	Data	Units
Flow	0.9529	Lbm/Hr	Tc	1239.7	Degs F
Thrust (meas)	82.637	MlbF	Tv	143.9	Degs F
Thrust (corr)	82.637	MlbF	Tf	71.2	Degs F
Fuel Pressure	221.28	Psia	T1	1197.7	Degs F
Chamber Pressure	168.00	Psia	T2	1253.8	Degs F
Alt. Pressure	112.33	Mtorr	T3	1934.9	Degs F
E ht.	47.769	Volts	T4	1788.9	Degs F
I ht.	11.659	Amps	T5	1776.3	Degs F
Ht. Power	556.928	Watts	T6	231.0	Degs F
Ht. Resistance	4.09733	Ohms			
Ht Temperature	4120.01	Degs F	CD	0.00000	
P/Mdot	4.63878	MJ/Kg	Cf	1.34494	
Gas Temperature	0.0	Degs.	C*	7483.1	Ft/Sec
PSP	6.72652		Reynolds#	0	
ISP	312.9	Secs.			

Remarks ______________________________

End of run Data ______________________________

OLIN/ROCKET RESEARCH CO. DATE: 01-22-1990 10:36

CONTRACT NUMBER 121587-4330 SEQ.

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-07 Sample Number 36

Parameter	Data	Units	Parameter	Data	Un
Flow	0.8983	Lbm/Hr	Tc	1220.6	De
Thrust (meas)	76.920	MlbF	Tv	146.3	De
Thrust (corr)	76.920	MlbF	Tf	72.2	De
Fuel Pressure	206.71	Psia	T1	1191.5	De
Chamber Pressure	159.53	Psia	T2	1247.8	De
Alt. Pressure	108.56	Mtorr	T3	1934.5	De
E ht.	46.313	Volts	T4	1797.8	De
I ht.	11.327	Amps	T5	1777.6	De
Ht. Power	524.574	Watts	T6	228.8	De
Ht. Resistance	4.08880	Ohms			
Ht Temperature	4111.24	Degs F	CD	0.00000	
P/Mdot	4.63452	MJ/Kg	Cf	1.31843	
Gas Temperature	0.0	Degs.	C*	7537.4	Ft
PSP	6.80610		Reynolds#	0	
ISP	308.9	Secs.			

Remarks

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 01-30-1990 09:53:50

CONTRACT NUMBER 121587-4330

SEQ 43

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-08 Sample Number 10

Parameter	Data	Units	Parameter	Data	Units
Flow	1.1888	Lbm/Hr	Tc	1259.9	Degs F
Thrust (meas)	105.293	MlbF	Tv	131.0	Degs F
Thrust (corr)	105.293	MlbF	Tf	66.7	Degs F
Fuel Pressure	298.66	Psia	T1	1220.4	Degs F
Chamber Pressure	213.69	Psia	T2	1277.1	Degs F
Alt. Pressure	134.58	Mtorr	T3	1960.9	Degs F
E ht.	54.813	Volts	T4	1772.4	Degs F
I ht.	13.078	Amps	T5	1795.1	Degs F
Ht. Power	716.827	Watts	T6	232.1	Degs F
Ht. Resistance	4.19141	Ohms			
Ht Temperature	4216.67	Degs F	CD	0.00000	
P/Mdot	4.78578	MJ/Kg	Cf	1.34710	
Gas Temperature	0.0	Degs.	C*	7629.5	Ft/Sec
PSP	6.79560		Reynolds#	0	
ISP	319.4	Secs.			

Remarks __________

End of run Data __________

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OLIN/ROCKET RESEARCH CO.                          DATE: 01-30-1990    10:41
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SEQ44

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CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

                   Run Number 102-08    Sample Number  16


Parameter            Data      Units      Parameter              Data     Un
---------------     --------  --------   ---------------       --------  --

Flow                 1.1040   Lbm/Hr     Tc                     1249.8   De

Thrust (meas)        97.084   MlbF       Tv                      138.1   De

Thrust (corr)        97.084   MlbF       Tf                       69.0   De

Fuel Pressure        272.71   Psia       T1                     1215.9   De

Chamber Pressure     200.41   Psia       T2                     1272.8   De

Alt. Pressure        124.57   Mtorr      T3                     1962.0   De

E ht.                52.569   Volts      T4                     1786.8   De

I ht.                12.572   Amps       T5                     1796.9   De

Ht. Power           660.923   Watts      T6                      238.6   De

Ht. Resistance      4.18130   Ohms

Ht Temperature      4206.29   Degs F     CD                    0.00000

P/Mdot              4.75117   MJ/Kg      Cf                    1.32439

Gas Temperature         0.0   Degs.      C*                     7704.5   Ft

PSP                 6.79536              Reynolds#                   0

ISP                   317.1   Secs.



Remarks ____________________________________________________________
End of run Data ____________________________________________________
```

OLIN/ROCKET RESEARCH CO. DATE: 01-30-1990 11:11:49

SEQ45

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-08 Sample Number 22

Parameter	Data	Units	Parameter	Data	Units
Flow	1.0258	Lbm/Hr	Tc	1238.5	Degs F
Thrust (meas)	89.797	MlbF	Tv	142.6	Degs F
Thrust (corr)	89.797	MlbF	Tf	70.4	Degs F
Fuel Pressure	250.66	Psia	T1	1208.2	Degs F
Chamber Pressure	188.65	Psia	T2	1264.8	Degs F
Alt. Pressure	117.71	Mtorr	T3	1971.3	Degs F
E ht.	50.965	Volts	T4	1806.2	Degs F
I ht.	12.143	Amps	T5	1804.5	Degs F
Ht. Power	618.844	Watts	T6	238.6	Degs F
Ht. Resistance	4.19716	Ohms			
Ht Temperature	4222.58	Degs F	CD	0.00000	
P/Mdot	4.78786	MJ/Kg	Cf	1.30138	
Gas Temperature	0.0	Degs.	C*	7805.4	Ft/Sec
PSP	6.87883		Reynolds#	0	
ISP	315.7	Secs.			

Remarks ______________________________

End of run Data ______________________________

OLIN/ROCKET RESEARCH CO. DATE: 01-30-1990 11:4

CONTRACT NUMBER 121587-4330

SEQ

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-08 Sample Number 28

Parameter	Data	Units	Parameter	Data	Ur
Flow	0.9574	Lbm/Hr	Tc	1227.3	De
Thrust (meas)	83.389	MlbF	Tv	146.0	De
Thrust (corr)	83.389	MlbF	Tf	71.4	De
Fuel Pressure	231.75	Psia	T1	1200.6	De
Chamber Pressure	177.67	Psia	T2	1256.7	De
Alt. Pressure	112.25	Mtorr	T3	1965.4	De
E ht.	48.996	Volts	T4	1812.6	De
I ht.	11.732	Amps	T5	1801.2	De
Ht. Power	574.815	Watts	T6	236.7	De
Ht. Resistance	4.17627	Ohms			
Ht Temperature	4201.12	Degs F	CD	0.00000	
P/Mdot	4.76507	MJ/Kg	Cf	1.28331	
Gas Temperature	0.0	Degs.	C*	7876.2	Ft
PSP	6.88005		Reynolds#	0	
ISP	314.2	Secs.			

Remarks ____________________

End of run Data ____________________

OLIN/ROCKET RESEARCH CO. DATE: 01-30-1990 12:56:47

CONTRACT NUMBER 121587-4330 SEQ47

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP ON MODIFIED ETT S/N 001

Run Number 102-08 Sample Number 34

Parameter	Data	Units	Parameter	Data	Units
Flow	0.8950	Lbm/Hr	Tc	1229.2	Degs F
Thrust (meas)	77.647	MlbF	Tv	146.1	Degs F
Thrust (corr)	77.647	MlbF	Tf	72.2	Degs F
Fuel Pressure	214.70	Psia	T1	1193.1	Degs F
Chamber Pressure	167.68	Psia	T2	1249.4	Degs F
Alt. Pressure	109.66	Mtorr	T3	1973.8	Degs F
E ht.	47.568	Volts	T4	1832.5	Degs F
I ht.	11.350	Amps	T5	1810.9	Degs F
Ht. Power	539.879	Watts	T6	219.4	Degs F
Ht. Resistance	4.19117	Ohms			
Ht Temperature	4216.43	Degs F	CD	0.00000	
P/Mdot	4.78756	MJ/Kg	Cf	1.26621	
Gas Temperature	0.0	Degs.	C*	7952.0	Ft/Sec
PSP	6.93911		Reynolds#	0	
ISP	313.0	Secs.			

Remarks

End of run Data

```
OLIN/ROCKET RESEARCH CO.                              DATE: 01-30-1990    13:30:
CONTRACT NUMBER 121587-4330
HI PERF. RESISTO-JET PERFORMANCE MAP   (Ver 1.00)
PERFORMANCE MAP ON MODIFIED ETT S/N 001
                       Run Number 102-0S    Sample Number   40

Parameter                 Data       Units       Parameter               Data      Uni
----------------        --------    --------     ----------------      --------    ---
Flow                      0.8399    Lbm/Hr       Tc                      1220.2    Deg
Thrust (meas)             72.379    MlbF         Tv                       149.7    Deg
Thrust (corr)             72.379    MlbF         Tf                        72.6    Deg
Fuel Pressure             199.63    Psia         T1                      1187.5    Deg
Chamber Pressure          158.16    Psia         T2                      1243.4    Deg
Alt. Pressure             105.90    Mtorr        T3                      1973.5    Deg
E ht.                     45.981    Volts        T4                      1644.5    Deg
I ht.                     10.982    Amps         T5                      1814.4    Deg
Ht. Power                504.969    Watts        T6                       226.5    Deg
Ht. Resistance           4.18683    Ohms
Ht Temperature           4211.97    Degs F       CD                     0.00000
P/Mdot                   4.77159    MJ/Kg        Cf                     1.25148
Gas Temperature              0.0    Degs.        C*                      7992.0    Ft
PSP                      6.96233                 Reynolds#                    0
ISP                        310.9    Secs.

Remarks. ____________________________________________________________
End of run Data _____________________________________________________
```

SEQ 4

OLIN/ROCKET RESEARCH CO. DATE: 01-31-1990 12:19:43

CONTRACT NUMBER 121587-4330 SEQ 1

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

HEALTH CHECK ON MODIFIED ETT S/N 001 AT START OF LIFE TEST

Run Number 103-01 Sample Number 8

Parameter	Data	Units	Parameter	Data	Units
Flow	1.4832	Lbm/Hr	Tc	1264.9	Degs F
Thrust (meas)	83.415	MlbF	Tv	118.2	Degs F
Thrust (corr)	83.415	MlbF	Tf	63.4	Degs F
Fuel Pressure	323.46	Psia	T1	1232.8	Degs F
Chamber Pressure	186.14	Psia	T2	1287.8	Degs F
Alt. Pressure	162.90	Mtorr	T3	1172.1	Degs F
E ht.	0.002	Volts	T4	1237.5	Degs F
I ht.	0.010	Amps	T5	1177.0	Degs F
Ht. Power	0.000	Watts	T6	174.8	Degs F
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.22635	
Gas Temperature	0.0	Degs.	C*	5326.4	Ft/Sec
PSP	0.00000		Reynolds#	0	
ISP	203.0	Secs.			

Remarks ______________________________

End of run Data ______________________________

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OLIN/ROCKET RESEARCH CO.                          DATE: 01-31-1990    13:03
CONTRACT NUMBER 121587-4330
HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)
HEALTH CHECK ON MODIFIED ETT S/N 001 AT START OF LIFE TEST
                    Run Number 103-01    Sample Number  16

Parameter           Data      Units     Parameter          Data      Un
---------------     -------   -------   ---------------    -------   --
Flow                1.2511    Lbm/Hr    Tc                  1266.0   De
Thrust (meas)       106.826   MlbF      Tv                   135.0   De
Thrust (corr)       106.826   MlbF      Tf                    68.0   De
Fuel Pressure        323.68   Psia      T1                  1229.7   De
Chamber Pressure     229.08   Psia      T2                  1286.2   De
Alt. Pressure        136.70   Mtorr     T3                  1845.2   De
E ht.                50.070   Volts     T4                  1675.7   De
I ht.                12.971   Amps      T5                  1706.4   De
Ht. Power           649.442   Watts     T6                   248.9   De
Ht. Resistance      3.86028   Ohms
Ht Temperature      3876.44   Degs F    CD                 0.00000
P/Mdot              4.11991   MJ/Kg     Cf                 1.27490
Gas Temperature         0.0   Degs.     C*                  7771.6   Ft
PSP                 6.06841             Reynolds#                0
ISP                   307.9   Secs.

Remarks ____________________________________________________________
End of run Data ____________________________________________________
```

SEQ :

```
OLIN/ROCKET RESEARCH CO.                    DATE: 01-31-1990    14:24:08

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP AN MODIFIED ETT S/N 001 AT 300 PSIA

                    Run Number 103-02    Sample Number  8


Parameter          Data      Units    Parameter          Data      Units
---------------    -------   -------  ---------------    -------   ------

Flow                1.1445   Lbm/Hr   Tc                  1263.1   Degs F

Thrust (meas)      100.743   MlbF     Tv                   141.2   Degs F

Thrust (corr)      100.743   MlbF     Tf                    70.7   Degs F

Fuel Pressure       298.65   Psia     T1                  1223.1   Degs F

Chamber Pressure    220.51   Psia     T2                  1277.9   Degs F

Alt. Pressure       126.41   Mtorr    T3                  1962.8   Degs F

E ht.               53.462   Volts    T4                  1779.9   Degs F

I ht.               12.780   Amps     T5                  1796.5   Degs F

Ht. Power          683.231   Watts    T6                   250.4   Degs F

Ht. Resistance     4.18338   Ohms

Ht Temperature     4208.42   Degs F   CD                 0.00000

P/Mdot             4.73778   MJ/Kg    Cf                 1.24898

Gas Temperature        0.0   Degs.    C*                  8177.3   Ft/Sec

PSP                6.76990            Reynolds#                0

ISP                  317.4   Secs.
```

SEQ3

Remarks ____

End of run Data ____

WORK SHEET

Date 4-9-9

Page

USING DRY ARGON + Hydrogen + Amonia

RUN #	SEQ#		Flow Lbs/hr		Heater Temp	
104-01	NO	DATA			°F	
104-02	1	DRY Argon	2.2944		3809	USING DRY ARGON ↓
104-02	2		2.3275		3904	
104-02	3		2.2892		4023	
104-02	4		2.3107		4117	
		4 –	10 –	90		
104-03	5		2.3108		4188	
104-03	6		2.2943		0	
10c		4 –	11 –	90		
104-04	7		2.6840		0	
		4 –	30 –	90		
104-05		NO	DATA			
104-06	8		.1306		3806	USING HYDROGEN ↓
104-07	9		.1342		3889	
104-07	10		.1316		4004	
104-07	11		.1302		4102	
		5 –	15 –	90		
104-08	12		.1304		4211	
104-08	13		.1306		4228	→ 3 min run only
104-09	14		.1244		4320	
104-09	15		.2602		4004	
		5 –	16 –	90		
104-10	16		.2587		4113	
104-10	17		.2623		4202	
		5 –	16 –	90		USING AMONIA ↓
104-11	18		.5119		3708	→ ≈ 20 min RUN time
104-11	19		.5030		3778	
104-11	20		.5030		3896	
		5 –	17 –	90		
104-12	21		.5005		4003	
104-12	22		.4980		4091	
104-12	23		.4967		4148	
105-1	1					UNAUGmented
	2					NG
105-2	3				4000	
105-2	4				4100	

OLIN/ROCKET RESEARCH CO. DATE: 04-09-1990 09:47:33

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING ARGON

Run Number 104-01 Sample Number 10

Parameter	Data	Units	Parameter	Data	Unit
Flow	2.3474	Lbm/Hr	Tc	67.7	Degs
Thrust (meas)	34.137	MlbF	Tv	65.9	Degs
Thrust (corr)	34.137	MlbF	Tf	69.3	Degs
Fuel Pressure	14.85	Psia	Ti	69.5	Degs
Chamber Pressure	82.00	Psia	T2	69.6	Degs
Alt. Pressure	71.93	Mtorr	T3	64.0	Degs
E ht.	-0.009	Volts	T4	66.1	Degs
I ht.	0.003	Amps	T5	66.7	Degs
Ht. Power	-0.000	Watts	T6	65.6	Degs
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.13742	
Gas Temperature	0.0	Degs.	C*	1482.7	Ft/S
PSP	-0.00000		Reynolds#	0	
ISP	52.5	Secs.			

Remarks

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OLIN/ROCKET RESEARCH CO.                          DATE: 04-09-1990   09:49:

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING ARGON

                    Run Number 104-01    Sample Number  12

Parameter           Data       Units     Parameter                Data      Un
---------------     -------    -------   ---------------          -------   --

Flow                2.6788     Lbm/Hr    Tc                       67.6      De

Thrust (meas)       39.685     MlbF      Tv                       65.5      De

Thrust (corr)       39.685     MlbF      Tf                       70.0      De

Fuel Pressure        14.67     Psia      T1                       69.5      De

Chamber Pressure     93.76     Psia      T2                       69.6      De

Alt. Pressure        77.18     Mtorr     T3                       63.9      De

E ht.               -0.010     Volts     T4                       66.4      De

I ht.               -0.002     Amps      T5                       66.7      De

Ht. Power            0.000     Watts     T6                       64.7      De

Ht. Resistance     0.00000     Ohms

Ht Temperature        0.00     Degs F    CD                    0.00000

P/Mdot             0.00000     MJ/Kg     Cf                    1.15823

Gas Temperature        0.0     Degs.     C*                     1465.6    Ft

FSP                0.00000               Reynolds#                   0

ISP                   53.5     Secs.



Remarks ____________________________________________________________
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OLIN/ROCKET RESEARCH CO.                                  DATE: 04-09-1990    10:58:0

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING DRY ARGON

                    Run Number 104-02    Sample Number   8


Parameter             Data      Units     Parameter           Data      Unit
----------------     -------   -------   ----------------    -------   ----

Flow                 2.2944    Lbm/Hr    Tc                     95.8   Degs
Thrust (meas)        78.418    MlbF      Tv                     75.0   Degs
Thrust (corr)        78.418    MlbF      Tf                     76.3   Degs
Fuel Pressure         14.49    Psia      T1                    126.1   Degs
Chamber Pressure     166.81    Psia      T2                    177.6   Degs
Alt. Pressure         71.14    Mtorr     T3                   1023.8   Degs
E ht.                28.813    Volts     T4                    954.8   Degs
I ht.                 7.592    Amps      T5                    521.4   Degs
Ht. Power           218.764    Watts     T6                    114.8   Degs
Ht. Resistance      3.79497    Ohms
Ht Temperature      3809.33    Degs F    CD                  0.00000
P/Mdot              0.75674    MJ/Kg     Cf                  1.28453
Gas Temperature         0.0    Degs.     C*                   3085.8   Ft/
PSP                 2.78613              Reynolds#                 0
ISP                   123.2    Secs.


Remarks      SEQ 1      @ 3800 °F      2.3 lbm/hr
End of run Data
```

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OLIN/ROCKET RESEARCH CO.                                DATE: 04-09-1990    11:5
CONTRACT NUMBER 121567-4330
HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)
PERFORMANCE MAP USING DRY ARGON
                          Run Number 104-02    Sample Number  19

Parameter               Data       Units      Parameter               Data     L
---------------       --------    --------   ---------------        --------   -
Flow                   2.3275     Lbm/Hr     Tc                       104.3    I
Thrust (meas)          80.318     MlbF       Tv                        89.3    I
Thrust (corr)          80.318     MlbF       Tf                        81.4    I
Fuel Pressure           14.49     Psia       T1                       133.4    I
Chamber Pressure       170.53     Psia       T2                       185.2    I
Alt. Pressure           71.31     Mtorr      T3                      1043.7    D
E ht.                  29.514     Volts      T4                       974.9    D
I ht.                   7.593     Amps       T5                       520.5    D
Ht. Power             224.098     Watts      T6                       136.2    D
Ht. Resistance        3.88705     Ohms
Ht Temperature        3903.94     Degs F     CD                     0.00000
P/Mdot                0.76415     MJ/Kg      Cf                     1.28696
Gas Temperature           0.0     Degs.      C*                      3109.6    F
PSP                   2.78664                Reynolds#                    0
ISP                     124.4     Secs.
```

Remarks SEQ 2 @ 3900 °F 2.3 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 04-09-1990 14:21:15

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING DRY ARGON

Run Number 104-02 Sample Number 29

Parameter	Data	Units	Parameter	Data	Units
Flow	2.2892	Lbm/Hr	Tc	103.4	Degs
Thrust (meas)	79.996	MlbF	Tv	86.9	Degs
Thrust (corr)	79.996	MlbF	Tf	79.7	Degs
Fuel Pressure	14.47	Psia	T1	133.9	Degs
Chamber Pressure	170.37	Psia	T2	188.0	Degs
Alt. Pressure	71.01	Mtorr	T3	1069.6	Degs
E ht.	30.098	Volts	T4	1002.8	Degs
I ht.	7.518	Amps	T5	498.4	Degs
Ht. Power	226.289	Watts	T6	132.9	Degs
Ht. Resistance	4.00324	Ohms			
Ht Temperature	4023.33	Degs F	CD	0.00000	
P/Mdot	0.78454	MJ/Kg	Cf	1.28297	
Gas Temperature	0.0	Degs.	C*	3158.8	Ft/S
PSP	2.82519		Reynolds#	0	
ISP	126.0	Secs.			

Remarks SEQ 3 @ 4000 °F 2.3 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 04-09-1990 15:08

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING DRY ARGON

Run Number 104-02 Sample Number 39

Parameter	Data	Units	Parameter	Data	Un
Flow	2.3107	Lbm/Hr	Tc	108.9	De
Thrust (meas)	80.638	MlbF	Tv	95.2	De
Thrust (corr)	80.638	MlbF	Tf	83.6	De
Fuel Pressure	14.48	Psia	T1	139.4	De
Chamber Pressure	172.47	Psia	T2	194.3	De
Alt. Pressure	70.05	Mtorr	T3	1088.7	De
E ht.	30.689	Volts	T4	1023.5	De
I ht.	7.495	Amps	T5	534.9	De
Ht. Power	230.025	Watts	T6	141.2	De
Ht. Resistance	4.09435	Ohms			
Ht Temperature	4116.94	Degs F	CD	0.00000	
P/Mdot	0.79009	MJ/Kg	Cf	1.27749	
Gas Temperature	0.0	Degs.	C*	3168.0	Ft
PSP	2.84907		Reynolds#	0	
ISP	125.8	Secs.			

Remarks SEQ 4 @ 4100 °F 2.3 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 04-10-1990 13:13:47

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING DRY ARGON

Run Number 104-03 Sample Number 39

Parameter	Data	Units	Parameter	Data	Units
Flow	2.3108	Lbm/Hr	Tc	109.5	Degs
Thrust (meas)	78.800	MlbF	Tv	100.1	Degs
Thrust (corr)	78.800	MlbF	Tf	87.6	Degs
Fuel Pressure	14.00	Psia	Ti	135.4	Degs
Chamber Pressure	167.91	Psia	T2	181.6	Degs
Alt. Pressure	68.70	Mtorr	T3	963.5	Degs
E ht.	29.837	Volts	T4	899.9	Degs
I ht.	7.166	Amps	T5	482.0	Degs
Ht. Power	213.813	Watts	T6	139.2	Degs
Ht. Resistance	4.16377	Ohms			
Ht Temperature	4188.27	Degs F	CD	0.00000	
P/Mdot	0.73435	MJ/Kg	Cf	1.28229	
Gas Temperature	0.0	Degs.	C*	3084.0	Ft/Se
PSP	2.71001		Reynolds#	0	
ISP	122.9	Secs.			

Remarks SEQ 5 @ 4200 °F 2.3 lbm/hr
End of run Data

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OLIN/ROCKET RESEARCH CO.                               DATE: 04-10-1990    14:5

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING DRY ARGON

                          Run Number 104-03    Sample Number  45


Parameter                Data        Units       Parameter                Data      U
---------------          --------    --------    ---------------          --------  --

Flow                       2.2943    Lbm/Hr      Tc                          78.8   D

Thrust (meas)             33.424     MlbF        Tv                          80.5   D

Thrust (corr)             33.424     MlbF        Tf                          79.4   D

Fuel Pressure             13.91      Psia        T1                          80.4   D

Chamber Pressure          82.25      Psia        T2                          80.4   D

Alt. Pressure             67.10      Mtorr       T3                          74.6   D

E ht.                     -0.016     Volts       T4                          76.9   D

I ht.                      0.002     Amps        T5                          77.4   D

Ht. Power                 -0.000     Watts       T6                          77.2   D

Ht. Resistance           0.00000     Ohms

Ht Temperature              0.00     Degs F      CD                       0.00000

P/Mdot                   0.00000     MJ/Kg       Cf                       1.11209

Gas Temperature              0.0     Degs.       C*                        1521.6   F

PSP                     -0.00000                 Reynolds#                      0

ISP                         52.6     Secs.
```

Remarks ______ SEQ 6 ______ Unaugmented
End of run Data ______

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OLIN/ROCKET RESEARCH CO. DATE: 04-11-1990 09:08:33

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING DRY AARGON

Run Number 104-04 Sample Number 4

Parameter	Data	Units	Parameter	Data	Units
Flow	2.6840	Lbm/Hr	Tc	70.9	Degs F
Thrust (meas)	39.266	MlbF	Tv	70.5	Degs F
Thrust (corr)	39.266	MlbF	Tf	71.0	Degs F
Fuel Pressure	14.64	Psia	T1	73.0	Degs F
Chamber Pressure	94.68	Psia	T2	72.9	Degs F
Alt. Pressure	74.57	Mtorr	T3	67.4	Degs F
E ht.	-0.014	Volts	T4	69.9	Degs F
I ht.	0.002	Amps	T5	71.1	Degs F
Ht. Power	-0.000	Watts	T6	69.7	Degs F
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	1.13479	
Gas Temperature	0.0	Degs.	C*	1497.2	Ft/Sec
PSP	-0.00000		Reynolds#	0	
ISP	52.3	Secs.			

Remarks SEQ 7 Unaugmented

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 04-30-1990 13:21:

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP WITH DRY HYDROGEN

Run Number 104-05 Sample Number 8

Parameter	Data	Units	Parameter	Data	Un
Flow	0.1326	Lbm/Hr	Tc	69.0	De
Thrust (meas)	6.489	MlbF	Tv	67.4	De
Thrust (corr)	6.489	MlbF	Tf	68.4	De
Fuel Pressure	14.57	Psia	T1	71.5	De
Chamber Pressure	22.93	Psia	T2	71.1	De
Alt. Pressure	101.71	Mtorr	T3	62.1	De
E ht.	0.000	Volts	T4	66.9	De
I ht.	0.019	Amps	T5	68.6	De
Ht. Power	0.000	Watts	T6	66.2	De
Ht. Resistance	0.00000	Ohms			
Ht Temperature	0.00	Degs F	CD	0.00000	
P/Mdot	0.00000	MJ/Kg	Cf	0.78962	
Gas Temperature	0.0	Degs.	C*	7336.6	Ft
PSP	0.00000		Reynolds#	0	
ISP	180.1	Secs.			

Remarks Unaugmented

This is not EOR Data

OLIN/ROCKET RESEARCH CO. DATE: 04-30-1990 15:40:03

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-06 Sample Number 17

Parameter	Data	Units	Parameter	Data	Units
Flow	0.1306	Lbm/Hr	Tc	83.5	Degs F
Thrust (meas)	16.599	MlbF	Tv	85.1	Degs F
Thrust (corr)	16.599	MlbF	Tf	80.2	Degs F
Fuel Pressure	14.73	Psia	T1	85.6	Degs F
Chamber Pressure	39.51	Psia	T2	90.7	Degs F
Alt. Pressure	95.90	Mtorr	T3	342.6	Degs F
E ht.	27.155	Volts	T4	472.8	Degs F
I ht.	8.219	Amps	T5	258.1	Degs F
Ht. Power	223.189	Watts	T6	101.8	Degs F
Ht. Resistance	3.30393	Ohms			
Ht Temperature	3805.79	Degs F	CD	0.00000	
F/Mdot	13.56237	MJ/Kg	Cf	1.15605	
Gas Temperature	0.0	Degs.	C*	12840.9	Ft/Sec
PSP	13.33337		Reynolds#	0	
ISP	461.4	Secs.			

Remarks SEQ 8 @ 3800°F .13 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 25-01-1990 06:56

CONTRACT NUMBER 121537-4332

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMAANCE MAP USING HYDROGEN

Run Number 104-07 Sample Number 17

Parameter	Data	Units	Parameter	Data	Un
Flow	0.1342	Lbm/Hr	Tc	80.1	De
Thrust (meas)	17.443	MlbF	Tv	82.5	De
Thrust (corr)	17.443	MlbF	Tf	75.9	De
Fuel Pressure	14.35	Psia	T1	80.0	De
Chamber Pressure	40.17	Psia	T2	87.1	De
Alt. Pressure	113.41	Mtorr	T3	555.9	De
E ht.	27.753	Volts	T4	484.0	De
I ht.	8.234	Amps	T5	272.1	De
Ht. Power	231.582	Watts	T6	99.9	De
Ht. Resistance	3.37452	Ohms			
Ht Temperature	3889.32	Degs F	CD	0.00000	
P/Mdot	13.69296	MJ/Kg	Cf	1.19542	
Gas Temperature	0.0	Degs.	C*	12709.0	Ft
PSP	13.15333		Reynolds#	0	
ISP	472.2	Secs.			

Remarks SEQ 9 @ 3900°F .13 lbm/hr

End of run Data

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OLIN/ROCKET RESEARCH CO.                        DATE: 05-01-1990    10:27:22

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMAANCE MAP USING HYDROGEN

                  Run Number 104-07    Sample Number  32


Parameter           Data      Units     Parameter            Data     Units
---------------   --------   -------   ---------------    --------   -------

Flow                0.1316   Lbm/Hr    Tc                     82.9   Degs F

Thrust (meas)       17.179   MlbF      Tv                     86.0   Degs F

Thrust (corr)       17.179   MlbF      Tf                     73.1   Degs F

Fuel Pressure        14.01   Psia      T1                     84.9   Degs F

Chamber Pressure     40.00   Psia      T2                     90.7   Degs F

Alt. Pressure       110.93   Mtorr     T3                    594.8   Degs F

E ht.               28.573   Volts     T4                    524.0   Degs F

I ht.                8.230   Amps      T5                    293.6   Degs F

Ht. Power          235.156   Watts     T6                    103.7   Degs F

Ht. Resistance     3.47170   Ohms

Ht Temperature     4004.31   Degs F    CD                  0.00000

P/Mdot            14.17700   MJ/Kg     Cf                  1.18270

Gas Temperature        0.0   Degs.     C*                  12896.4   Ft/Sec

PSP               13.56470             Reynolds#                 0

ISP                  474.1   Secs.
```

Remarks SEQ 10 @ 4000°F .13 lbm/hr
End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 05-01-1990 11:4

CONTRACT NUMBER 121597-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMAANCE MAP USING HYDROGEN

Run Number 104-07 Sample Number 47

Parameter	Data	Units	Parameter	Data	U
Flow	0.1302	Lbm/Hr	Tc	85.3	D
Thrust (meas)	17.265	MlbF	Tv	88.9	D
Thrust (corr)	17.265	MlbF	Tf	79.8	D
Fuel Pressure	13.99	Psia	T1	87.4	D
Chamber Pressure	40.13	Psia	T2	93.8	D
Alt. Pressure	109.57	Mtorr	T3	629.6	D
E ht.	29.193	Volts	T4	559.4	D
I ht.	8.214	Amps	T5	305.2	D
Ht. Power	239.784	Watts	T6	107.2	D
Ht. Resistance	3.55425	Ohms			
Ht Temperature	4102.00	Degs F	CD	0.00000	
P/Mdot	14.61624	MJ/Kg	Cf	1.18472	
Gas Temperature	.0.0	Degs.	C*	13080.5	F
PSP	13.76468		Reynolds#	0	
ISP	481.7	Secs.			

Remarks SEQ 11 @ 4100°F .13 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 05-15-1990 09:39:59

CONTRACT NUMBER 101557-4730

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-08 Sample Number 28

Parameter	Data	Units	Parameter	Data	Units
Flow	0.1304	Lbm/Hr	Tc	86.9	Degs F
Thrust (meas)	17.593	MlbF	Tv	91.0	Degs F
Thrust (corr)	17.593	MlbF	Tf	81.6	Degs F
Fuel Pressure	14.91	Psia	T1	88.8	Degs F
Chamber Pressure	41.41	Psia	T2	95.1	Degs F
Alt. Pressure	104.32	Mtorr	T3	652.9	Degs F
E ht.	30.371	Volts	T4	579.7	Degs F
I ht.	8.329	Amps	T5	315.1	Degs F
Ht. Power	252.963	Watts	T6	109.2	Degs F
Ht. Resistance	3.64649	Ohms			
Ht Temperature	4211.12	Degs F	CD	0.00000	
P/Mdot	15.39560	MJ/Kg	Cf	1.16924	
Gas Temperature	0.0	Degs.	C*	13476.7	Ft/Sec
PSP	14.25878		Reynolds#	0	
ISP	489.8	Secs.			

Remarks SEQ 12 @ 4200°F .13 lbm/hr

End of run Data

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OLIN/ROCKET RESEARCH CO.                         DATE: 05-15-1990     10:10

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

                    Run Number 104-03     Sample Number  30


Parameter            Data        Units      Parameter            Data     Un
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Flow                   0.1306     Lbm/Hr     Tc                      85.7  De

Thrust (meas)          17.461     MlbF       Tv                      85.4  De

Thrust (corr)          17.461     MlbF       Tf                      78.2  De

Fuel Pressure           14.72     Psia       T1                      86.4  De

Chamber Pressure        41.31     Psia       T2                      90.9  De

Alt. Pressure          104.57     Mtorr      T3                     610.0  De

E ht.                  30.778     Volts      T4                     530.6  De

I ht.                   8.406     Amps       T5                     220.7  De

Ht. Power             258.719     Watts      T6                      95.5  De

Ht. Resistance        3.66133     Ohms

Ht Temperature        4228.70     Degs F     CD                   0.00000

P/Mdot               15.72593     MJ/Kg      Cf                   1.16319

Gas Temperature           0.0     Degs.      C*                   13429.2  Ft

PSP                  14.69215                Reynolds#                  0

ISP                     485.5     Secs.
```

Remarks SEQ 13 @ 4300 °F .13 lbm/hr

End of run Data

(only 3 min)

OLIN/ROCKET RESEARCH CO. DATE: 05-15-1990 11:49:57

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-09 Sample Number 17

Parameter	Data	Units	Parameter	Data	Units
Flow	0.1294	Lbm/Hr	Tc	87.0	Degs F
Thrust (meas)	17.229	M1bF	Tv	91.3	Degs F
Thrust (corr)	17.229	M1bF	Tf	81.1	Degs F
Fuel Pressure	14.61	Psia	T1	89.2	Degs F
Chamber Pressure	41.25	Psia	T2	96.3	Degs F
Alt. Pressure	104.29	Mtorr	T3	695.0	Degs F
E ht.	30.993	Volts	T4	623.6	Degs F
I ht.	8.291	Amps	T5	339.2	Degs F
Ht. Power	256.947	Watts	T6	112.6	Degs F
Ht. Resistance	3.73835	Ohms			
Ht Temperature	4319.83	Degs F	CD	0.00000	
P/Mdot	15.75588	MJ/Kg	Cf	1.14966	
Gas Temperature	0.0	Degs.	C*	13526.1	Ft/Sec
PSP	14.78669		Reynolds#	0	
ISP	483.3	Secs.			

Remarks SEQ 14 @ 4300°F .13 lbm/hr

End of run Data

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OLIN/ROCKET RESEARCH CO. DATE: 05-15-1990 14:49:

CONTRACT NUMBER 121597-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-09 Sample Number 33

Parameter	Data	Units	Parameter	Data	Uni
Flow	0.2602	Lbm/Hr	Tc	90.3	Deg
Thrust (meas)	37.842	MlbF	Tv	102.1	Deg
Thrust (corr)	37.842	MlbF	Tf	82.0	Deg
Fuel Pressure	14.58	Psia	T1	86.6	Deg
Chamber Pressure	31.63	Psia	T2	87.3	Deg
Alt. Pressure	195.44	Mtorr	T3	505.9	Deg
E ht.	42.604	Volts	T4	351.7	De
I ht.	12.272	Amps	T5	266.5	De
Ht. Power	522.853	Watts	T6	132.0	De
Ht. Resistance	3.47149	Ohms			
Ht Temperature	4204.06	Degs F	CD	0.00000	
P/Mdot	15.95069	MJ/Kg	Cf	1.27074	
Gas Temperature	0.0	Degs.	C*	13350.4	Ft
PSP	13.72147		Reynolds#	0	
ISP	527.3	Secs.			

Remarks SEQ 15 @ 4000 °F .26 lbm/hr

End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 05-16-1990 08:17:37

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-10 Sample Number 16

Parameter	Data	Units	Parameter	Data	Units
Flow	0.2587	Lbm/Hr	Tc	85.1	Degs F
Thrust (meas)	38.293	MlbF	Tv	96.1	Degs F
Thrust (corr)	38.295	MlbF	Tf	77.0	Degs F
Fuel Pressure	14.62	Psia	T1	81.6	Degs F
Chamber Pressure	81.88	Psia	T2	82.4	Degs F
Alt. Pressure	190.80	Mtorr	T3	516.6	Degs F
E ht.	43.563	Volts	T4	361.0	Degs F
I ht.	12.226	Amps	T5	271.4	Degs F
Ht. Power	502.672	Watts	T6	126.5	Degs F
Ht. Resistance	3.56356	Ohms			
Ht Temperature	4113.01	Degs F	CD	0.20000	
P/Mdot	16.34495	MJ/Kg	Cf	1.28534	
Gas Temperature	0.0	Degs.	C*	13436.2	Ft/Sec
PSP	13.81218		Reynolds#	0	
ISP	536.8	Secs.			

Remarks SEQ 16 @ 4100 °F .26 Lbm/hr
End of run Data

OLIN/ROCKET RESEARCH CO. DATE: 05-16-1990 09:33:

CONTRACT NUMBER 121557-4332

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING HYDROGEN

Run Number 104-10 Sample Number 32

Parameter	Data	Units	Parameter	Data	Uni
Flow	0.2623	Lbm/Hr	Tc	89.8	Deg
Thrust (meas)	38.799	MlbF	Tv	103.2	Deg
Thrust (corr)	38.799	MlbF	Tf	80.9	Deg
Fuel Pressure	14.65	Psia	T1	95.8	Deg
Chamber Pressure	83.59	Psia	T2	66.7	Deg
Alt. Pressure	183.11	Mtorr	T3	535.0	Deg
E ht.	44.809	Volts	T4	376.5	Deg
I ht.	12.313	Amps	T5	286.3	Deg
Ht. Power	551.735	Watts	T6	133.5	De
Ht. Resistance	3.63915	Ohms			
Ht Temperature	4202.45	Degs F	CD	0.00000	
P/Mdot	16.69486	MJ/Kg	Cf	1.27523	
Gas Temperature	0.0	Degs.	C*	13525.4	Ft
FSP	14.12593		Reynolds#	0	
ISP	536.1	Secs.			

Remarks SEQ 17 @ 4200 °F .26 lbm/

End of run Data

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OLIN/ROCKET RESEARCH CO.
                                                        DATE: 05-16-1990     11:21:56
CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.02)

PERFORMANCE MAP USING AMONIA

                         Run Number 104-11     Sample Number  10

Parameter                Data       Units      Parameter              Data       Units
-----------------        -------    -------    -------------------    -------    --------
Flow                     0.5119     Lbm/Hr     Tc                        89.1    Degs F
Thrust (meas)            34.905     MlbF       Tv                        84.7    Degs F
Thrust (corr)            34.905     MlbF       Tf                        77.1    Degs F
Fuel Pressure             14.71     Psia       T1                       104.2    Degs F
Chamber Pressure          66.26     Psia       T2                       127.3    Degs F
Alt. Pressure             39.65     Mtorr      T3                       657.6    Degs F
E Ht.                    32.456     Volts      T4                       581.7    Degs F
I Ht.                     9.432     Amps       T5                       349.8    Degs F
Ht. Power               297.888     Watts      T6                       113.5    Degs F
Ht. Resistance          3.22207     Ohms
Ht Temperature          3708.94     Degs F     CD                     0.00000
P/Mdot                  4.46321     MJ/Kg      Cf                     1.44278
Gas Temperature             0.0     Degs.      C*                      5493.7    Ft/Sec
PSP                     8.21782                Reynolds#                    0
ISP                       246.4     Secs.
```

Remarks SEQ 18 @ 3800°F .50 lbm/hr

End of run Data

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OLIN/ROCKET RESEARCH CO.
                                                        DATE: 05-16-1990    12:46:
CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING AMONIA

                   Run Number 104-11     Sample Number  25

Parameter                Data      Units      Parameter              Data      Uni
----------------       --------   --------    ----------------     --------   ----
Flow                    0.5030    Lbm/Hr      Tc                       95.3   Degs
Thrust (meas)           33.564    MlbF        Tv                       93.4   Degs
Thrust (corr)           33.564    MlbF        Tf                       80.4   Degs
Fuel Pressure            14.70    Psia        T1                      109.5   Degs
Chamber Pressure         64.50    Psia        T2                      136.0   Degs
Alt. Pressure            96.80    Mtorr       T3                      689.4   Degs
E ht.                   30.371    Volts       T4                      617.3   Degs
  ht.                    9.258    Amps        T5                      373.6   Degs
Ht. Power              281.178    Watts       T6                      124.2   Degs
Ht. Resistance         3.28743    Ohms
Ht Temperature         3777.99    Degs F      CD                    0.00000
P/Mdot                 4.43663    MJ/Kg       Cf                    1.42529
Gas Temperature            0.0    Degs.       C*                     5442.6   Ft/Se
PSP                    8.34670                Reynolds#                   0
ISP                      241.1    Secs.

Remarks      RUN 104-11      SEQ 19   @   3800 °F          .50 lbm/h
End of run Data ________________________________________________________________
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OLIN/ROCKET RESEARCH CO. DATE: 05-16-1990 13:57:51

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING AMONIA

Run Number 104-11 Sample Number 40

Parameter	Data	Units	Parameter	Data	Units
Flow	0.5030	Lbm/Hr	Tc	98.6	Degs F
Thrust (meas)	33.402	MlbF	Tv	96.6	Degs F
Thrust (corr)	33.402	MlbF	Tf	82.3	Degs F
Fuel Pressure	14.73	Psia	T1	113.5	Degs F
Chamber Pressure	64.48	Psia	T2	142.2	Degs F
Alt. Pressure	85.81	Mtorr	T3	719.9	Degs F
E ht.	31.116	Volts	T4	650.1	Degs F
ht.	9.206	Amps	T5	384.6	Degs F
t. Power	286.443	Watts	T6	127.2	Degs F
Ht. Resistance	3.38001	Ohms			
Ht Temperature	3895.82	Degs F	CD	0.00000	
/Mdot	4.51967	MJ/Kg	Cf	1.41882	
as Temperature	0.0	Degs.	C*	5440.8	Ft/Sec
SP	8.54462		Reynolds#	0	
SP	239.9	Secs.			

emarks SEQ 20 @ 3900°F .50 lbm/hr

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OLIN/ROCKET RESEARCH CO. DATE: 05-17-1990 08:34

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING AMONIA

Run Number 104-12 Sample Number 17

Parameter	Data	Units	Parameter	Data	Un
Flow	0.5005	Lbm/Hr	Tc	90.8	De
Thrust (meas)	33.526	MlbF	Tv	87.5	De
Thrust (corr)	33.526	MlbF	Tf	75.0	De
Fuel Pressure	14.72	Psia	T1	106.9	De
Chamber Pressure	65.21	Psia	T2	137.5	De
Alt. Pressure	89.35	Mtorr	T3	743.4	De
E ht.	31.978	Volts	T4	674.6	De
I ht.	9.214	Amps	T5	402.0	De
Ht. Power	294.627	Watts	T6	121.6	De
Ht. Resistance	3.47073	Ohms			
Ht Temperature	4003.16	Degs F	CD	0.00000	
P/Mdot	4.67183	MJ/Kg	Cf	1.40841	
Gas Temperature	0.0	Degs.	C*	5529.4.	Ft/
FSP	8.75497		Reynolds#	0	
ISP	242.0	Secs.			

Remarks SEQ 21 @ 4000 °F .50 lbm/hr

End of run Data

ORIGINAL PAGE IS OF POOR QUALITY

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OLIN/ROCKET RESEARCH CO.                          DATE: 05-17-1992    09:48:47

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP  (Ver 1.00)

PERFORMANCE MAP USING AMONIA

                     Run Number 104-12     Sample Number  32


Parameter               Data       Units      Parameter             Data       Units
----------------      --------   --------   ----------------      --------   --------

Flow                    0.4980   Lbm/Hr      Tc                      94.8    Degs F

Thrust (meas)           34.734   MlbF        Tv                      92.7    Degs F

Thrust (corr)           34.734   MlbF        Tf                      77.7    Degs F

Fuel Pressure            14.73   Psia        T1                     110.8    Degs F

Chamber Pressure         67.08   Psia        T2                     141.5    Degs F

Alt. Pressure            59.37   Mtorr       T3                     763.3    Degs F

E ht.                   33.231   Volts       T4                     692.8    Degs F

I ht.                    9.316   Amps        T5                     404.9    Degs F

Ht. Power              307.729   Watts       T6                     125.8    Degs F

Ht. Resistance         3.54555   Ohms

Ht Temperature         4091.70   Degs F      CD                   0.00000

P/Mdot                 4.90406   MJ/Kg       Cf                   1.41825

Gas Temperature            0.0   Degs.       C*                    5716.5    Ft/Sec

PSP                    8.82758               Reynolds#                  0

ISP                      252.0   Secs.
```

Remarks SEQ 22 @ 4100 °F .50lbm/hr

End of run Date

OLIN/ROCKET RESEARCH CO. DATE: 05-17-1992 11:

CONTRACT NUMBER 121587-4330

HI PERF. RESISTO-JET PERFORMANCE MAP (Ver 1.00)

PERFORMANCE MAP USING AMONIA

Run Number 104-12 Sample Number 48

Parameter	Data	Units	Parameter	Data	L
Flow	0.4967	Lbm/Hr	Tc	96.1	D
Thrust (meas)	35.170	MlbF	Tv	94.0	D
Thrust (corr)	35.170	MlbF	Tf	78.3	D
Fuel Pressure	14.74	Psia	T1	112.7	D
Chamber Pressure	68.08	Psia	T2	144.7	D
Alt. Pressure	39.39	Mtorr	T3	791.4	D
E ht.	33.964	Volts	T4	721.4	D
I ht.	9.343	Amps	T5	427.1	D
Ht. Power	317.315	Watts	T6	128.3	D
Ht. Resistance	3.63526	Ohms			
Ht Temperature	4197.85	Degs F	CD	0.00000	
P/Mdot	5.06982	MJ/Kg	Cf	1.41498	
Gas Temperature	0.0	Degs.	C*	5816.5	F
PSP	8.98986		Reynolds#	0	
ISP	255.8	Secs.			

Remarks SEQ 23 @ 4200 °F .50 lbm/h

End of run Data

APPENDIX F

Immersed Heater Injector Redesign

Applied Technology Division
TRW Space & Technology Group

One Space Park
Redondo Beach, CA 90278
213.535.4321

Mail Station: 01/2260

89.K536.1-051
12 July 1989

Mr. Mark Simon
Rocket Research Company
11441 Willows Rd. N.E.
Redmond, WA 98073 - 9709

Dear Mark:

The long-awaited heat exchanger analysis report has finally emerged and I am enclosing a copy for your reading pleasure. I have requested additional copies with color reproduction of figures and will supply one to NASA-Lewis as soon as available.

Sincerely,

Rein

Rein Grabbi

Enclosures (30)

Interoffice Correspondence
TRW Space & Technology Group
TRW

Subject
Recommendations for
Increasing the ISP of the
HiPEHT Thruster

Date
July 11, 1989
89.K314.3-017

From
J. E. Eninger
P. D. Lohn
E. Y. Wong

To
Rein Grabbi

cc
H. W. Behrens
D. E. Fritz
R. L. Sackheim

Location/Phone
R1/1038
Ext. 20478

1. BACKGROUND AND SUMMARY

We were asked to make recommendations for design modifications to the HiPEHT thruster for increasing the specific impulse. The ground rules were to focus on increasing the heat transfer between the electrical heater coil and the gas. Also, it is beyond the scope of the task to consider any changes in the design of the heating coil itself.

The first step was to review the thermodynamics, heat transfer, and gasdynamics of the current thruster design. The results are presented in Section 2. An estimate was made of the potential for increasing specific impulse by enhancing the heat-transfer coefficient between the heater coil and the gas, and by operating the coil at a higher temperature. The estimate shows, for example, that for the mass flow rate of 3×10^{-4} lb/s and for the filament temperature maintained at the operating temperature of 3700°F, a doubling of the heat-transfer coefficient would increase the specific impulse from the current measured value of 306 seconds to 328 seconds. If, in addition, the filament temperature can be increased to 5000°F, then the potential specific impulse is estimated to be 380 seconds. Although 5000°F is probably above the practical operating temperature for the coil (tungsten deposits were observed in the nozzle throat after tests at this temperature), the calculations serve as an upper bound for the specific impulse that can be expected.

The nature of the flow in the heating section has a major effect on the heat transfer from the coil. For efficient heat transfer, one wants:

1) a high gas velocity over the coil,
2) good mixing so all the gas is uniformly processed by the coil,
3) small-scale disturbances in the main flow[1], and
4) minimum radial flow at the ends of the chamber that allows gas to leave unheated.

Internal rotating flows are complicated and difficult to predict. It is often advisable to evaluate candidate designs with a flow-simulation experiment. Such an experiment, however, is beyond the scope of the present task. Insight into the features of the flow was obtained from visualization experiments of similar flows reported in the literature. The understanding obtained from the body of past work was crucial in formulating our recommendations. A critical review of the rotational-flow literature pertaining to the current situation is presented in Section 3. References cited include a videotape of classic flow-visualization experiments of rotational flows. A copy in VHS format is included as part of this memorandum.

---

[1] "It should be noted that, if the turbulence level in the oncoming air is increased by placing a grid or some other type of turbulence promoter upstream of the cylinder, the surface conductance may increase by as much as 50 percent."

- Frank Krieth, Reference 1

It is challenging to recommend improvements in the current design, which works well and is the result of much excellent engineering development at TRW. Recent improvements in the mechanical support of the heating coil, however, should allow it to withstand more severe flow-field forces at higher operating temperatures. This will allow more heat to be transferred to the gas.

Our recommendation concerns the method by which momentum is transferred from the injected gas to the vortex flow. The specific recommendations are presented in Section 4. The current design employs a narrow slit extending over only 20% of the chamber length that injects at high velocity exactly tangential to the inner cylindrical surface. Wall friction can be expected to immediately dissipate as much as 50% of the injected momentum (Section 3). We recommend that the slit be replaced with a row of 8 orifices, equally spaced along the entire length of the heating chamber. The orifices are sized so the total discharge is identical to that of the slit. They should be angled inward 26° from the tangential direction. The intent is to maximize the momentum transferred to the vortex by minimizing the momentum dissipated by the wall. In addition to higher velocity over the coil, discrete injection promotes mixing of the gas and introduces small-scale disturbances that should further enhance heat transfer. Extending the row of orifices to the ends of the chamber lessens the effect of end-wall boundary layer and should minimize the amount of flow leaving the chamber without being processed by the coil.

2. ESTIMATE OF THE POTENTIAL SPECIFIC-IMPULSE INCREASE

An analysis was carried out 1) to assess the heat-transfer from the coil to the gas in the current design, and 2) to estimate the potential for increasing specific impulse by increasing the heat-transfer to the gas.

2.1 Gas Properties Entering the Heating Chamber

The first step in the analysis is to calculate the gas temperature and composition leaving the catalyst bed and entering the heating chamber. We assume that hydrazine is decomposed adiabatically in the catalyst bed according to the reaction:

$$N_2H_4 \;\; {-}{>} \;\; (4/3)(1 - \alpha)NH_3 \;+\; (1/3)(1 + 2\alpha)N_2 \;+\; 2\alpha H_2$$

where α is the NH_3 dissociation fraction, which is defined as the fraction of the maximum possible NH_3 that decomposes. Thus $\alpha = 1$ corresponds to complete dissociation of NH_3, and $\alpha = 0$ corresponds to no dissociation (maximum possible NH_3 in the gas). We focused on a dissociation fraction of 0.6, which is representative of the Rocket Research Corporation (RRC) catalyst bed. The gas temperature exiting the catalyst bed is found by 1) calculating the net heat of reaction for decomposition as a function of temperature, and 2) selecting the temperature where the net is zero.

Table I gives the enthalpies and heats of formation required for the calculation, as well as the heat of reaction for N_2H_4 decomposition as a function of temperature. The calculation shows that for a dissociation fraction $\alpha = 0.6$, the heat of reaction vanishes at 1186^oK (1675^oF). The composition exiting the catalyst bed is given by:

TABLE I
THERMODYNAMIC DATA FOR N_2H_4 DECOMPOSITION WITH A NH_3 DECOMPOSITION FRACTION OF 0.60

N_2H_4 HEAT OF FORMATION AT 298K: 12.1 KCAL/MOL

						PRODUCT PROPERTIES					
	H(T) - H(298K)			NH_3 HEAT OF	HEAT OF	WITH NH_3			NH_3 DISSOCIATED		
T (K)	N_2	H_2	NH_3	FORMAT'N	REACTION	ENTHALPY KCAL/MOL	C_p CAL/MOL-K	C_p/C_v	ENTHALPY KCAL/MOL	C_p CAL/MOL-K	C_p/C_v
298	0.000	0.000	0.000	-10.970	17.951	0.000			0.000		
400	0.710	0.707	0.903	-11.482	16.100	0.750	7.47	1.36	0.708	6.98	1.40
500	1.413	1.406	1.867	-11.919	14.232	1.508	7.72	1.35	1.408	7.07	1.39
600	2.152	2.106	2.909	-12.282	12.294	2.293	7.89	1.34	2.121	7.07	1.39
700	2.853	2.808	4.027	-12.582	10.341	3.085	8.06	1.33	2.823	7.10	1.39
800	3.596	3.514	5.215	-12.824	8.315	3.906	8.32	1.31	3.541	7.23	1.38
900	4.355	4.226	6.470	-13.016	6.235	4.750	8.54	1.30	4.269	7.32	1.37
1000	5.129	4.944	7.787	-13.163	4.104	5.614	8.75	1.29	5.006	7.42	1.36
1100	5.917	5.670	9.163	-13.271	1.921	6.499	8.95	1.28	5.752	7.52	1.36
1200	6.718	6.404	10.592	-13.343	-0.310	7.403	9.14	1.28	6.509	7.61	1.35
1300	7.529	7.148	12.071	-13.385	-2.586	8.326	9.32	1.27	7.275	7.71	1.35
1400	8.350	7.902	13.596	-13.402	-4.906	9.266	9.49	1.26	8.051	7.82	1.34
1500	9.179	8.668	15.162	-13.399	-7.269	10.224	9.66	1.26	8.838	7.92	1.33
1600	10.015	9.446	16.765	-13.381	-9.670	11.198	9.81	1.25	9.636	8.02	1.33
1700	10.858	10.233	18.402	-13.347	-12.106	12.185	9.94	1.25	10.441	8.10	1.32
1800	11.707	11.030	20.066	-13.303	-14.572	13.185	10.13	1.24	11.256	8.29	1.31
1900	12.560	11.868	21.754	-13.250	-17.104	14.211	10.16	1.24	12.099	8.26	1.32
2000	13.418	12.651	23.465	-13.191	-19.585	15.217	10.19	1.24	12.907	8.22	1.32
2100	14.280	13.475	25.197	-13.125	-22.130	16.249	10.36	1.24	13.743	8.40	1.31
2200	15.146	14.307	26.950	-13.053	-24.698	17.290	10.46	1.23	14.587	8.46	1.31
2300	16.015	15.146	28.723	-12.973	-27.288	18.340	10.54	1.23	15.436	8.52	1.30
2400	16.886	15.993	30.515	-12.877	-29.899	19.398	10.63	1.23	16.291	8.58	1.30
2500	17.761	16.848	32.326	-12.797	-32.532	20.466	10.71	1.23	17.152	8.64	1.30
2600	18.638	17.708	34.154	-12.697	-35.182	21.540	10.78	1.22	18.018	8.68	1.30
2700	19.517	18.575	35.999	-12.592	-37.851	22.622	10.86	1.22	18.889	8.73	1.29
2800	20.398	19.448	37.861	-12.480	-40.538	23.712	10.92	1.22	19.765	8.78	1.29
2900	21.280	20.326	39.739	-12.360	-43.240	24.807	10.99	1.22	20.644	8.82	1.29
3000	22.165	21.210	41.631	-12.236	-45.959	25.909	11.05	1.22	21.528	8.86	1.29

$$N_2H_4 \; -> \; 0.533 \; NH_3 \; + \; 0.733 \; N_2 \; + \; 1.2 \; H_2$$

Table I also includes the enthalpy, specific heat at constant pressure, and the ratio of specific heats, both for the mixture exiting the catalyst bed at $\alpha = 0.6$, and for a mixture after the remaining NH_3 dissociates in the heating chamber. These data are used in the performance calculations below.

2.2 Performance of the Current Design

The electrical heating of the gas in the current design was found by calculating the gas total-temperature increase that gives the experimentally measured specific impulse. For this purpose, the isentropic-flow formula for specific impulse was modified by a multiplicative efficiency factor to account for the neglected viscous effects. A factor of 0.90 was found by taking the ratio of the specific impulse computed in Reference 2 by a full viscous analysis of the thruster to the specific impulse computed by the simple isentropic-flow formula.

The gas-heating computations were carried out based on two assumptions regarding NH_3 dissociation in the heating chamber: 1) no additional NH_3 dissociation, and 2) complete NH_3 dissociation. The actual situation was assessed by computing, according to Reference 3, the time for 99% dissociation as a function of temperature. The results are given in Table II.

TABLE II - 99% DISSOCIATION TIME FOR NH_3

Temp. (°K)	1000	1200	1500	1700	2000
Temp. (°F)	1340	1700	2240	2600	3140
$\tau_{.99}$ (s)	$3.0x10^8$	3.6x104	4.3	0.06	$5x10^{-4}$

The gas residence time was estimated based on an average axial velocity in the heater section given by

$$u_a = m/(\rho A) ,$$

where m is the mass flow rate, ρ is the gas density, and A is the cross-sectional area of the heater section. The residence time is given by

$$\tau = L/u_a ,$$

where L is the length of the heater section. For the nominal 3.0×10^{-4} lb/s mass flow, the residence time is estimated to be 0.001 seconds. Therefore, for gas temperatures below 1700°K (2600°F), the assumption of no additional NH_3 dissociation is the proper one. Ammonia dissociation in the heater section becomes significant as 2000°K (3140°F) is approached.

Results of the performance assessment of the current design are summarized in Table III for the particular operating condition specified by a mass flow of 3.0×10^{-4} lb/s and a dissociation fraction of $\alpha = 0.6$ out of the catalyst bed. Table III is actually a portion of a PC spreadsheet used to carry out the computations.

Section 1 of Table III gives conditions just before the gas is electrically heated. The total temperature is 1186°K (1675°F). Note that the unheated gas gives a predicted specific impulse of 227 seconds.

Section 2 of Table III gives the heat transfer for the case when all the NH_3 in the heater section dissociates. The total temperature of the gas is adjusted until the predicted specific impulse matches the RRC measured value of 306 seconds. The final

TABLE III
PERFORMANCE ASSESSMENT OF CURRENT DESIGN AT MASS FLOW OF 3×10^{-4} LB/S AND DISSOCIATION FRACTION OF $\alpha = 0.6$

NOZZLE EXIT MACH No.: 7.2
NOZZLE EFFICIENCY FACTOR: 0.9

1. CONDITIONS BEFORE GAS IS ELECTRICALLY HEATED

$$1.000\ N_2H_4 \rightarrow 0.533\ NH_3 + 0.733\ N_2 + 1.200\ H_2$$

MOLECULAR WEIGHT: 12.97 G/MOLE
GAS TEMPERATURE: 1186 K
ENTHALPY: 7.28 KCAL/MOL
GAMMA (Cp/Cv): 1.28
SPECIFIC IMPULSE: 2231 M/S = 227 SECONDS

2. CONDITIONS AFTER GAS ELECTRICALLY HEATED (TOTAL NH_3 DISSOCIATION)

RRC MEASURED
  SPECIFIC IMPULSE: 3003 M/S = 306 SECONDS
MOLECULAR WEIGHT: 10.67 G/MOLE
INITIAL TEMPERATURE: 1186 K
  NH3 HEAT OF FORMATION: -13.33 KCAL/MOL
  ENTHALPY (NO NH_3): 6.40 KCAL/MOL
FINAL TEMPERATURE: 1922 K
  FINAL ENTHALPY: 12.28 KCAL/MOL
  GAMMA (C_p/C_v): 1.32
HEAT TRANSFER TO GAS
  NH3 DISSOCIATION: 0.030 KCAL/S = 127 WATTS
  SENSIBLE HEATING: 0.062 KCAL/S = 258 WATTS
  TOTAL: 0.092 KCAL/S = 384 WATTS
FILAMENT TEMPERATURE: 2311 K
  ENTHALPY: 15.53 KCAL/MOLE
HX EFFECTIVENESS: 0.729

3. CONDITIONS AFTER GAS ELECTRICALLY HEATED (NO ADDITIONAL NH_3 DISSOCIATION)

RRC-MEASURED
  SPECIFIC IMPULSE: 3003 M/S = 306 SECONDS
FINAL TEMPERATURE: 1959 K
  FINAL ENTHALPY: 14.80 KCAL/MOL
  GAMMA (C_p/C_v): 1.24
SENSIBLE HEATING: 0.079 KCAL/S = 331 WATTS
FILAMENT TEMPERATURE: 2311 K

  ENTHALPY: 18.46 KCAL/MOLE
HX EFFECTIVENESS: 0.673
NUMBER OF TRANSFER UNITS: 1.12

temperature is 1922°K (3000°F). To reach this temperature, 127 watts are needed to dissociate the NH_3, and 258 watts of sensible heating are needed to raise the temperature. The total of 384 watts is below the experimentally measured input of 530 watts. The difference can be attributed in part to conductive heat loss. The calculations are based on the assumption of no heat transfer to the surroundings from 1) the catalyst chamber, 2) the heating chamber, or 3) the plumbing connecting them. A detailed assessment of the heat loss from the hardware in the test configuration was not made, and we cannot say at this time how much of the difference between the estimated and measured power to the heating section is due to heat losses.

The stated heat-transfer effectiveness of 0.729 is the ratio of the 384 watts transferred to the gas to the amount that would be transferred if the gas were heated to the measured filament temperature of 2311°K (3700°F).

Section 3 of Table III gives the heat transfer for the case when no additional NH_3 in the heater section dissociates. Again, the total temperature of the gas is adjusted until the predicted specific impulse matches the measured value of 306 seconds. The final temperature in this case is 1959°K (3067°F). To reach this temperature, 331 watts of sensible heating are needed. This is only 14% less than the case of total NH_3 dissociation. The heat-transfer effectiveness in this case is 0.673.

The estimated gas temperatures are in a range where it is not clear whether significant NH_3 dissociation will take place in the heating chamber. Table III shows, however, that the performance of the current design, in terms of total temperature of the gas, the total amount of heat transferred to the gas, and the heat-transfer effectiveness, is nearly the same under the widely different assumptions of 1) no additional NH_3

dissociation and 2) total NH_3 dissociation. This is in spite of the fact that there is a large difference in the final molecular weights and in final specific-heat ratios under the two assumptions. The simpler assumption is no additional dissociation in the heating chamber. Then, all heat transfer is in the form of sensible heating of the gas. Because of the demonstrated insensitivity of the performance to the assumption employed and for reasons of simplicity, the estimated potential for specific-impulse improvement in the next section is based on the assumption of no additional NH_3 dissociation. This allows a simple single-pass heat-exchanger model to employed.

2.3 Potential for Specific-Impulse Improvement

An estimate of the improvement in specific impulse by enhancement of heat transfer between the coil and the gas can be made by treating the heating chamber as a simple single-stream heat exchanger. The effectiveness e , defined as the actual heat transferred divided by the maximum possible is given by (Reference 4):

$$e = 1 - e^{-Ntu} , \qquad (1)$$

where the Ntu is the "number of transfer units" given by the dimensionless quantity

$$N_{tu} = (h\ A)/(m\ c_p) . \qquad (2)$$

Here, h is the overall heat-transfer coefficient between the coil and the gas, A is the surface area of the coil, m is the mass flow rate, and c_p is the specific heat of the gas. For a single-pass heat exchanger, the final temperature difference between the heating element and the fluid stream is reduced by a factor of $e^{-1} = 0.368$ for every Ntu. When the effectiveness has been calculated, such as in our assessment of the performance of the current design in Table III, then the number of transfer units can be found from

$$N_{tu} = - \ln (1 - e) . \tag{3}$$

For example, in Table III, Section 3 (no additional NH_3 dissociation), for an effectiveness of 0.673, the number of transfer units is 1.12 .

The NTUs are directly proportional to the heat-transfer coefficient h (Equation 2). Therefore, a specified percentage enhancement in the heat-transfer coefficient results in the same percentage increase in the NTUs, and Equation (1) can be used to calculate the enhanced effectiveness. Then the new gas temperature T_{exit} exiting the heating chamber can be determined from the definition of effectiveness:

$$e = [H(T_{exit}) - H(T_{entrance})]/[H(T_{filament}) - H(T_{entrance})] , \tag{4}$$

where $H(T)$ is the enthalpy of the gas at temperature T . The exiting gas temperature, along with the molecular weight and ratio of specific heats, is used to calculate the enhanced specific impulse.

The results are shown in Figures 1 and 2 for a mass flow of 3.0×10^{-4} lb/s for two cases: 1) the filament is maintained at the current measured temperature of 3700°F, and 2) the filament is increased to 5000°F.

An estimate for the heat-transfer coefficient for the current design can be obtained from Equation (2) with the following data:

FIGURE 1

GAS-TEMPERATURE INCREASE FROM HEAT-TRANSFER ENHANCEMENT

MASS FLOW: 3E-04 LBM/S - FILAMENT: 3700F & 5000F

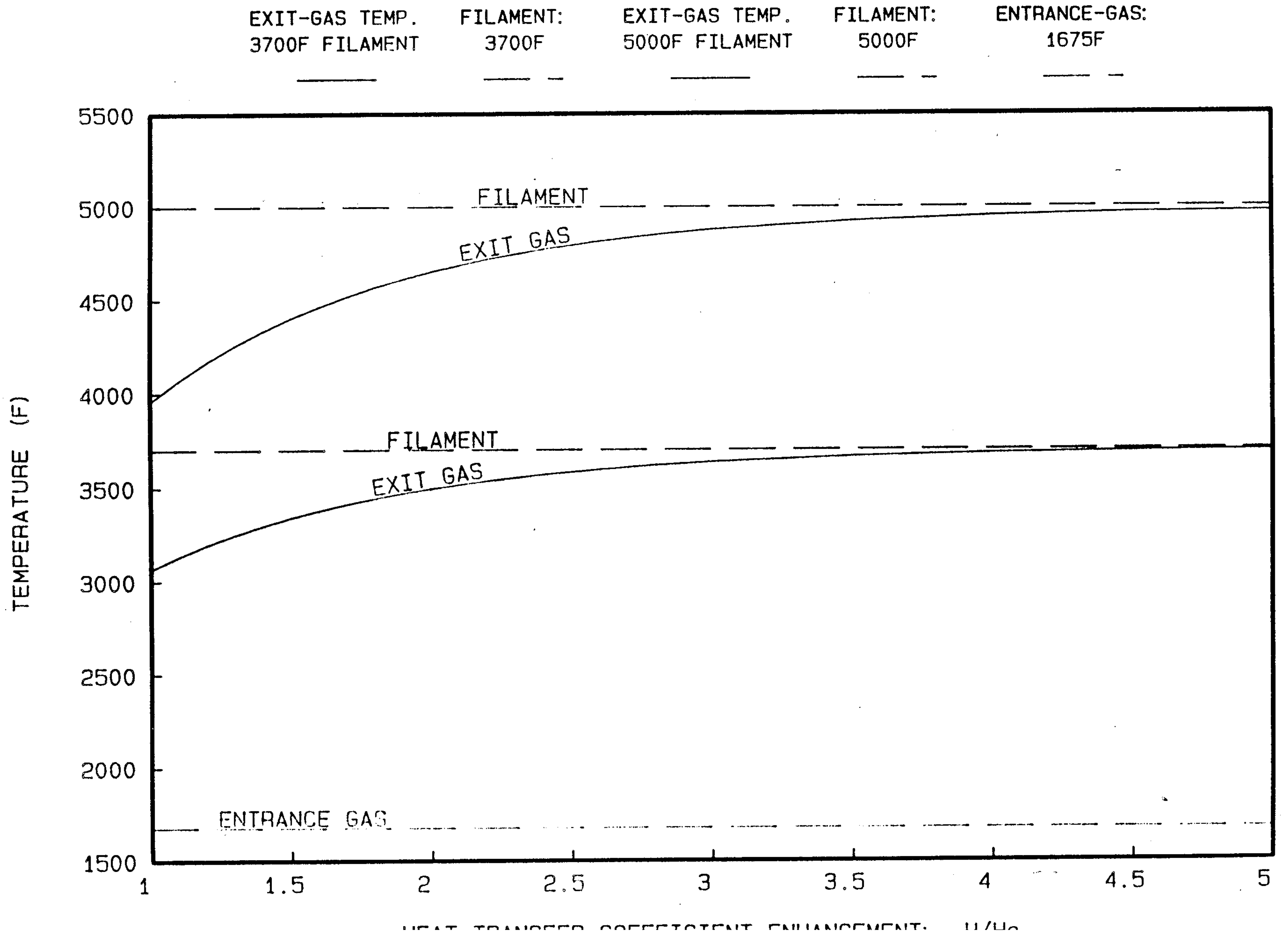
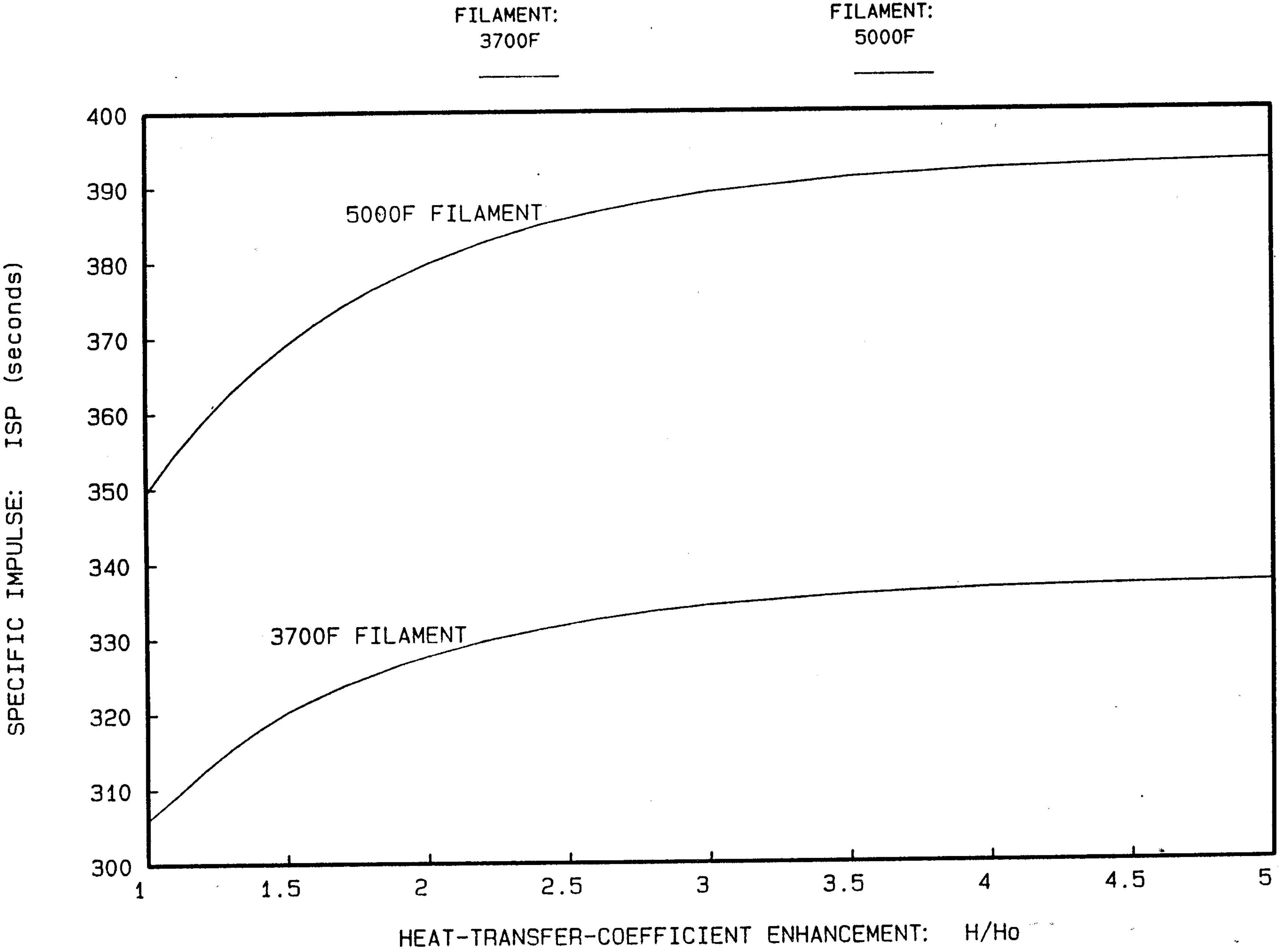


FIGURE 2

ISP INCREASE FROM HEAT-TRANSFER ENHANCEMENT
MASS FLOW: 3E-04 LBM/S - FILAMENT: 3700F & 5000F



Number of Transfer Units . . . . . N_{tu} = 1.12
Total Wire Surface Area
of Heating Coil. . . . . A = 1.82×10^{-4} m^2
Mass Flow Rate . . . . m = 3.0×10^{-4} lb/s
= 1.4×10^{-4} kg/s
Specific Heat . . . . c_p = 0.73 kcal/kg-K

The calculated heat-transfer coefficient is

$$h = 0.61 \text{ kcal/s-m}^2\text{-K} . \qquad (5)$$

If the heat-transfer from the heater element is idealized as resulting from flow over a cylinder, then an estimate can be made of the flow velocity over the coil, and for the heat-transfer enhancement resulting from a velocity increase. The Nusselt number $Nu_D = h D/k$, based on the cylinder diameter D , is related to the Prandtl number Pr and Reynolds number Re_D by (Reference 1):

$$Nu_D = 1.1 \, C \, Re_D{}^n \, Pr^{0.31} \qquad (6)$$

where $C = 0.615$ and $n = 0.466$ for Reynolds numbers in the range 40 - 4,000 . The following average data are used to carry out the calculations:

Gas Conductivity. . . . . k = 2.8×10^{-5} kcal/s-m-K
Gas Viscosity . . . . μ = 2.8×10^{-5} kg/m-s
Gas Density . . . . ρ = 1.2 kg/m3
Heater-Wire Diameter . . . . D = 0.009 in.
= 2.29×10^{-4} m

With these data, we calculate:

Nusselt Number. . . . . Nu_D = 5.0
Reynolds Number . . . . Re_D = 93
Gas Velocity Over Wire. . . . u = 9.1 m/s

where the gas velocity is calculated from the Reynolds number by $u = \mu \, Re_D/(\rho D)$. The velocity of 9.1 m/s over the coil falls between the estimated velocity of 240 m/s exiting the injection slit and the estimated average axial velocity of 2.6 m/s in the heating chamber. Equation (6) shows that the heat-transfer coefficient varies with the 0.47th power of the Reynolds number, and hence of the velocity. Thus to enhance the heat-transfer coefficient by a factor of two, the velocity would have to be increased by a factor of 4.4 from 9.1 m/s to 40 m/s.

A realistic expectation would be to double the velocity over the coil. The heat-transfer coefficient would be increased by the factor $2^{0.47} = 1.4$. According to Figure 2, without increasing the filament temperature from its current operating level of 3700°F the expected specific impulse would increase from 306 seconds to 318 seconds. Higher values would result from the beneficial effects of:

1) small-scale turbulence induced by discrete injection,
2) improvements in preventing flow exiting unheated at the ends of the chamber, and
3) operating at a higher filament temperature.

3. FLOW-FIELD CONSIDERATIONS

The design modification we propose is to replace the current single-slit injector located axially near the center of the chamber with an array of orifices distributed along the length of the chamber. The orifices are angled inward relative to the tangential direction of the chamber wall to minimizing momentum loss from the jets due to viscous drag on the wall. For the proposed injection configuration, there will be an optimum both for the number of orifices and for the injection angle. The optimal design of the thruster configuration from the heat-transfer standpoint is the one that maximizes the vortex strength.

The optimum angle for injection is a compromise between two opposing factors. For an injection angle β measured inward from the tangential direction, the jet velocity can be decomposed into to a tangential component $V \cos \beta$ and a radial component $V \sin \beta$. Only the tangential component transfers momentum to the vortex, and for this reason β should be as small as possible. On the other hand, if β is too small, momentum is lost to the wall due to viscous drag. An optimum angle could be determined by a flow simulation experiment. For example, vortex strength measured by pressure depression at the core could be found as a function of injection angle. A flow simulation experiment is beyond the scope of the current work. A review of rotating-flow literature, however, produced much data from past experiments that help support the proposed design. A summary is given below, and selected reference to the rotating-flow literature is given at the end.

The friction loss due to the cylindrical wall has been investigated by Kendall and Roschke (References 1 & 3-6). In the hope of reducing momentum loss to the side wall, Roschke had the jet orifices drilled tangent to a circle having a diameter 92% of the chamber diameter. Although not mentioned by Roschke, the 92%-configuration appears to be consistent with experimental results obtained by Keyes (Reference 7), which showed optimal vortex strength occurs when the injection is tangent to a circle having a diameter approximately 90% of the chamber diameter. For this case, the injection angle is given by

$$\beta = \cos^{-1}(0.90) = 25.8^{\circ}$$

The penalty paid for angling the jets inward is the reduction of the tangential component of the injection velocity, which in this case is reduced by the factor $\cos\beta = 0.90$.

In addition to the angle of injection, the number of orifices must be specified. The proposed design modification is to replace the current 0.008-in. x 0.0~~0~~73-in. single-slit injector an array of 8 orifices distributed along the entire length of the chamber. The center-to-center orifice spacing is 0.045 in. The diameter of the orifices is selected to give the same total mass flow as the single slit. If the discharge coefficient were the same for the orifices as for the slit, then the diameter of the orifices would be 0.00964 in. The actual diameter should be increased in the final mechanical design to account for the smaller discharge coefficient for the orifices than for the slit.

The selection of the number of orifices was based on the maximum number that gives an orifice diameter of the same order as the slit width. There is concern that a larger number of very small diameter orifices would be dominated by viscous effects. The proposed configuration has a spacing-to-diameter ratio of 4.5, which is close to the ratio of 4 used by Roschke in the construction of his vortex tube (Reference 5).

In rotating flows, the primary circumferential flow dominates. An idealized two-dimensional rotating flow with no end walls is relatively simple. In actual hardware, however, the core-flow interaction with the end-wall boundary layers results in complex radial and axial secondary flows (References 9 - 10). The complexity of these secondary flows is illustrated in Figures 6 - 12 reproduced from Reference 9, and in the videotape accompanying this memorandum. Some observations are made below of flow features that pertain to the heating chamber of the current application.

The effect of the chamber end walls is shown in Figure 7. According to the theoretical studies of interaction of the end-wall boundary layers with the rotating core flow (References 11-20), the flow features can be summarized as follows. In the boundary layer, the tangential velocity is slower than the outer flow, thus reducing the centrifugal force which can no longer balance the radial pressure gradient. As a result, fluid flows radial inward at the end walls to a radial position where its reduced centrifugal force can balance the radial pressure gradient. For reasons of continuity, the radial flow is accompanied by an axial flow in a cylindrical layer across the core region. The process repeats at the other end wall. In this way, a serpentine secondary flow pattern is set up as the path by which injected fluid finds its way to the central core and exits. For a given diameter, shorter chambers have more flow reversals. For a length-to-diameter ratio L/D = 1 , which is close to the current application, Figure 7 shows seven axial flow reversals.

The secondary flow pattern is very sensitive to hardware protruding into the chamber. The Figure 11 shows a dramatic change in the flow pattern resulting from small wires of various diameters stretched across the diameter. Figure 12 shows similar major effects from a probe inserted diametrically into the flow. In the current application, the presence of the heating coil can be expected to have a major effect on the flow. Any analyses that neglect its presence are suspect.

4. SUMMARY OF RECOMMENDATIONS FOR DESIGN MODIFICATIONS

Based on the literature review and private communications with J. Kendall and E. Roschke we would like to recommend the followings:

1) Replace the current slit injector with an array of 8 circular orifices extending along the entire length of the chamber.

2) Size the orifice diameters at approximately 0.010 inches so they have the same discharge as the slit.

3) Angle the injection orifices inward 26° from the tangential direction to minimize drag on the chamber wall.

4) Position the end orifices close to end walls in order to energize the boundary layer and minimize end loss of unheated gas.

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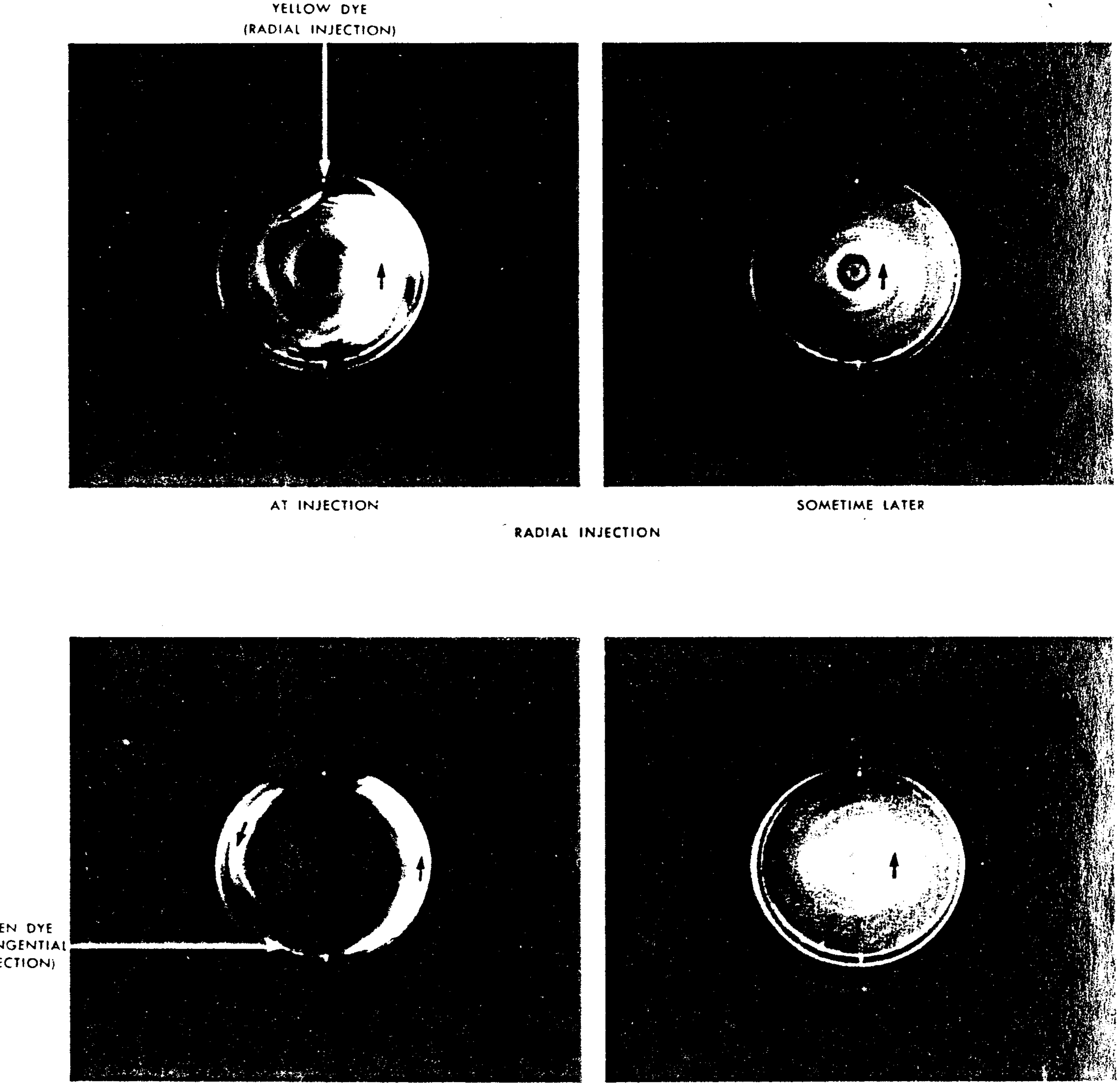


AT INJECTION

SOMETIME LATER

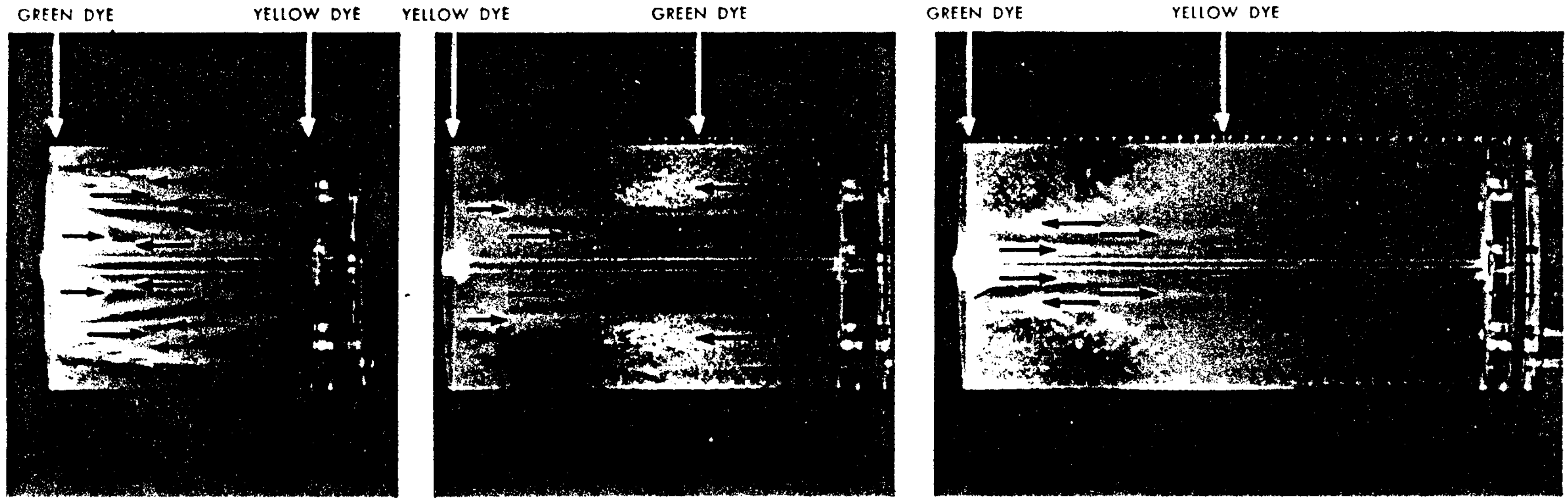
RADIAL INJECTION

AT INJECTION

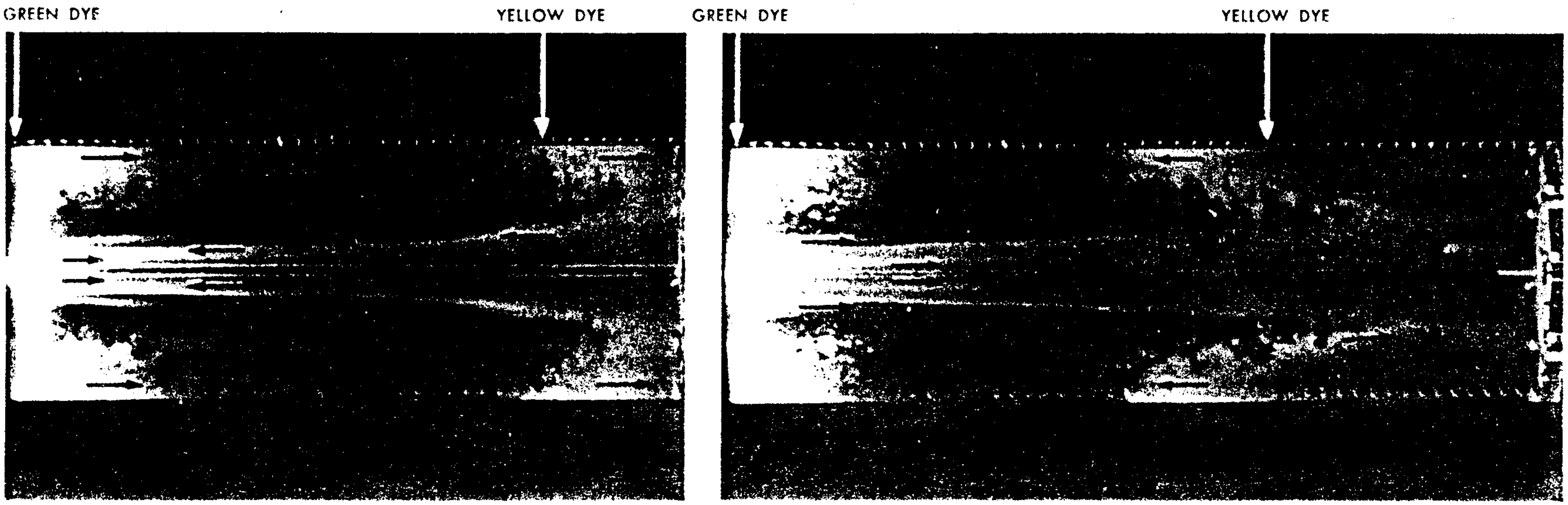
SOMETIME LATER

TANGENTIAL INJECTION

Fig. 6. End views of standard configuration with nominal ½-in. exit hole; $L/D = 6$; $p_v - p_a = 5$ psig; illumination through ¼-in. slit at $L/D = 2$; dye released at $L/D = 2$

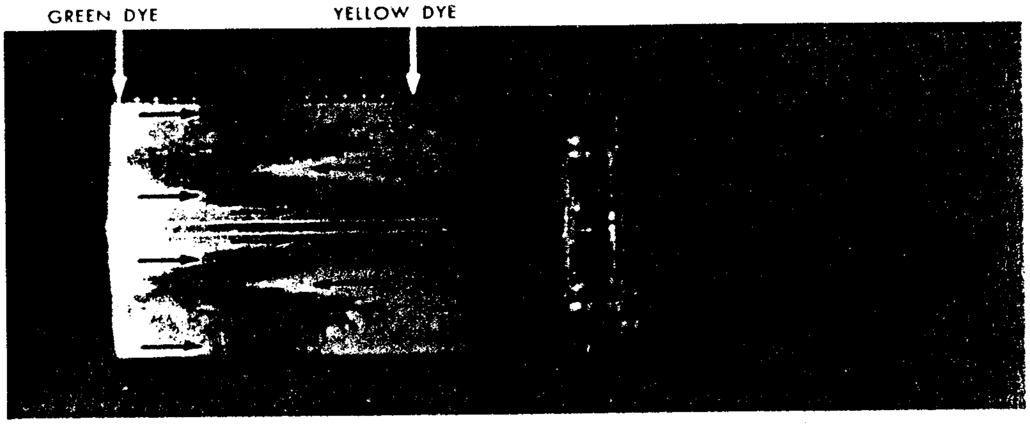


$L/D = 1$ $L/D = 1.5$ $L/D = 2$

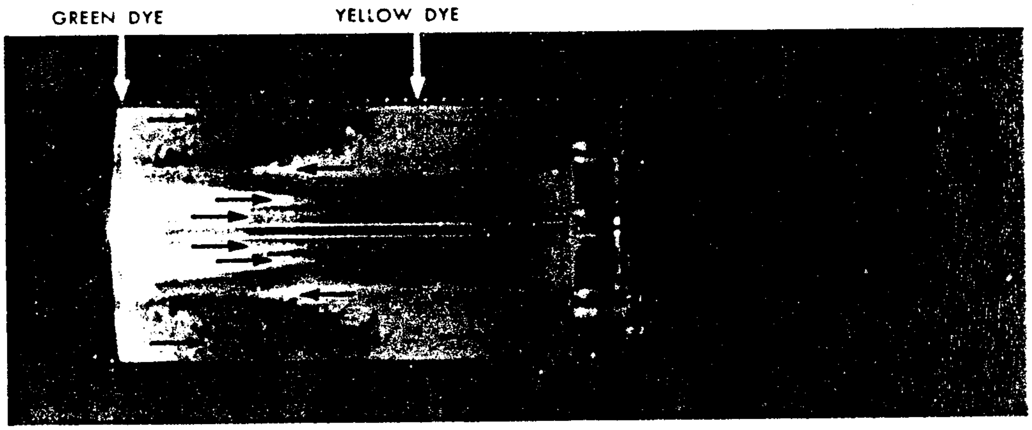


L/D 2.5 L/D 3

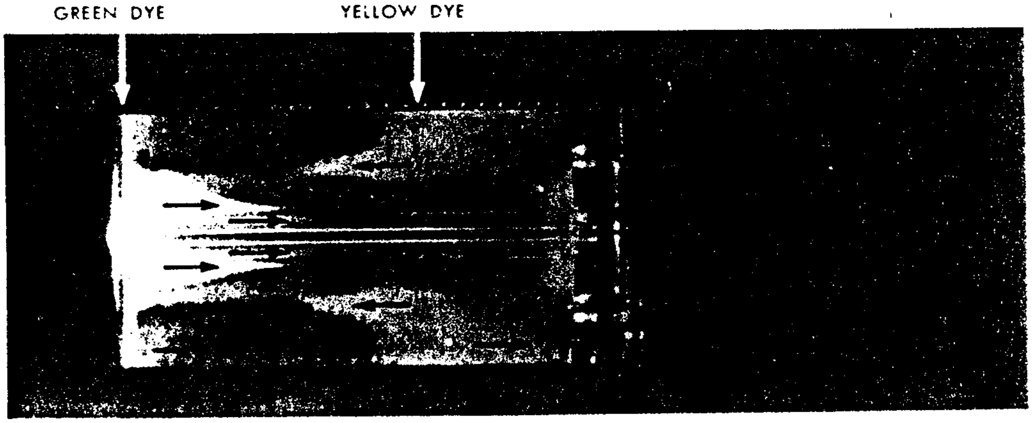
Fig. 7. Dye studies in standard configuration: Effect of aspect ratio at low values of L/D and $p_o - p_a = 5$ psig with nominal ½-in. exit hole (at $L/D = 3$, $p_o - p_a = 2$ psig)



$p_w - p_a = 2$ psig



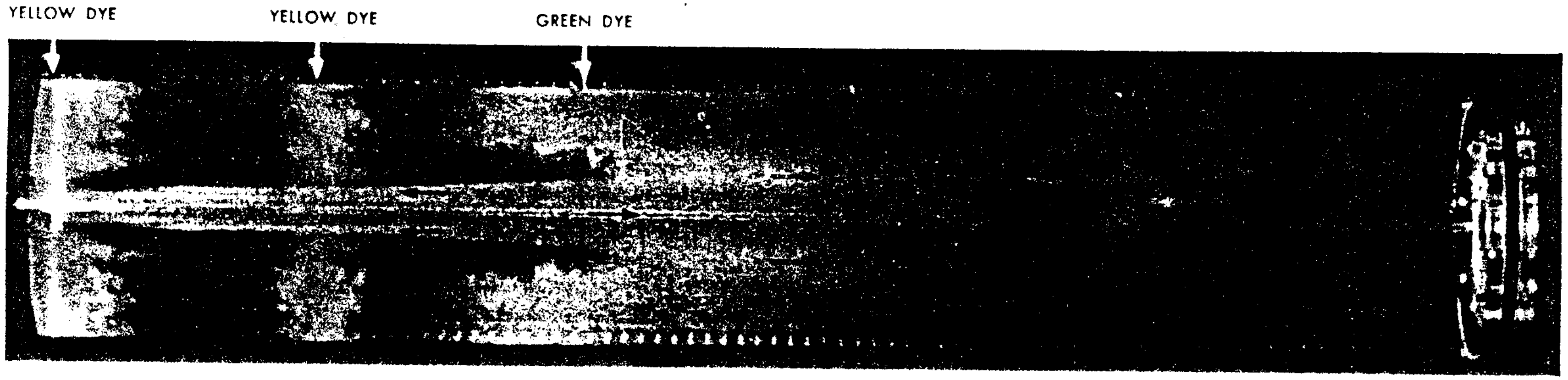
$p_w - p_a = 5$ psig



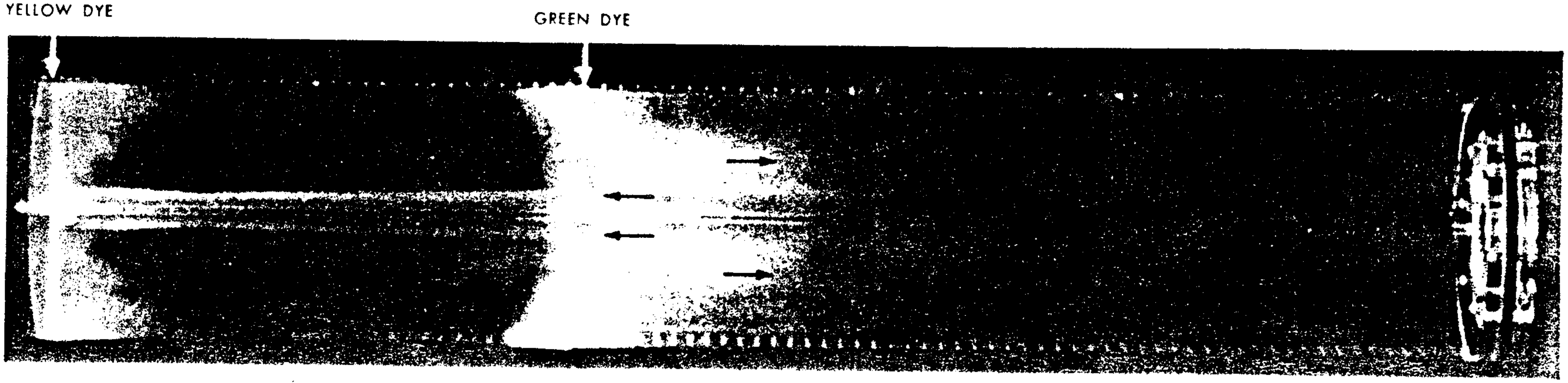
$p_w - p_a = 20$ psig

Fig. 8. Dye studies in standard configuration: Effect of static wall pressure at $L/D = 1.5$ with nominal ½-in. exit hole

p_w p_a 2 psig

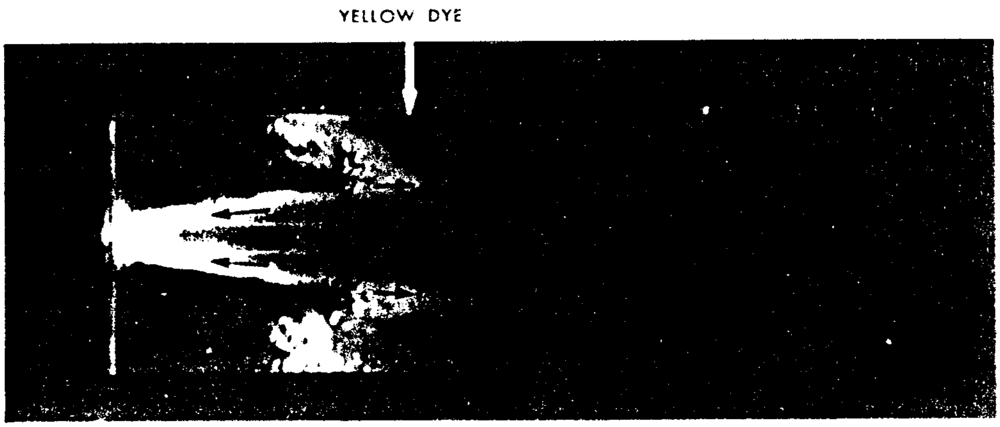


p_w p_a 5 psig

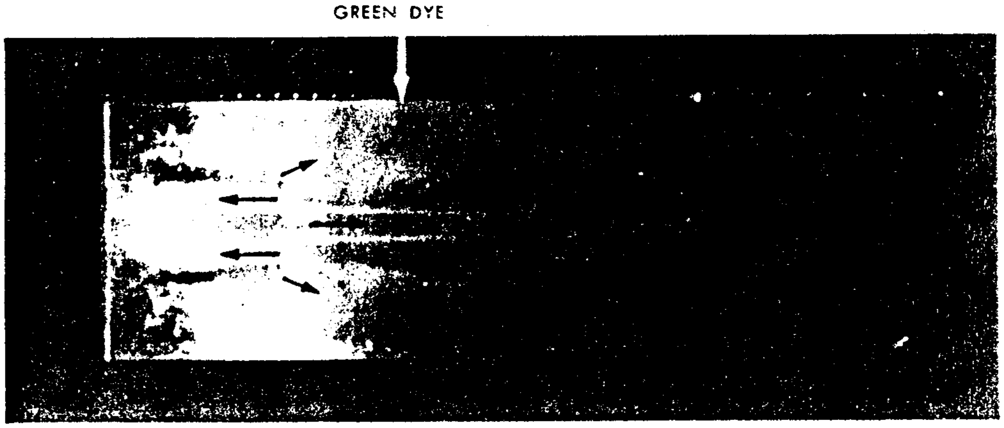


p_w p_a 20 psig

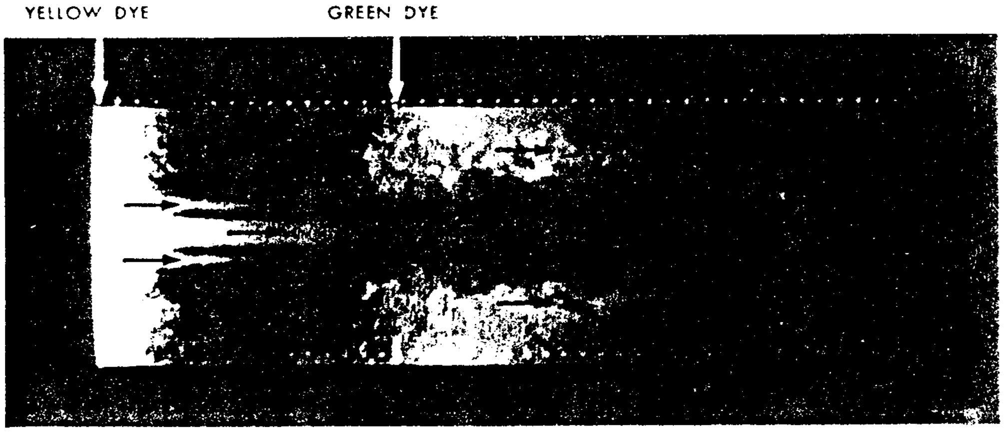
Fig. 9. Dye studies in standard configuration: Effect of static wall pressure at $L/D = 5.33$ with nominal 9/16-in. exit hole



$p_v - p_a = 5$ psig

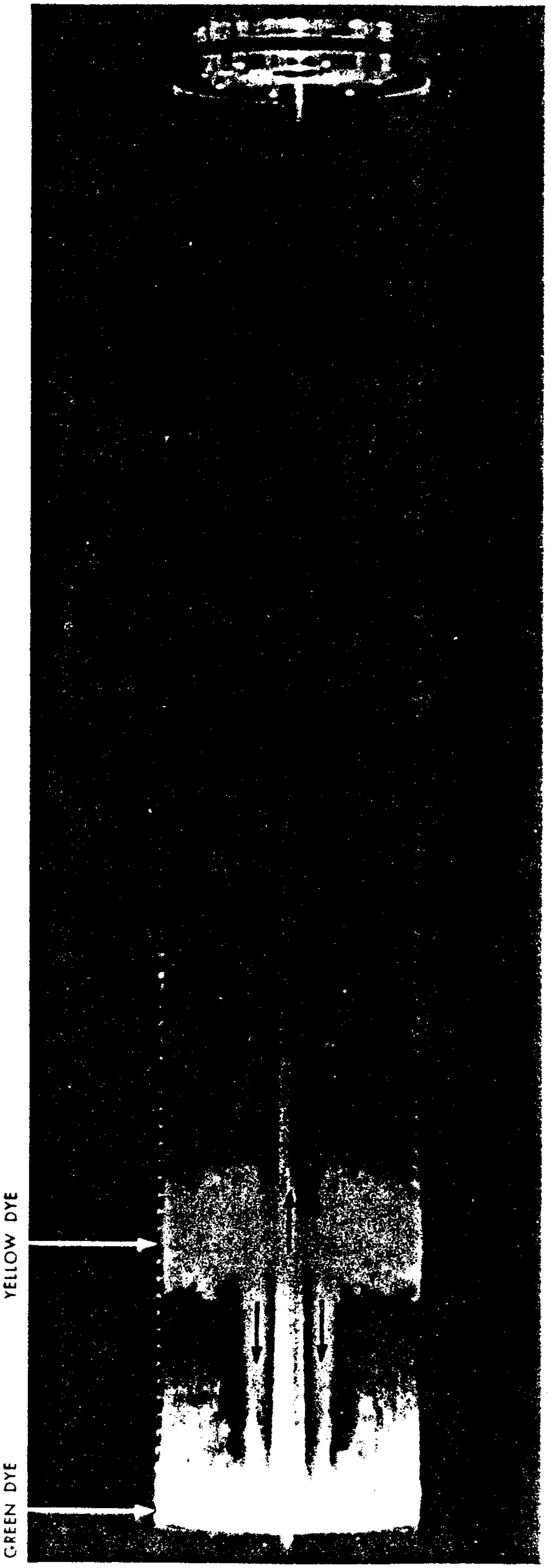


$p_v - p_a = 5$ psig

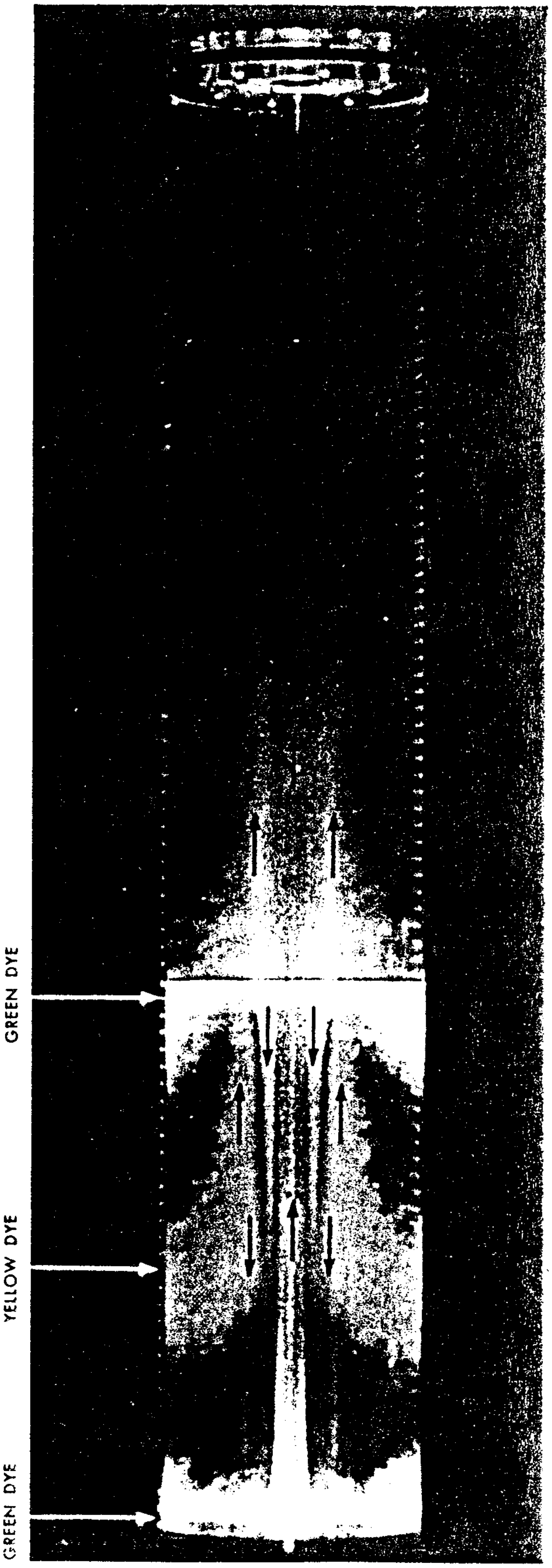


$p_v - p_a = 20$ psig

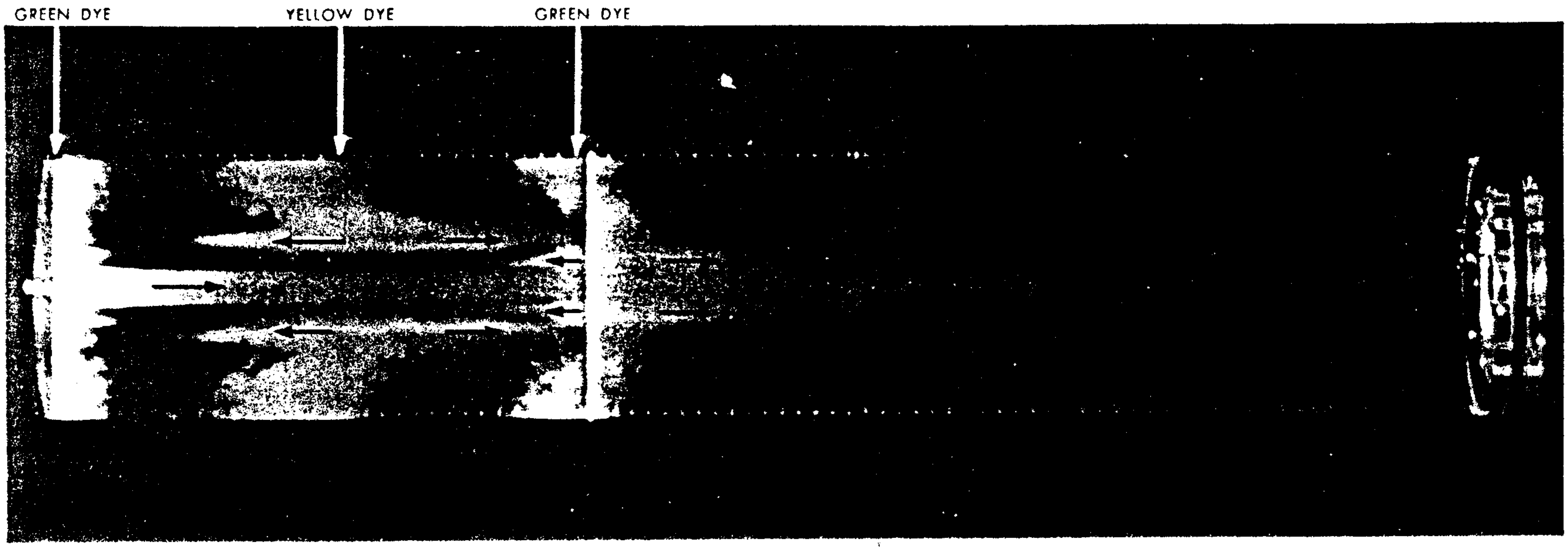
Fig. 10. Dye studies in standard configuration: Views of a portion of the vortex near the closed endwall, at $L/D = 6$ with nominal ½-in. exit hole



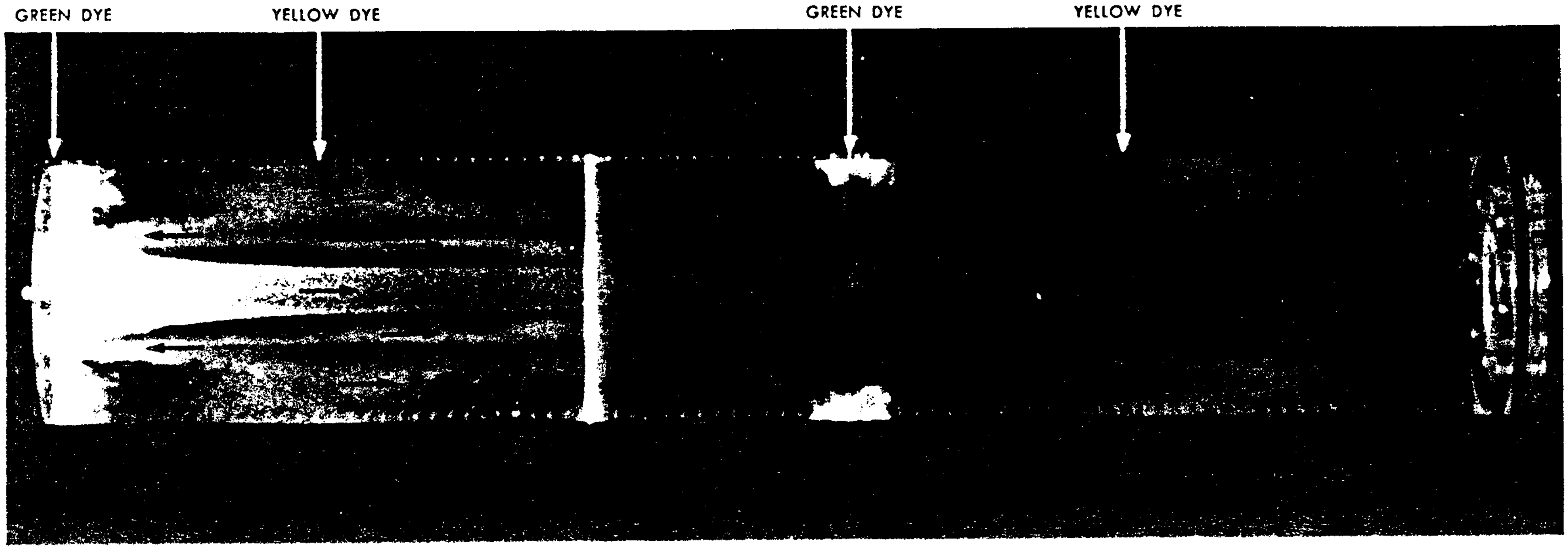
NO WIRE IN VORTEX



0.005 in diam WIRE

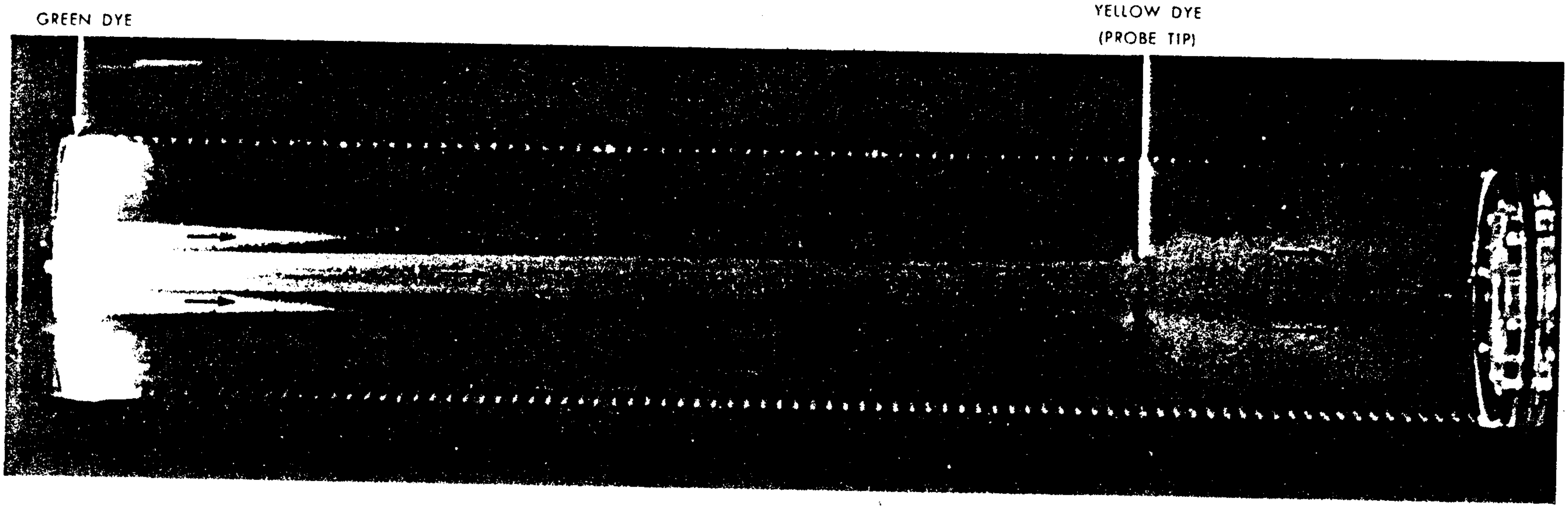


0.018-in.-diam WIRE

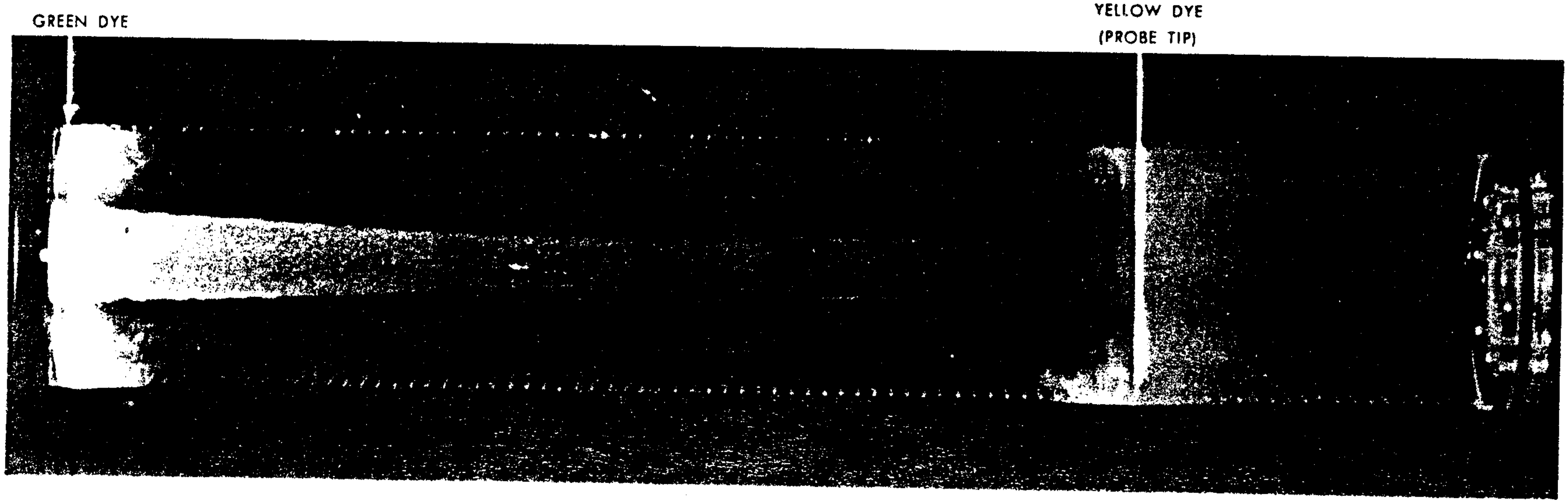


0.050-in.-diam WIRE

Fig. 11. Dye studies in standard configuration: Effect of various-size-diameter probe wires stretched across a vortex diameter, at $L/D = 5.33$ and p [illegible] − p [illegible] = 5 psig with nominal 9/10-in. exit hole



PROBE TIP LOCATED NEAR VORTEX CORE; $p_{\bullet} - p_{a}$ 10 psig

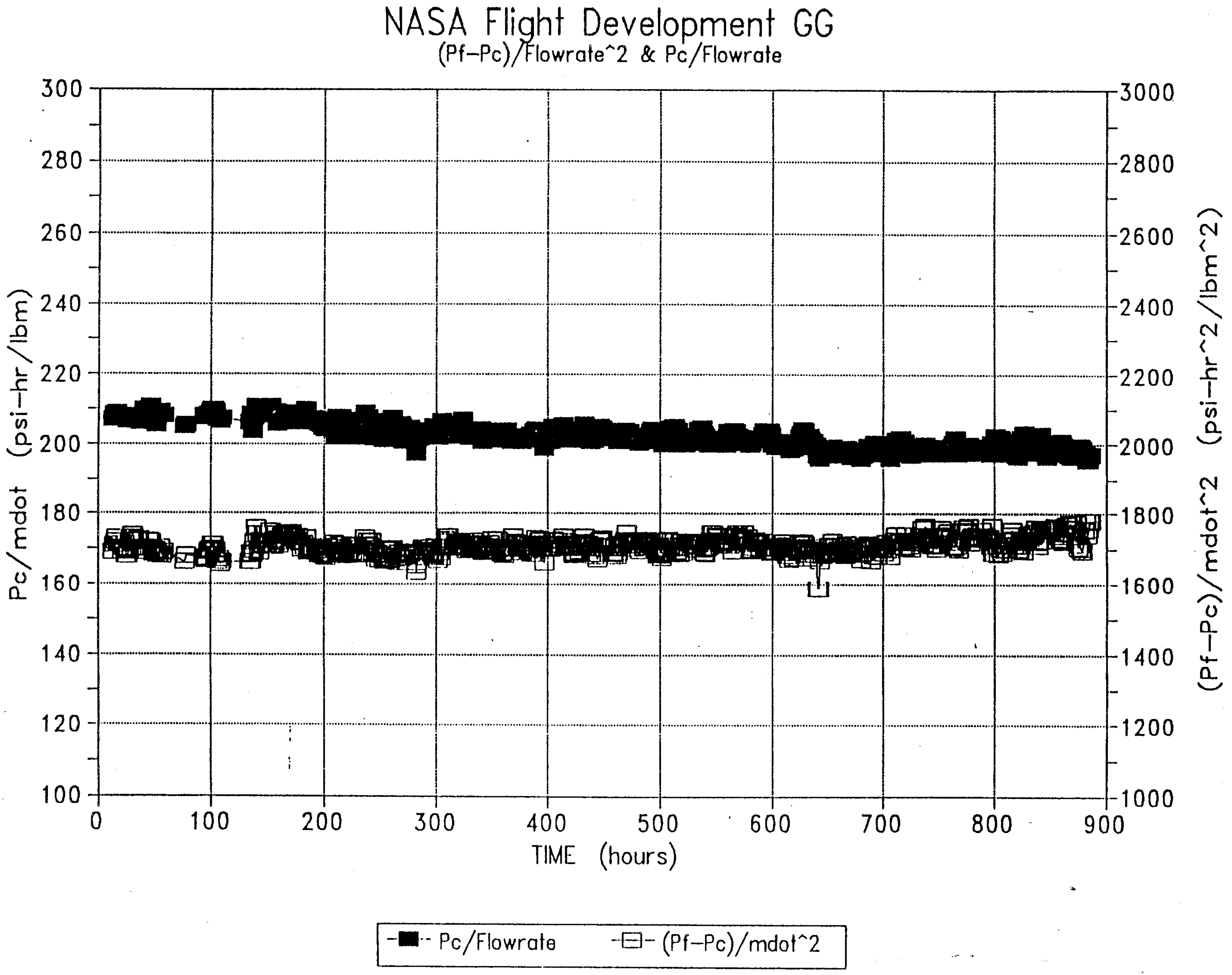


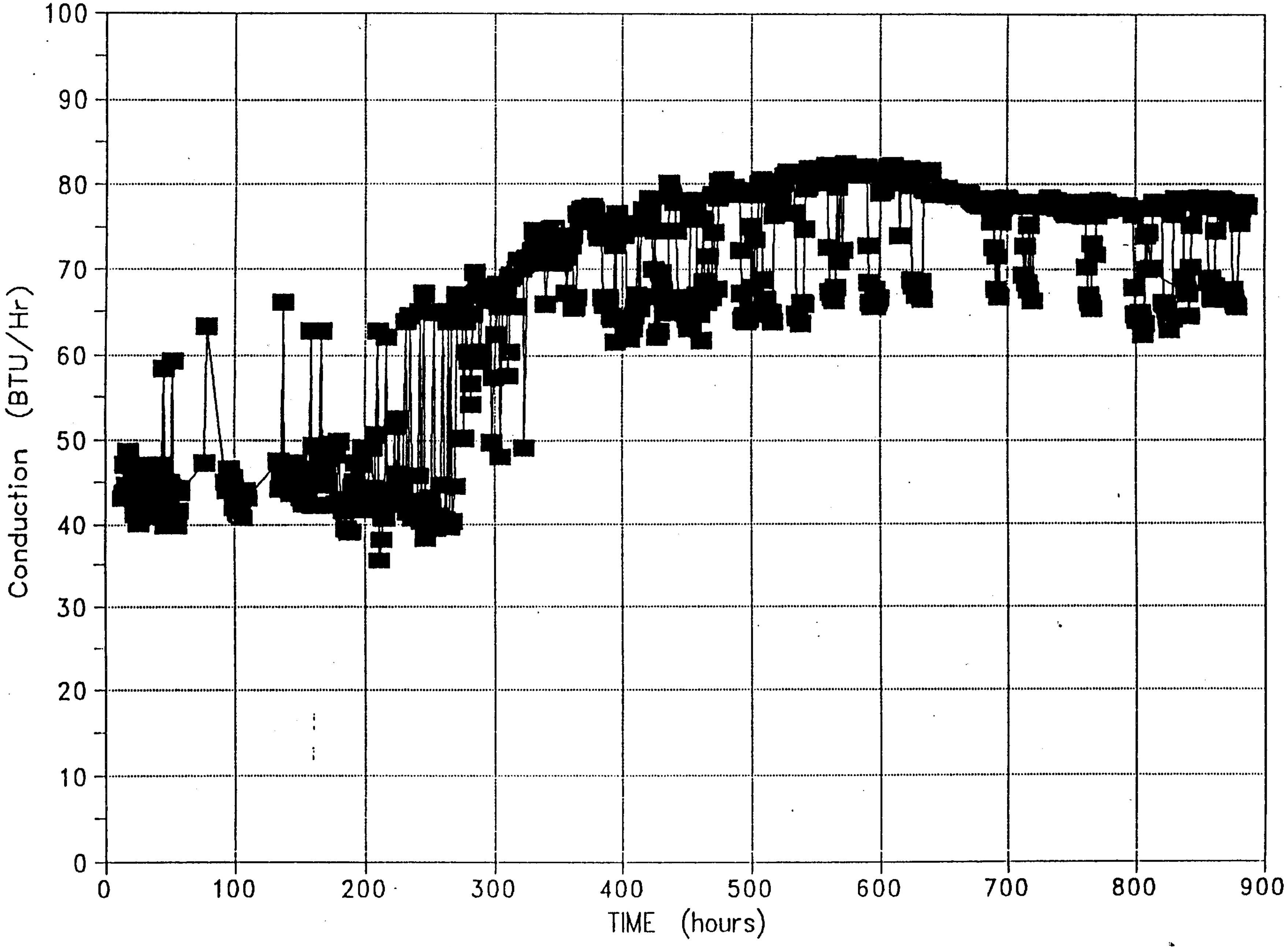
PROBE TIP LOCATED NEAR OPPOSITE WALL; $p_{\bullet}$ p_{a} 5 psig

Fig. 12. Dye studies in standard configuration: Effect of cantilever-mounted probes, at $L/D = 5.33$ with nominal 9/16-in. exit hole

APPENDIX G

Advanced Gas Generator Data


NASA Flight Development GG
(Pf−Pc)/Flowrate^2 & Pc/Flowrate
Pc/mdot (psi−hr/lbm)
300
280
260
240
220
200
180
160
140
120
100
(Pf−Pc)/mdot^2 (psi−hr^2/lbm^2)
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
0
100
200
300
400
500
600
700
800
900
TIME (hours)
■ Pc/Flowrate
⊟ (Pf−Pc)/mdot^2

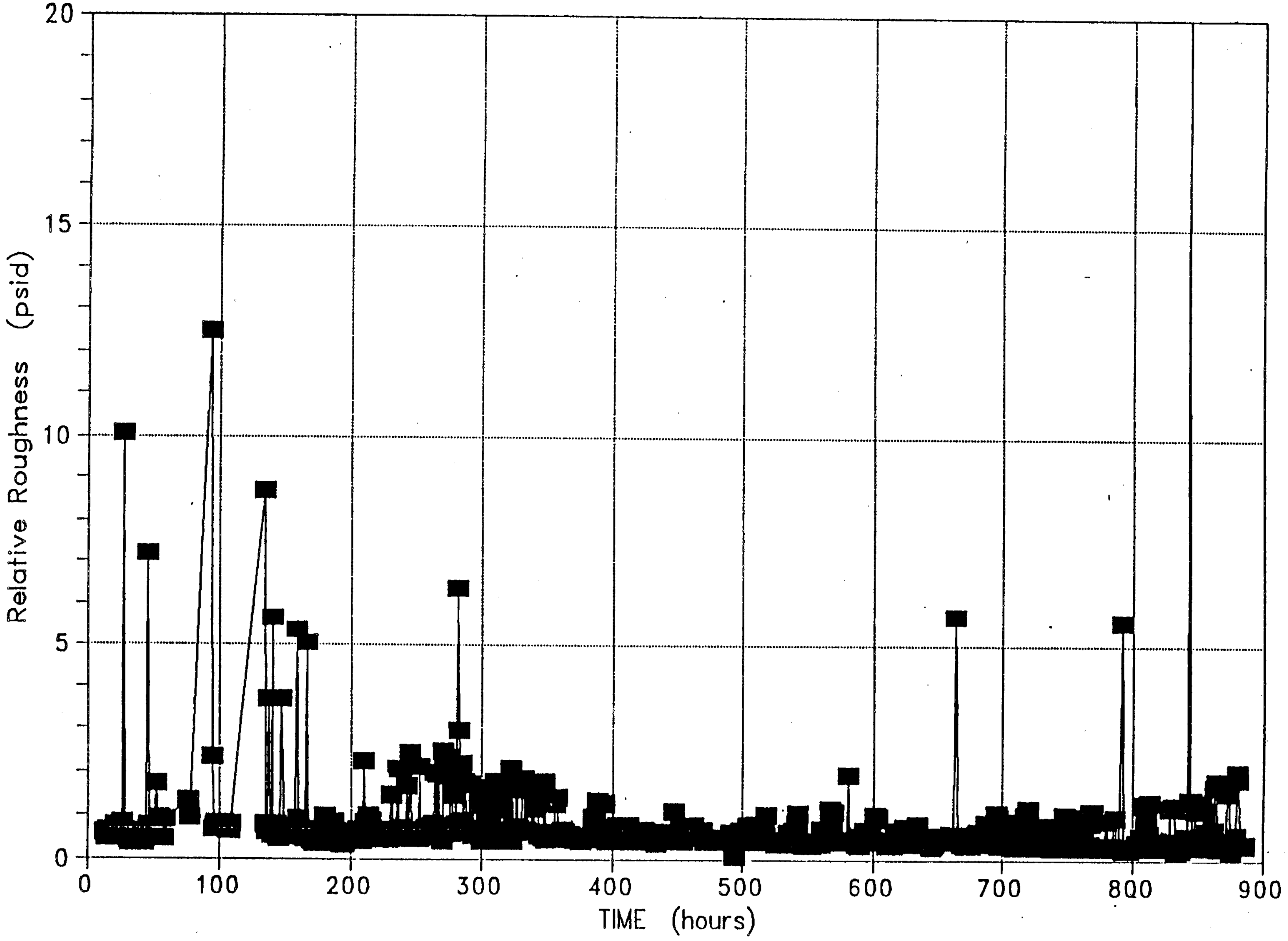


NASA Flight Development GG

Q-cond (Injector shunt) (Ts1r-Ts2r)

NASA Flight Development GG

Relative Roughness



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13. ABSTRACT ***(Maximum 200 words)***

From 1965 until 1985 resistojets were used for a limited number of space missions. Capability increased in stages from an initial application using a 90 W gN_2 thruster operating at 123 sec specific impulse (Isp) to a 830 W N_2H_4 thruster operating at 305 sec Isp. Prior to 1985 fewer than 100 resistojets were known to have been deployed on spacecraft. Building on this base NASA embarked upon the High Performance Storable Propellant Resistojet (HPSPR) program to significantly advance the resistojet state-of-the-art. Higher performance thrusters promised to increase the market demands for resistojets and enable space missions requiring higher performance. During the program three resistojets were fabricated and tested. High temperature wire and coupon materials tests were completed. A life test was conducted on an advanced gas generator.

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