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ARCJET THRUSTER RESEARCH AND TECHNOLOGY

Phase I

EXECUTIVE SUMMARY

NAS 3-24631

Prepared for:

NASA LEWIS RESEARCH CENTER
21000 Brookpark Road
Cleveland, Ohio 44135

August 10, 1987

Olin DEFENSE SYSTEMS ROCKET RESEARCH COMPANY

Redmond, Washington

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ARCJET THRUSTER RESEARCH AND TECHNOLOGY

PHASE 1

EXECUTIVE SUMMARY

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Prepared by:

Rocket Research Company
Olin Defense Systems Group
11441 Willows Road N.E.
Redmond, Washington 98073-9709

Prepared for:

NASA Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio 44135

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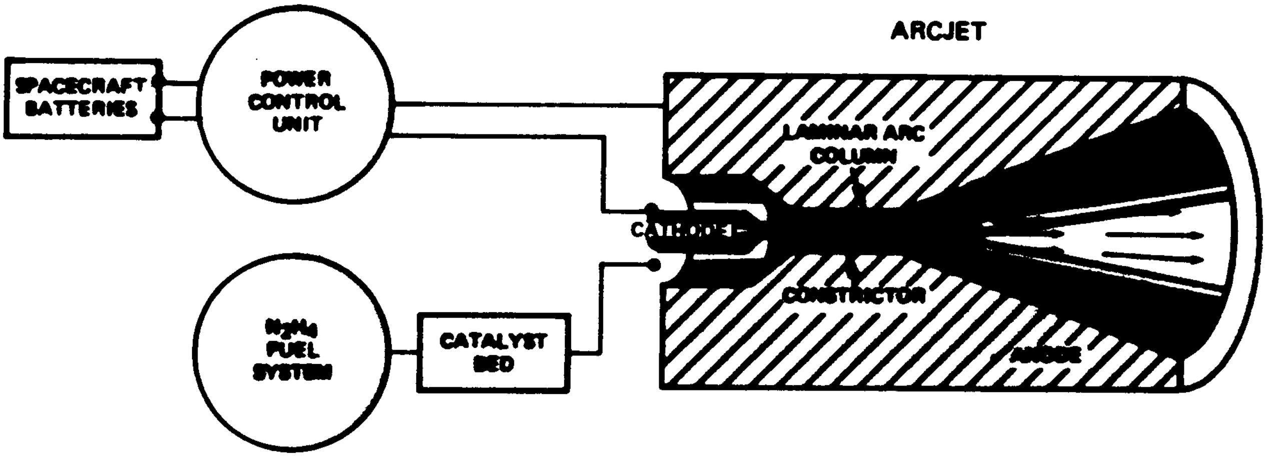
This executive summary was prepared by Rocket Research Company in fulfillment of the requirements of Phase I of contract NAS 3-24631, entitled Arcjet Thruster Research and Technology. The contract is under the technical direction of the NASA Lewis Research Center. Dr. Francis M. Curran is the NASA Project Manager. The period of performance of this phase was from October 1985 to February 1987.

1.0 SUMMARY

The principle objective of this two phase program is to conduct the development research required to make the low power arcjet a flight ready technology. Many important results were obtained during Phase I to move closer to this objective, as summarized in Figure 1-1. Fundamental analyses were performed of the arcjet nozzle, the gas kinetic reaction effects, the thermal environment, and the arc stabilizing vortex. These aided the conceptual understanding of the arcjet and guided design work. A hydrazine (N_2H_4) arcjet was designed that combined a flight qualified catalyst bed with a modular arcjet. Extensive testing was performed which demonstrated the feasibility of using this propellant in an arcjet for the first time. Startup techniques were developed, stability maintained, material compatibility tests conducted, and performance mapping tests performed. Specific impulse values from 400 to 730 seconds were produced with a non-optimized design. These levels are higher than were originally thought possible and proved that extremely high enthalpy values can be obtained with constricted arc technology. Erosion rate data are promising for lifetime extensions to meet flight application requirements. Power control unit (PCU) development was started with the design and fabrication of a laboratory high switching frequency supply. Valuable data were obtained on PCU operation and on the interaction with the dynamic arc. Figure 1-2 summarizes the program highlights.

Phase II efforts presently underway are resolving key issues for multi-hundred hour lifetimes, are continuing to investigate arcjet/PCU interactions, and will demonstrate duty cycle N_2H_4 arcjet/PCU operation in a simulated flight mode for lifetimes consistent with initial applications.

Phase I
Arcjet Technology Progress Assessment



TECHNOLOGY ISSUES, BEGINNING OF PHASE I	STATUS, END OF PHASE I
• IS AN N_2H_4 ARCJET FEASIBLE?	• YES. STABLE OPERATION DEMONSTRATED FOR MANY CONFIGURATIONS.
• WILL EXISTING N_2H_4 GRADES BE ACCEPTABLE?	• YES. NO OXIDATION SEEN WITH MIL-SPEC N_2H_4.
• CAN THE N_2H_4 ARCJET BE NONEROSIVELY & RELIABLY STARTED?	• YES. TWO TECHNIQUES DEMONSTRATED
• WILL PERFORMANCE BE ACCEPTABLE?	• YES. I_{sp} FROM 400 TO 730 SECONDS MEASURED
• CAN THE ARCJET OPERATE AT LOW (< 2 kW) POWER?	• YES. OPERATED FROM 1,000 TO 3,000 W.
• WHAT ROLE DOES POWER CONDITIONING PLAY?	• SIGNIFICANT. PCU AFFECTS RELIABLE STARTS, STEPS UP VOLTAGE, MAINTAINS DYNAMIC ARC STABILITY.
• IS THE ARCJET SYSTEM COMPATIBLE WITH EXISTING N_2H_4 PROPULSION SYSTEMS?	• YES. CAN USE FLIGHT-PROVEN N_2H_4 TECHNOLOGY, POWER CONDITIONING REQUIREMENTS ARE MODERATE.
• WHAT IS THE DOMINANT ISSUE FOR FLIGHT APPLICATION?	• LIFETIME. PHASE II EFFORTS FOCUSED ON THIS ISSUE

Figure 1-1

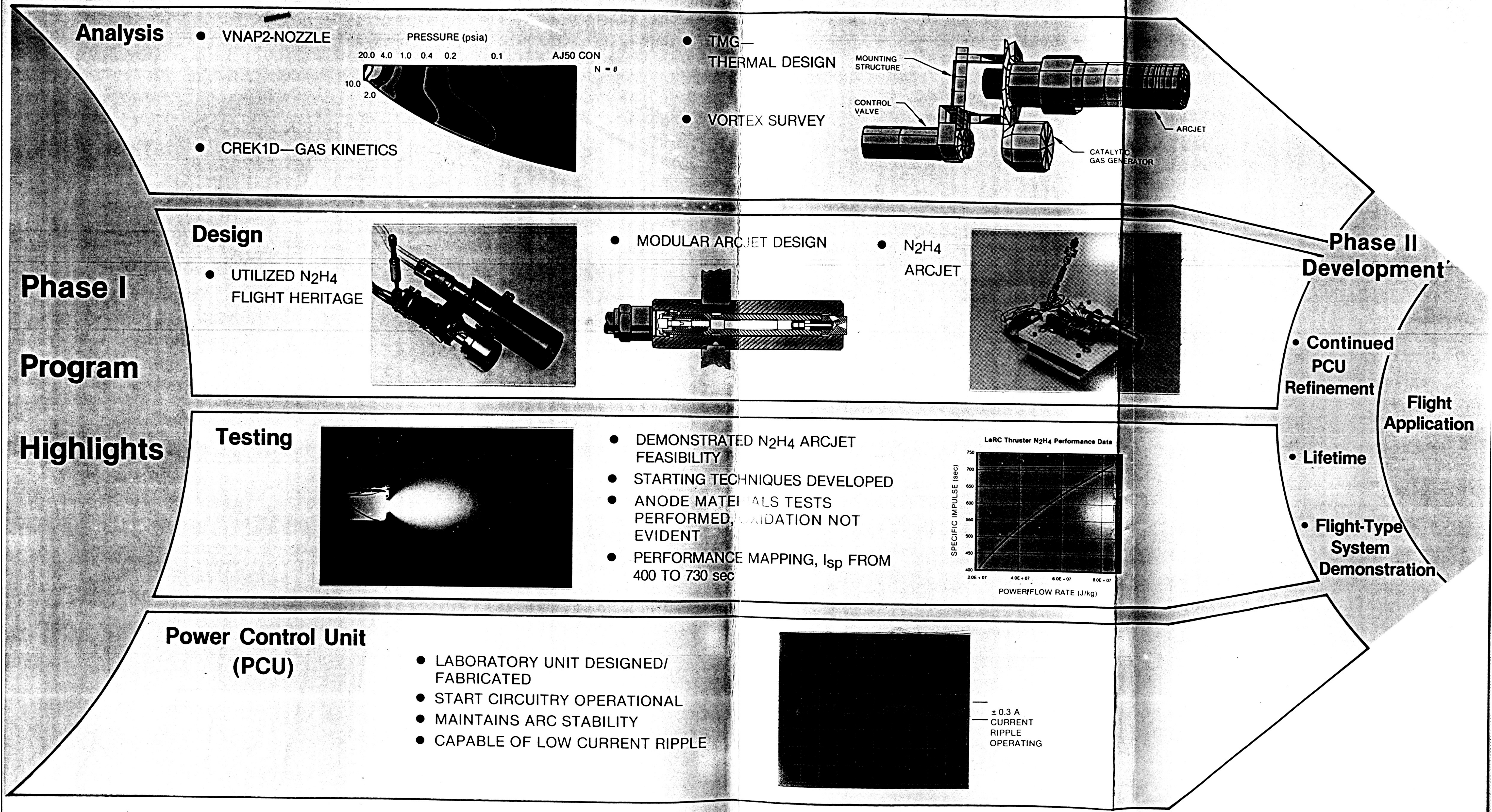


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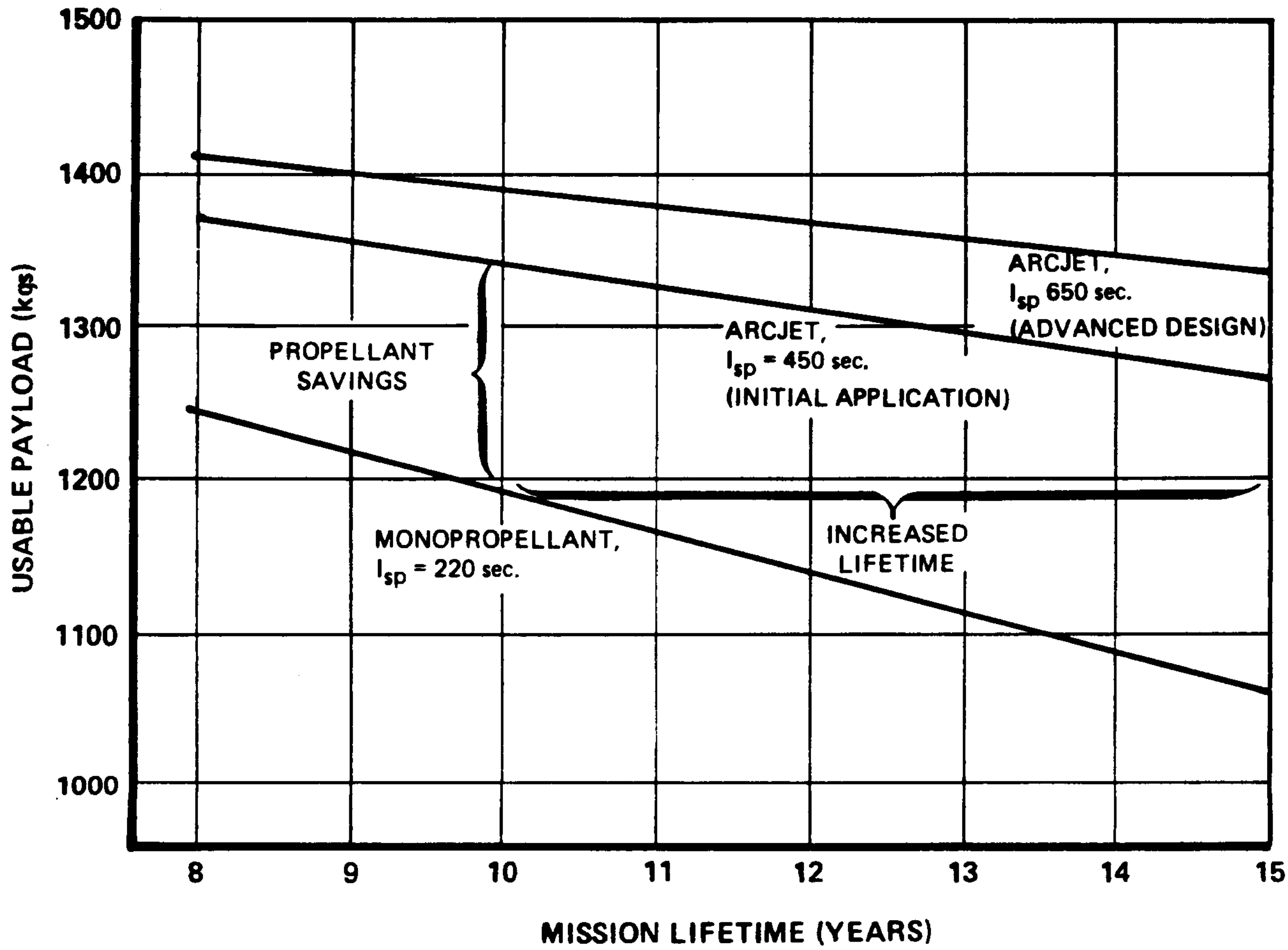
Figure 1-2

2.0 INTRODUCTION

Low power arcjet technology offers substantial mission benefits to near-term spacecraft with attitude control and stationkeeping requirements. Propellant mass savings enabled by the gain of 200 to 400 seconds in specific impulse over existing systems increase payload mass fractions and/or spacecraft lifetimes. These benefits are summarized in Figure 2-1. This can be accomplished using state-of-the-art storable propellant systems with a minimum influence on spacecraft integration or operation. The increased power available on current generation satellites has made application of this valuable technology feasible. The increased mass of these spacecraft has produced a definite need for low power arcjet development. This phase of the program has advanced the technology readiness of this auxilliary propulsion concept in response to these considerations. The following sections discuss the results of the tasks shown in Figure 2-2.

N_2H_4 Arcjet Mission Benefits

- *GEOSYCHRONOUS N-S STATIONKEEPING*
- *1500 kg TOTAL ON-ORBIT MASS = USABLE PAYLOAD + PROPELLANT MASS*
- *49 m/s PER YEAR*



BENEFITS

- *148 kg ADDITIONAL USABLE PAYLOAD FOR 10-YEAR MISSION AT 450 sec-I_{sp} DUE TO PROPELLANT SAVINGS*
- *>5 YEARS INCREASED LIFE FOR SAME INITIAL PROPELLANT MASS*

PHASE I Task Interrelationships

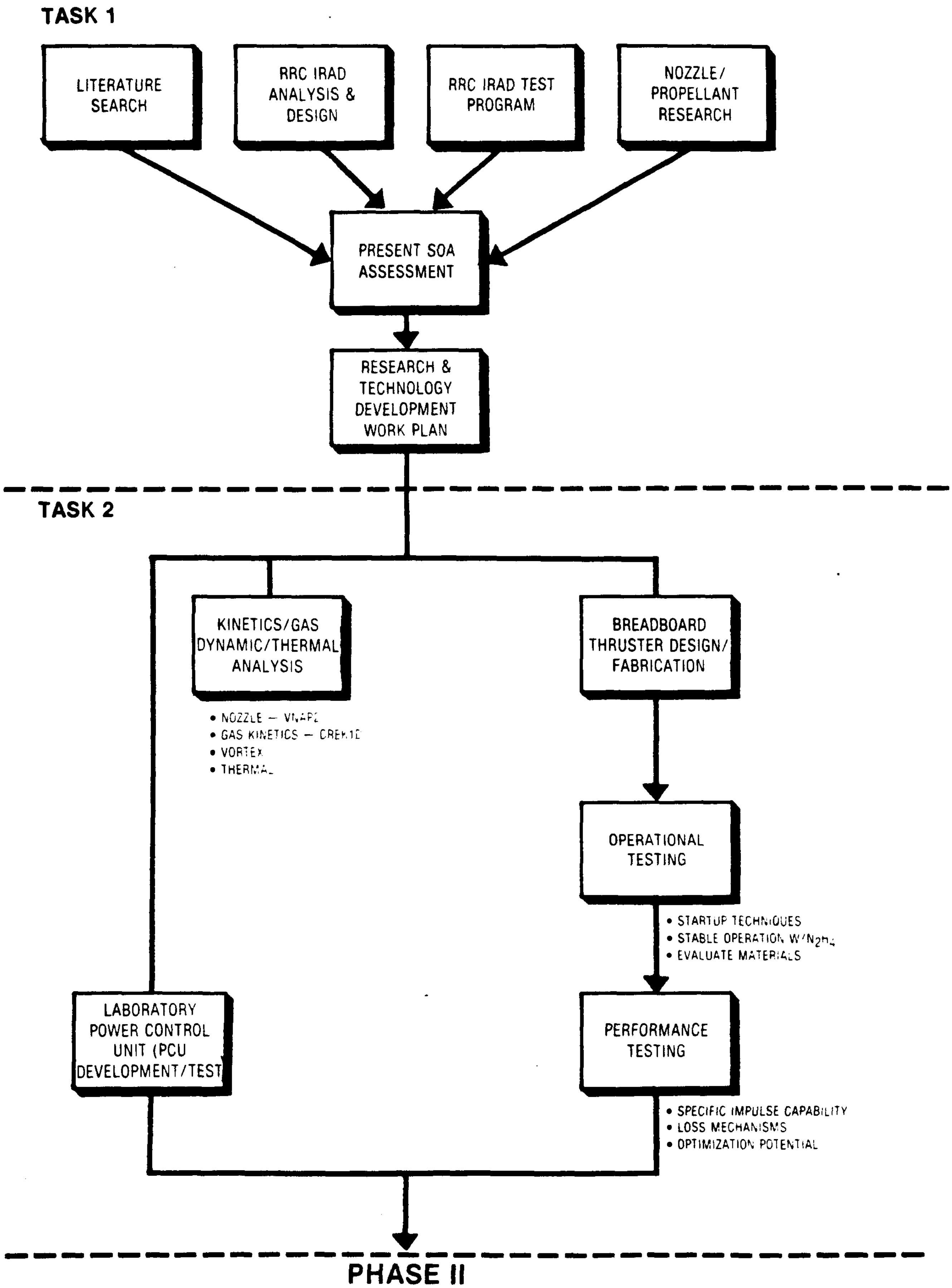


Figure 2-2

3.0 PROGRESS

3.1 Analysis

Analysis efforts were conducted to better characterize the kinetic, gas dynamic, and thermal environment of the arcjet. These studies were used to guide design efforts, to interpret test results, and to improve the fundamental understanding of arcjet behavior. The four areas investigated are summarized in Figure 3-1.

Figure 3-2 summarizes the nozzle analysis methodology and results. Because of the very low Reynolds numbers in a low power arcjet nozzle (< 800), viscous losses dominate for expansion ratios greater than 50. The results indicated that large efficiency gains could not be expected from nozzle optimization. The nozzle design may, however, influence the thermal efficiency by affecting the pressure gradients at the arc attachment point.

Analysis of the arcjet gas kinetic effects was performed using the computer code CREK1D. The reactions and results for an N_2H_4 system are summarized in Figure 3-3. The arc/gas energy transfer was shown to be a very non-equilibrium process due to the short gas residence times ($< 1 \times 10^{-6}$ sec) in the arc region. Frozen flow losses, then, cannot be treated accurately using equilibrium assumptions. Further work is dependent on obtaining reaction rate data above $5000^{o}K$.

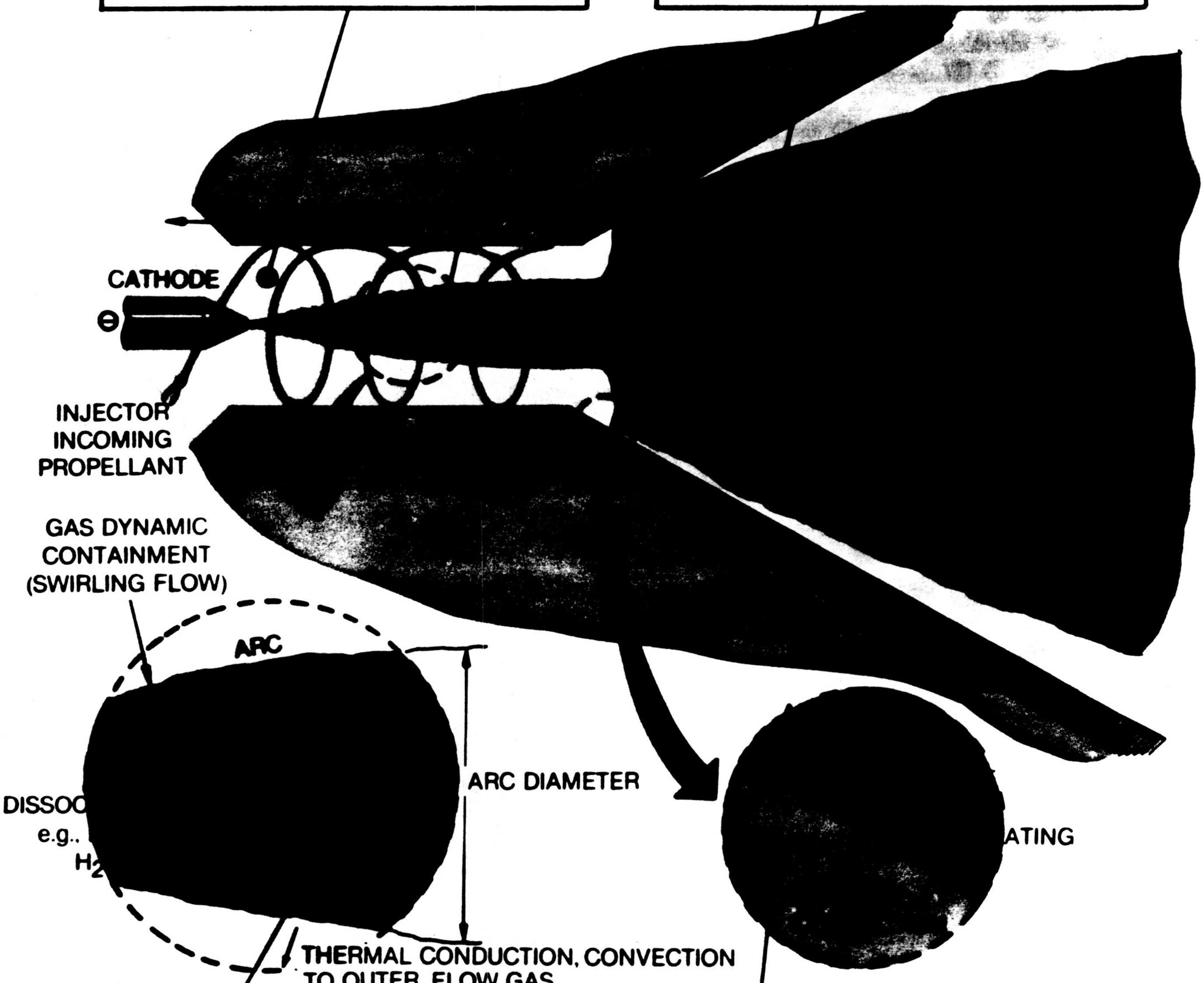
An extensive review of approaches to describing vortex phenomena was completed. The vortex helps to stabilize the arc and may assist during arc initiation. The key areas of interest were vortex generation parameters to guide injector design and vortex disruption through viscous dissipation or reversed flow effects. Existing formulations were found to be inadequate to the task of quantifying these phenomena. Detailed analysis of the arc/vortex interaction was deemed beyond the scope of the program, but is worthy of future efforts.

A detailed thermal model of the breadboard N_2H_4 arcjet was produced, as shown in Figure 3-4. This was used to guide design choices and to back out anode arc attachment losses based on test thermocouple data. Surface temperatures on the arcjet body are typically less than $1350^{o}K$. This is a less severe thermal environment than that of an

Arcjet Analysis Summary

- Vortex — Literature Survey
  - Arc stabilization
  - Injector design
  - Startup

- Nozzle — VNAP2
  - Nonuniform profile affects
  - Nozzle performance
  - Optimized design



- Gas Kinetics — CREK1D
  - Arc gas heat trasfer
  - Nonequilibrium effects
  - Frozen flow losses

- Thermal — TMG
  - Thermal design
  - Anode arc attachment heat losses

VNAP2 Arcjet Nozzle Analysis

- **NOZZLE INLET CONDITIONS CALCULATED WITH ARCJET III CODE**

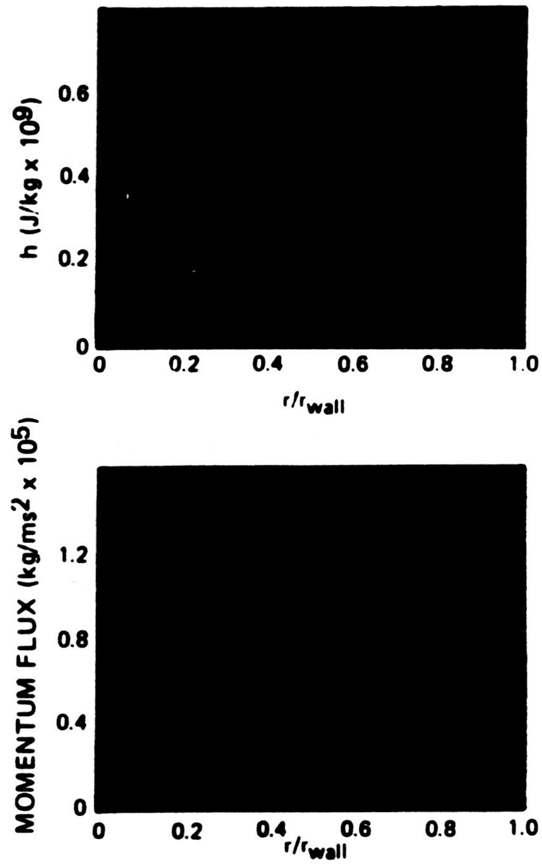
ARCJET III

COUPLED ENERGY, MOMENTUM, CONTINUITY EQUATIONS

$$\frac{\rho u\, \partial h_t}{\partial z} + \frac{\rho v\, \partial h_t}{\partial r} = \frac{I^2 \sigma}{(\int_A \sigma\, dA)^2} + \frac{1}{r}\frac{\partial \varphi}{\partial r} + \frac{\partial^2 \varphi}{\partial r^2} - \text{radiation}$$

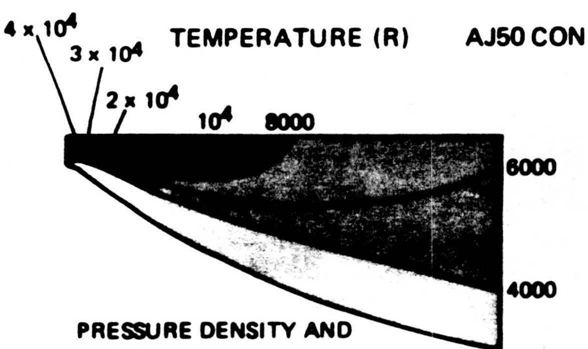
$$\frac{\rho u\, \partial u}{\partial z} + \frac{\rho v\, \partial u}{\partial r} = -\frac{dp}{dz} + \frac{1}{r}\frac{\partial}{\partial r}\left(r\mu \frac{\partial u}{\partial r}\right)$$

$$\int_A \sigma u\, dA = \dot{m};\ \varphi = \int k dT$$

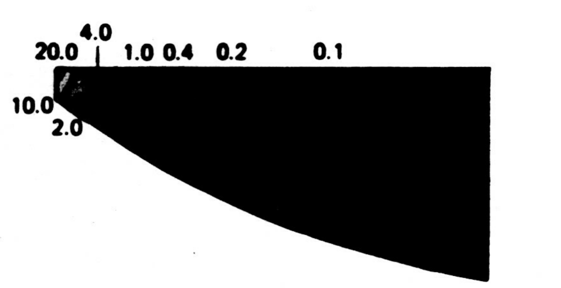


NONUNIFORM INLET PROFILES

- **VNAP2 RESULTS**



PRESSURE DENSITY AND TEMPERATURE PROFILE, CASE 6.



- **CONCLUSIONS**
  - VISCOUS LOSSES DOMINATE FOR $\epsilon > 50$
  - LARGER EXPANSION ANGLES MORE EFFICIENT
  - NOZZLE WILL NOT PROVIDE LARGE PERFORMANCE GAINS
  - VNAP2 COULD HELP STUDY OF ANODE ARC ATTACHMENT PRESSURE DEPENDENCE

Reaction Kinetics Modeling

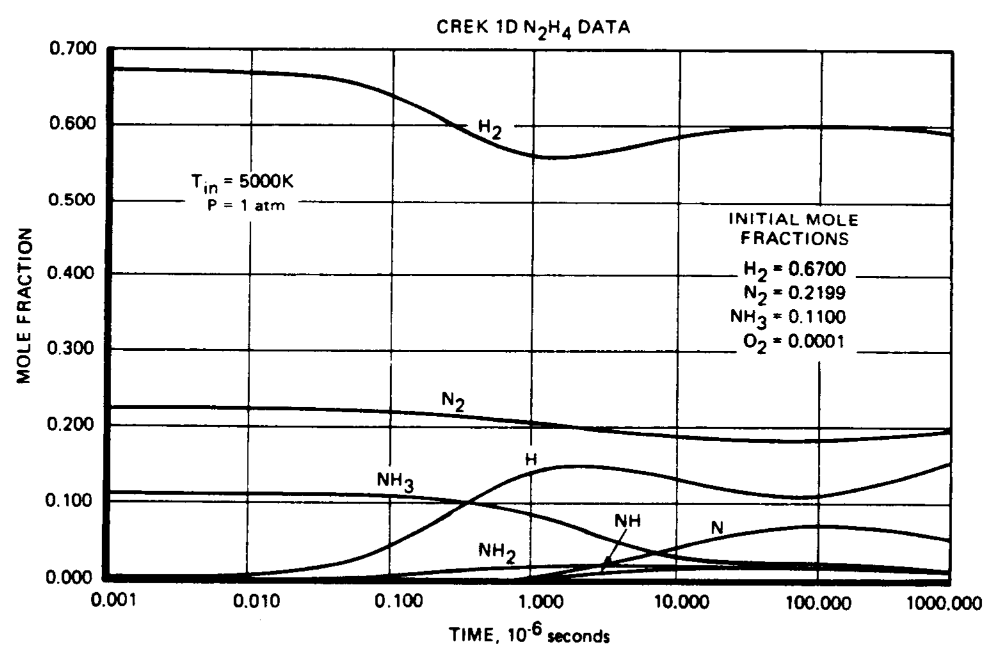
- **REACTION RATE CONSTANTS ASSEMBLIED FOR N-H SYSTEM**

Reaction	A	N	E kcal/mol
$NH_3 + M = NH_2 + M$*	E 14.52	0.0	84.2
$NH_2 + NH_2 = NH_3 + NH$*	E 12.60	0.0	5.56
$H + NH_3 = NH_2 + H_2$*	E 12.0	0.0	6.23
$H + NH_2 = NH + H_2$*	E 10.92	0.0	5.60
$H + O_2 = O + OH$	E 14.34	0.0	16.492
$H_2 + O = H + OH$	E 13.48	0.0	19.339
$H_2O + O = OH + OH$	E 13.92	0.0	18.121
$H + H_2O = H_2 + OH$	E 14.0	0.0	19.870
$N + O_2 = NO + O$	E 9.81	1.0	6.25
$N_2 + O = N + NO$	E 13.85	0.0	75.506
$NO + M = N + O + M$	E 20.6	-1.5	149.025
$H + H + M = H_2 + M$	E 18.0	-1.0	0.0
$O + O + M = O_2 + M$	E 18.14	-1.0	0.340
$H + OH + M = H_2O + M$	E 23.88	-2.6	0.0
$H_2 + O_2 = OH + OH$	E 13.0	0.0	4.3

* "Review and Evaluation of Rate Data for Gas Phase Reactions of the N-H System," Melvin C. Branch et al. 4D-755 855 California Univ., 1971.

$K = AT^N e^{-(E/RT)}$

- **CREK1D USED TO CALCULATE MOLAL SPECIES CONCENTRATION WITH TIME FOR N_2H_4 SYSTEM**



- **COMPARISON RUN MADE BY NASA LeRC WITH GCKP84. AGREEMENT WITHIN 1.5%**
- **CONCLUSION**
  - **REACTION KINETICS PLAY DOMINANT ROLE IN DETERMINING SPECIES, ENERGY DEPOSITION IN ARCJETS**

N_2H_4 Arcjet TMG Thermal Model

DESCRIPTION

- FINITE DIFFERENCE THERMAL ANALYSIS PROGRAM
- CHARACTERIZE TRANSIENT & STEADY-STATE THERMAL ENVIRONMENT
- DESIGN TOOL FOR PROTECTION OF CRITICAL ELEMENTS — VALVES, SEALS
- AID PERFORMANCE ANALYSES BY QUANTIFYING HEAT FLUXES

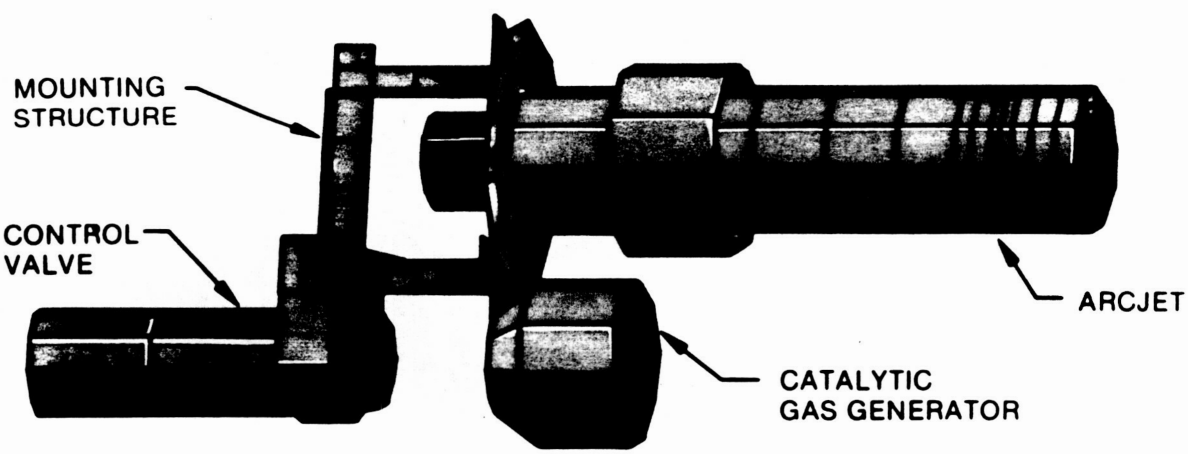


Figure 3-4

3.2 Design/Fabrication

The N_2H_4 arcjet design used for all testing was based on existing flight qualified hydrazine technology, and on arcjet literature review and analysis results. The design is shown in Figure 3-5. The design is highly modular to permit extensive parametric testing. The arcjet body is approximately 13 cm long by 3 cm in diameter. The constrictor (throat) is typically 0.076 cm in diameter. The electrode spacing ranges between 0.035 and 0.050 cm.

3.3 Operational Testing

The objectives of the operational testing phase are shown in Table 3-1.

Table 3-1
Operational Testing Objectives

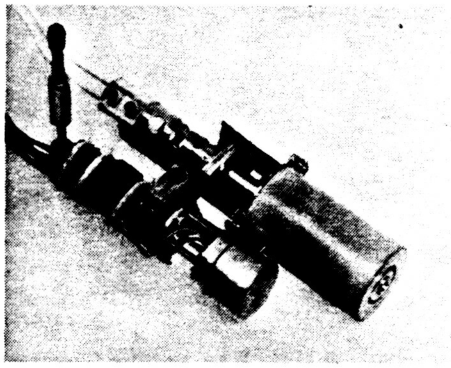
- o Develop starting techniques.
- o Demonstrate arc stability with catalytically decomposed N_2H_4.
- o Evaluate materials compatibility in N_2H_4 plasma environment.

Mission analysis indicates the arcjet must start from 200 to 500 times during a typical 10 year geosynchronous mission. These must be reliable, repeatable, and cause no compromising electrode erosion.

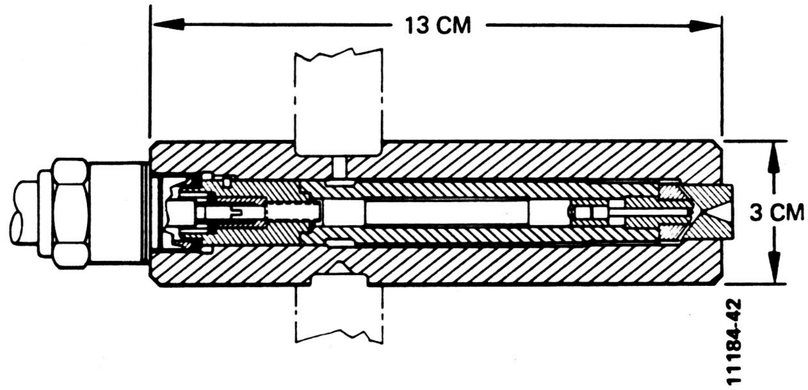
Starting the arc requires applying from 600 to 2000V across the electrodes to initiate an ionized path. Collisional effects cause a rapid increase in temperature and electrical conductivity and a corresponding drop in voltage as the arc is established. Figure 3-6 briefly describes the startup. Erosion can occur at the first anode attachment point if the localized heating is too severe. Preventing this involves using proper electrode geometries to avoid field concentrations, gas flow control, and limiting the current overshoot from the PCU.

It was demonstrated that non-erosive starts could be produced. Multiple startups were accomplished using a mass flow off-pulsing technique that allowed breakdowns from 600 - 800 V. Otherwise, upward of 2000V are required at steady state flow rates. PCU development was accelerated to allow further refinement of startup.

Low Power Hydrazine Arcjet

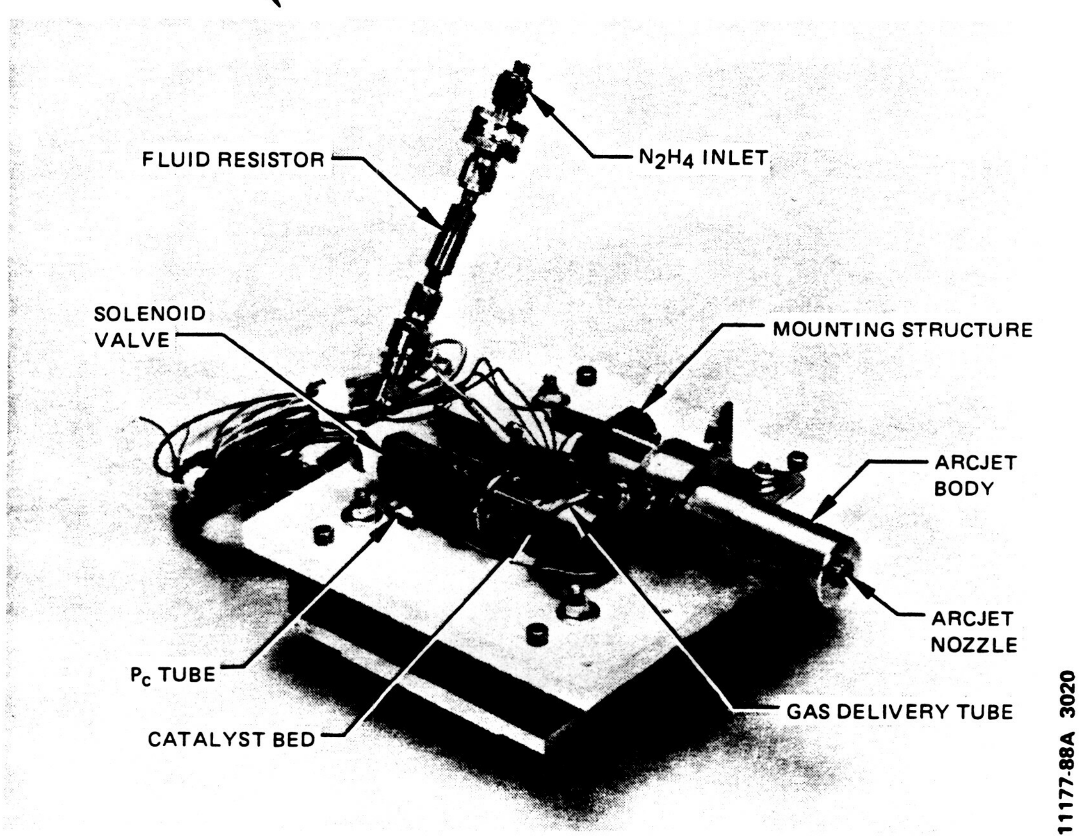


AUGMENTED CATALYTIC THRUSTER

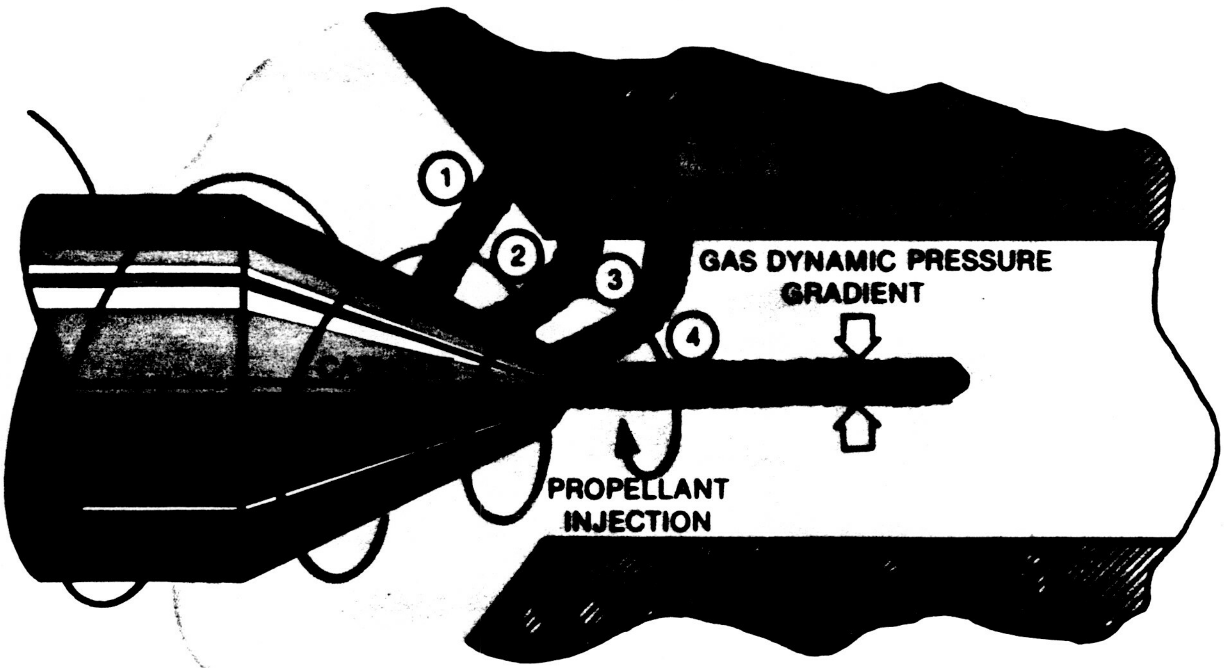


ARCJET CROSS SECTION

- RRC HAS DELIVERED OVER 60 ACT UNITS
- FLIGHT PROGRAMS:
  - – SATCOM F, G, H & I
  - – SPACENET I–IV
  - – G-STAR I–IV
  - – ASC I–III
  - – SATCOM Ku-BAND I–III



Arcjet Startup Sequence



(1) AT LOW MASS FLOW RATE, ARC STRIKES ACROSS GAP AT MINIMUM OR NEAR MINIMUM DISTANCE

(2) MASS FLOW RATE IS INCREASED, COOLING THE SURFACES AND INCREASING THE RESISTIVITY OF THE GAS — ARC REACTS BY MOVING DOWNSTREAM AHEAD OF HIGHER PRESSURE FRONT

(3) PROCESS FROM (2) CONTINUES AS ARC LENGTHENS, ITS AXIAL COMPONENT GETS LARGER. VORTEX INDUCES A GAS DYNAMIC PRESSURE GRADIENT IN THE CONSTRICTOR, WHICH ACTS TO DRIVE THE ARC TO THE CENTERLINE

(4) ARC IS ESTABLISHED ON THE CENTERLINE OF THE CONSTRICTOR

Arc stability was also demonstrated over broad ranges of operating conditions. It was not known prior to these tests how the arcjet would operate on the input 1100°K N_2H_4 decomposition products. No stability problems were encountered. Figure 3-7 shows an N_2H_4 arcjet firing.

Tests were conducted to assess the compatibility of several anode materials with the MIL-P-26536C, Amendment 2, Hi Purity grade N_2H_4, which contains approximately 1.0% H_2O. Table 3-2 lists the materials and summarizes the results. Rhenium alloys were selected for evaluation because of their increased resistance to oxidization.

The conclusions reached are:

1 No oxidization due to the H_2O content of N_2H_4 was observed. Short residence times may be responsible.

2. Some depositions were seen on upstream surfaces.

3. Startup erosion is melting point sensitive. PCU refinement may improve tolerance.

4. Tungsten and tungsten/25 rhenium appear to be best suited for erosion resistance. Longer duration tests are required for further assessment.

5. Very long life anodes appear feasible with N_2H_4.

3.4 Performance Testing

Performance testing was conducted for the first time with decomposed N_2H_4. The test objectives were to determine performance capabilities and to investigate the sensitivity of the specific impulse and efficiency to the configuration.

Tests were made over a range of power from 1000 to 2800 W. A consistent relationship was found between the specific impulse and the ratio of the electrical power to the mass flow rate, as shown in Figure 3-8, regardless of the configuration. Most of the data fell within ± 15 seconds of the curve shown. Apparently, the voltage/current characteristic of the arc is not strongly linked to the efficiency of the arc energy transfer. This allows the design to be driven by lifetime and operational requirements without a loss of performance.

N_2H_4 Low Power Arcjet

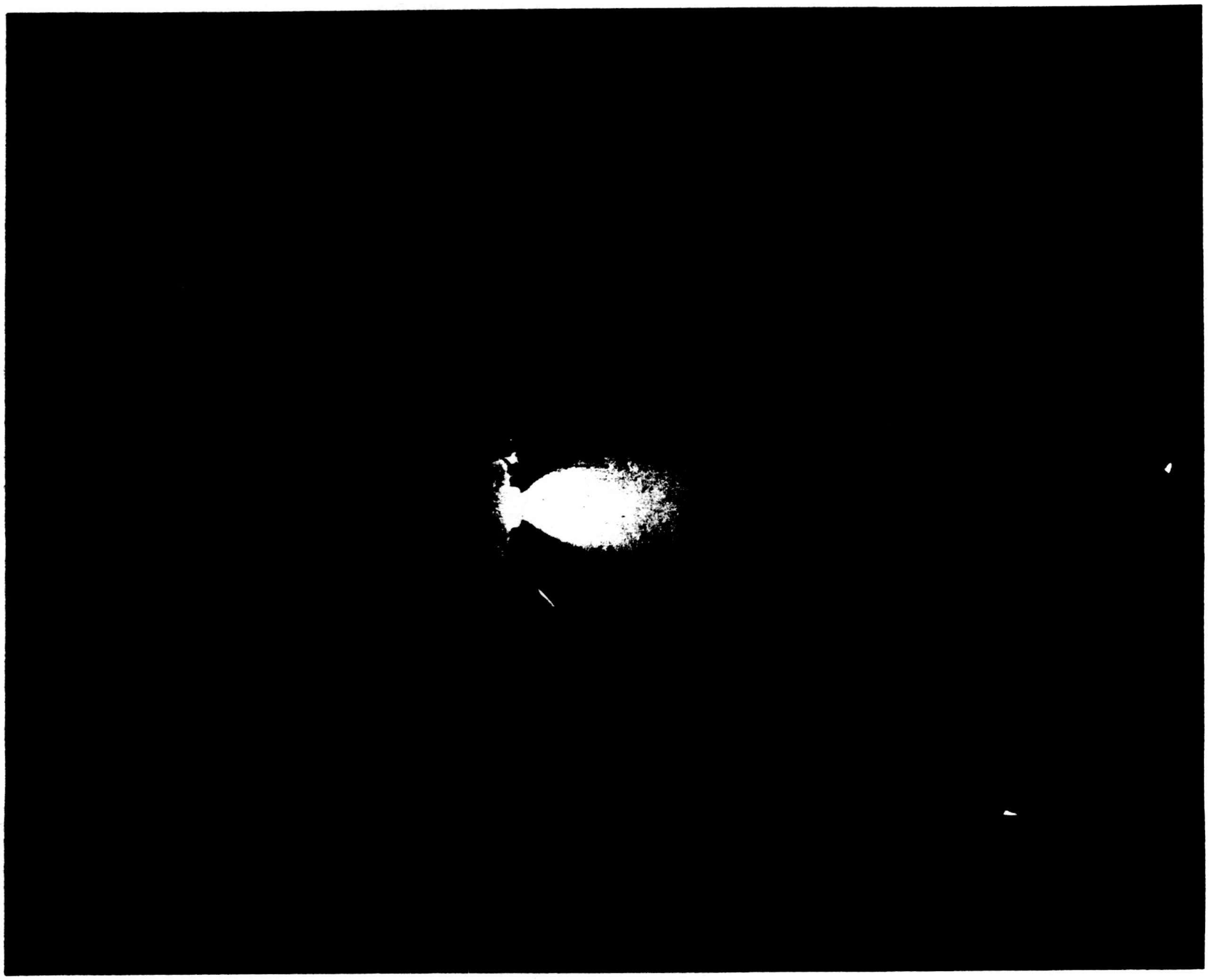


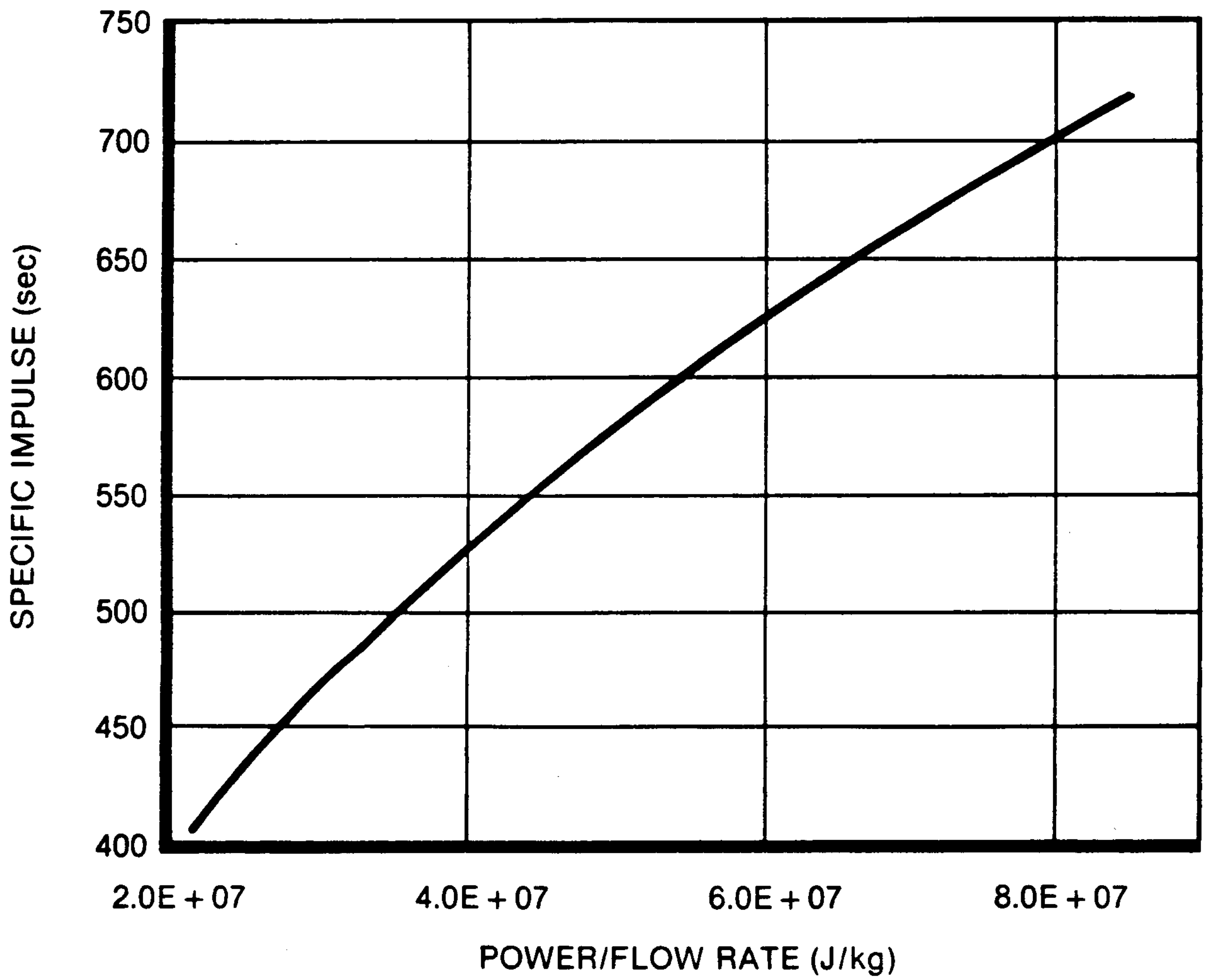
Figure 3-7

Table 3-2

Anode Materials Test

Materials	Power Level	Results
Tungsten	1.1 kW	No chemical erosion after 8 hours. Machine marks still evident in constrictor.
Tungsten	1.8 kW	No oxidation. Five radial fractures seen due to quenching by the injected gas.
Tungsten/25 Rhenium	2.0 kW	No oxidation, some upstream surface depositions. Slightly increased startup erosion.
Moly/41 Rhenium	1.9 kW	No oxidation, upstream surface pitting and depositions. Increased startup erosion.
Rhenium	1.9 kW	No oxidation, minor upstream depositions. Moderate startup erosion.

N_2H_4 Arcjet Performance
Curvefit Based on Test Data, 1000 — 2800 W



Furthermore, a specific impulse level of 730 seconds was demonstrated. This is significantly higher than was thought possible with N_2H_4. Even higher levels are feasible, as no high performance failure modes (e.g., anode spot formation) were observed.

Overall conversion efficiencies proved to be in the 30 - 35% range. There are several loss mechanisms. Thermal losses to the structure due to localized heating at the arc attachment points on the electrodes account for 10 - 20% of the losses. Frozen flow effects are responsible for roughly 50% of the overall losses. Ionization and dissociation reactions consume energy that is not converted to directed kinetic energy in the nozzle because of slow recombination rates. The nozzle accounts for 25 - 35% of the losses. The Reynolds numbers are below 1000, so a trade exists between expansion gains and viscous losses.

Table 3-3 summarizes the performance test results.

Table 3-3

N_2H_4 Arcjet Performance Testing Summary

- I_{sp} levels from 400 to 730 seconds demonstrated.
- Constrictor geometry, vortex, and electrode gap do not strongly effect the performance.
- A single geometry is quite versatile, operating over broad ranges of power and performance.
- Frozen flow losses are large; nozzle, thermal losses secondary.

3.5 Power Control Unit Development

The power control unit (PCU) is an important element of the arcjet system. For flight application, the PCU must operate off of the nominal 28 VDC of the batteries while starting and maintaining the steady state stability of the arcjet. Table 3-4 lists the PCU functional requirements. It was not originally intended during Phase I to begin PCU hardware development. Initial testing, however, demonstrated the importance of evaluating the arcjet with a properly designed PCU. Startup erosion, for instance, can be effectively eliminated by the PCU through control of the initial current level. The

Table 3-4

PCU Functional Requirements

- Operate over range of spacecraft battery letdown voltage (32-25 VDC)
- Start arcjet (2000V pulse)
- Ramp up current to steady state value with no overshoot
- Maintain DC and dynamic arc stability
- High conversion efficiency (>90%)
- Meet EMI standards
- Light weight, reliable

program was slightly re-structured to allow the procurement of a laboratory PCU during Phase I without compromising other on-going tasks.

The unit was developed under subcontract to Space Power, Incorporated and is shown schematically in Figure 3-9. A high degree of variability in the startup sequence and in the steady state operating controls was included for parametric tests. The voltage boost requirement was relaxed for this work.

Figure 3-10 summarizes the Phase I results with this unit. The supply was able to non-erosively start and stabilize the arcjet, and at the proper operating points, could reduce the output current ripple to near zero. Further work is continuing under Phase II to better define the starting parameters and the steady state stability criteria.

PCU Block Diagram

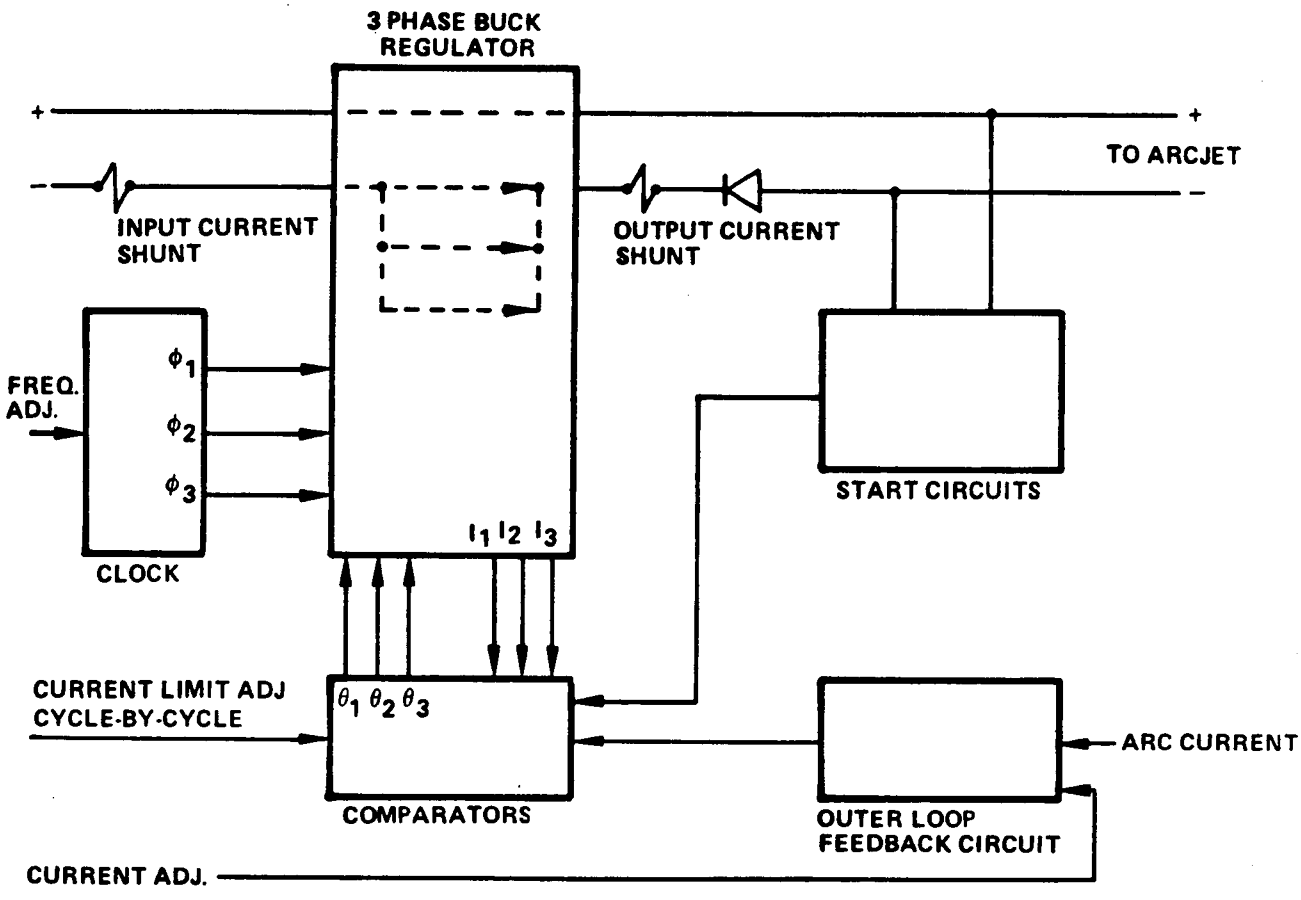
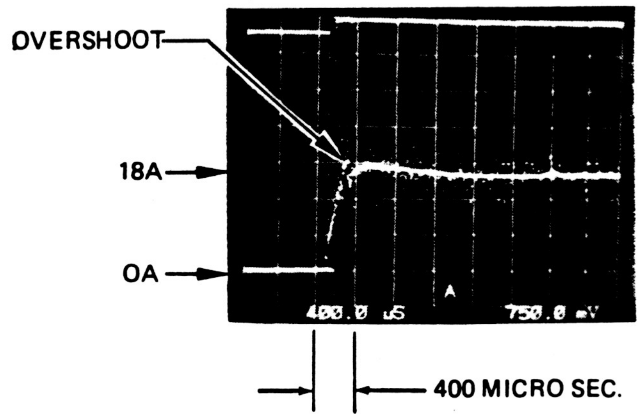


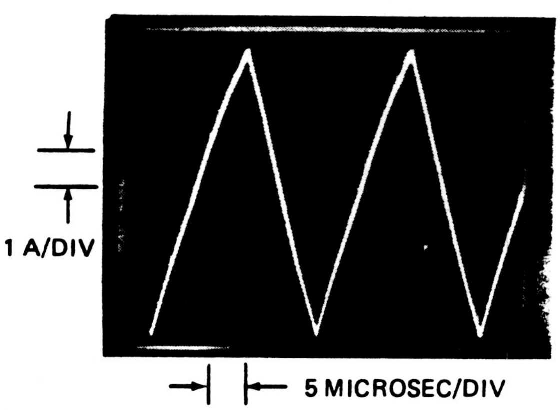
Figure 3-9

PCU Development Results

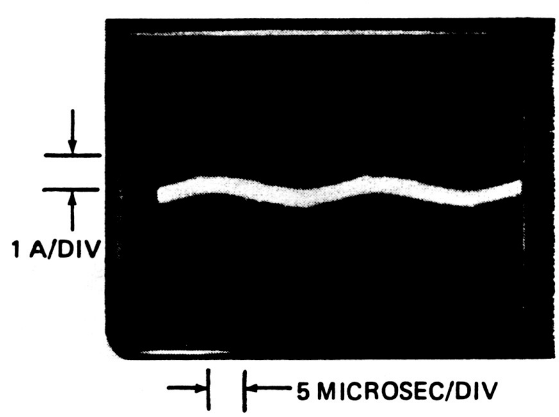
- STARTUP CIRCUITRY OPERATIONAL, SOME CURRENT OVERSHOOT STILL PRESENT



- ARCJET STABILITY MAINTAINED, 8–30 A
- 3-PHASE SUPER POSITION REDUCES CURRENT RIPPLE



- SINGLE LEG CURRENT VARIATION 7.5 A



- SUPERPOSITION REDUCES RIPPLE TO < 1 A, PEAK-TO-PEAK

Figure 3-10

4.0 FUTURE WORK

Phase II of the Arcjet Thruster Research and Technology program is presently being carried out at Rocket Research Company. The primary emphasis of this phase is to develop the technology to demonstrate multi-hundred hour lifetimes in a duty cycle mode. Reducing the steady state erosion of the cathode is the key lifetime issue. Additional tasks include a survey of the possible constraints imposed by the spacecraft on the arcjet system, further PCU development work, detailed measurements of the dynamic arcjet impedance to support stability analyses, and testing of hardware provided by the NASA Lewis Research Center to show repeatable results at a separate facility. During the final part of the program a flight type arcjet/PCU system will be developed and tested that will adhere to many of the design and operational requirements of a real flight system. This will serve to demonstrate the flight readiness of the N_2H_4 arcjet technology developed under this program. The Phase II task breakdown is given in Figure 4-1.

PHASE II TASK BREAKDOWN

TASK 1 FLIGHT REQUIREMENTS STUDY

- 1.1 SPACECRAFT SYSTEMS SURVEY
- 1.2 ARCJET SYSTEM SENSITIVITY ANALYSIS

TASK 2 RESEARCH AND TECHNOLOGY DEVELOPMENT

- 2.1 DEVELOPMENT TESTING HARDWARE DESIGN/FABRICATION
- 2.2 RRC/LeRC JOINT TESTING
- 2.3 LIFETIME EVALUATION TESTING
- 2.4 CATHODE PROCESSES MODELLING
- 2.5 PCU REQUIREMENTS DEFINITION
- 2.6 PCU DESIGN MODIFICATIONS
- 2.7 LIFETIME DEMONSTRATION THRUSTER DESIGN & FABRICATION
- 2.8 LIFETIME DEMONSTRATION TEST

TASK 3 FLIGHT-TYPE ARCJET DEVELOPMENT

- 3.1 ARCJET PRELIMINARY DESIGN/DOCUMENTATION/APPROVAL
- 3.2 DETAILED DESIGN DEVELOPMENT
- 3.3 ARCJET FABRICATION

TASK 4 FLIGHT-TYPE PCU DEVELOPMENT

- 4.1 PCU PRELIMINARY TESTING HARDWARE DESIGN/DOCUMENTATION/APPROVAL
- 4.2 DETAILED DESIGN DEVELOPMENT
- 4.3 PCU FABRICATION

TASK 5 ARCJET SYSTEM TECHNOLOGY DEMONSTRATION

- 5.1 SYSTEM PERFORMANCE CHARACTERIZATION
- 5.2 SYSTEM LIFE TESTING

TASK 6 REPORTING

- 6.1 MONTHLY TECHNICAL/FINANCIAL REPORT
- 6.2 QUARTERLY FINANCIAL MANAGEMENT REPORT
- 6.3 PROGRAM REVIEW
- 6.4 PRELIMINARY DESIGN REVIEW
- 6.5 DETAILED DESIGN REVIEW
- 6.6 FINAL REPORT
- 6.7 EXECUTIVE SUMMARY

11188-71

Figure 4-1