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New Developments and Research Findings: NASA Hydrazine Arcjets

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New Developments and Research Findings: NASA Hydrazine Arcjets

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Abstract

In 1984, the market for commercial geosynchronous communications satelites (comsats) was expanding and there was strong competition between spacecraft builders for market share. The propellant required for the north-south stationkeeping (NSSK) function was a major mission limiter, and the small chemical and resistojet systems then in use were at or near their physical limits. Thus, conditions were right for the development of a high performance NSSK system, and after an extensive survey of both propulsion technologies and the aerospace community, the NASA program chose hydrazine arcjets for development. A joint government/industry development program ensued which culminated in the acceptance of arcjet technology. NASA efforts included fundamental feasibility assessments, hardware development and verification, and multiple efforts aimed at the demonstration of critical operational characteristics of arcjet systems. Throughout the program, constant contact with the user community was maintained to determine system requirements. Both contracted and cooperative programs with industry were supported. First generation, kW-class arcjets are now operational for NSSK on the Telstar 401 satellite launched in December of 1993 and are baselined for use on multiple future satellite series (Intelsat 8, AsiaSat, Echostar). Arcjet development efforts are now focusing on the development of both high performance (600 s) , 2 kW thrusters for application on next generation comsats and low power (Pe ~ 0.5 kW) for a variety of applications on power limited satellites. This paper presents a review of the NASA's role in the development of hydrazine arcjets with a focus on approaches, lessons learned, and the future.

Introduction

The NASA On-Board Propulsion program develops innovative, high performance systems for a broad range of space missions.[1-3] Experience indicates that successful technology transfer requires both a high potential payoff to the user and technology demonstrations sufficient to reduce perceived risks to an acceptable level. Commercial communications satellites often represent targets of opportunity for first use of technology because of the economic leverage high performance systems can provide. In 1984, small chemical and resistojet systems were the state-of-art (SOA) for NSSK of geosynchronous communications satellites. These systems provide approximately 300 s of specific impulse and are near their physical limits of performance. Figure 1 shows the propulsion related mass fractions for several recent communications satellites. The chart illustrates that NSSK propellant is a major mission driver, and after a review of propulsion systems and a survey of the industry, hydrazine arcjet systems for NSSK were targeted for development by the NASA program. Estimates indicated that arcjets could provide a 1.5 - 2.5 increase in specific impulse over the SOA systems. For a typical comsat, this would translate into a mass savings of several hundred kilograms of propellant which could be used to increase satellite life and/or payload fraction and/or to reduce launch vehicle class. The latter payoff is illustrated in Figure 2. Here, the mass required in geosynchronous transfer orbit is plotted against the NSSK system specific impulse for a typical communications satellite. As shown, the reduction in GTO mass attained using arcjets is sufficient to create an international launch vehicle competition. Hydrazine arcjet systems also offered several other potential advantages. They were compatible with the emerging "dual mode" spacecraft system concept in which hydrazine is used for both apogee and NSSK propulsion. The use of power for propulsion was well also established and arcjets could take advantage of anticipated growth in commercial spacecraft power capabilities. Thus, it was felt that the potential benefits were large enough to attract potential users if perceived risks could be sufficiently reduced through an aggressive development and demonstration effort. The ensuing NASA/industry cooperation led to successful application of a new technology with NASA taking an active role from program inception through initial acceptance and beyond.

The objective of this paper is to provide a description of the NASA hydrazine arcjet development program focusing on program approaches, lessons learned, and current program directions.

Program Description

An overview of the NASA arcjet development program is shown in Figure 3 and the following sections describe efforts under the program from inception to this writing.

Feasibility Assessments

Initial arcjet testing was carried out at LeRC with arcjet hardware originally developed in the early 1960's for a kW-class hydrogen arcjet flight system.[4,5] For these short duration feasibility tests, nitrogen/hydrogen mixtures were used to simulate hydrazine decomposition products and the arcjet was operated with ballasted laboratory power supplies. Performance measurements indicated that specific impulses of 400 to 600 s were possible with hydrazine arcjets. While these performance levels were very encouraging, major life and reliability issues related both to starting and transition and to arc stability during steady state operation were uncovered in this early testing. Two approaches were taken to address these issues. First, changes in the electrode geometry and flow pattern were implemented in the next generation arcjet design to enhance the gasdynamic force acting on the arc both at startup and in the steady state condition. Next, and perhaps more importantly, a pulse-width modulated (PWM) power processing unit (PPU) with an integrated high voltage pulse starting circuit was designed to replace the ballasted dc supply.[6,7] This PPU design became the basis for future flight-like units. Together, these changes resulted in reliable, nondamaging arcjet startups and stable operation in the steady state condition as shown in Figure 4. Based on the early performance numbers and interest in the user community, industrial involvement was initiated. Two Phase I contracts were issued to further explore arcjet feasibility. One of these efforts was performed by the Rocket Research Co. (RRC - now the Olin Aerospace Co.) who successfully demonstrated high performance levels using hydrazine propellant across a wide range of conditions as shown in Figure 5.[8] The plots show specific impulse versus both thrust to power ratio and specific power (i.e. power to propellant mass flow rate) as these are of most interest to mission planners and propulsion system designers. The data were obtained during parametric testing designed to determine the impacts of electrode geometry on arcjet performance. The plots show first that there was a clear correlation between the specific impulse attained and the parameters of interest. These relations were quite insensitive to thruster geometry. This was an important conclusion in that it implied that the arcjet could be designed to optimize life and reliability without significantly impacting performance. Overall efficiencies measured ranged between 30 and 35 % and experimental data and calculations indicated that the major loss mechanisms were frozen flow, nozzle, and thermal inefficiencies in that order. Meanwhile, an autonomous, 1000 hour/500 cycle endurance test of a modular laboratory arcjet was performed at LeRC to demonstrate that the device could meet the life requirements of commercial spacecraft.[9] Following these initial demonstrations, the program took two directions. The RRC Phase II focused on determining system requirements and the development and verification of flight-type hardware. Discussions with potential arcjet users indicated that resolution of integration issues such as plume impacts and EMI was a key to the eventual application and the in-house program was focused on the assessment and mitigation of these integration impacts.

Hardware Development

Based on a survey of the user community performed by RRC, a set of generic interface requirements for communications satellites was defined and this became the foundation for the Phase II effort. The technical objectives were to develop two flight-type arcjet systems (including thruster, PPU, and gas generator) and to complete a qualification level life test of one of these systems. Programmatically, the effort was intended to both provide the technical maturity required to transfer the technology to end users and assist in establishing an industrial source for the technology. Life, performance, and integration issues drove the design. Throughout the development process, communications with potential users were maintained throughout the development effort so that user concerns/requirements could be addresses as they arose. A photograph of one of the flight-type arcjets which resulted from this effort is shown in Figure 6. Based on the user survey, a 1.4 kW system power level was chosen and the PPU was designed to operate from a 28 V bus. A gas generator design was selected which previously been flight qualified for use with resistojets. Over the course of the development program, the thruster evolved from a modular laboratory model to a flight representative design developed to meet required thermomechanical and electrical specifications and interfaces. To meet these specifications and interfaces, new joining and coating technologies were required. For example, a high emissivity coating for the nozzle was developed to reduce the temperature required to radiate waste heat from this component (Figure 7). The temperature reduction achieved led to acceptable heat loads both at the arcjet/spacecraft interface and at the arcjet electrical cable connector. Thermomechanical qualification tests were successfully performed and one of the systems was subjected to an autonomous, cycled lifetest.[10,11] The thruster and PPU perfomed nominally throughout the qualification test and a mission average specific impulse of more than 450 s was achieved. Problems with the gas generator were encountered during the test, however, and the unit had to be replaced after 680 hours. Inspection revealed a buildup of non-volatile residues (NVR) in the injection tube. Deposits of this magnitude had not been encountered in previous resistojet tests requiring significantly higher hydrazine throughputs. The problem was traced to thermal issues resulting from the lower mass flow rates required in the arcjet system. To ensure adequate gas generator life, two approaches were taken. RRC developed a thermally modified single injector design under IRAD funding and this device was tested for more than 900 hours by the NASA program. Under the NASA-sponsored Phase II effort, a dual inlet injector concept was fabricated and successfully demonstrated. Details of the Phase II program can be found in the literature.[11]

Integration Issues

As noted above, a substantial portion of the arcjet effort was directed toward the assessment and mitigation of integration issues critical to successful flight application. Interactions with potential users indicated that the major concerns were 1) impacts of the partially ionized arcjet plume on both uplink and downlink communications signals and 2) conducted and radiated EMI. Other issues and concerns were contamination, thermal and momentum exchange, and radiated energy (IR to UV). In response to these user inputs, a series of in-house, contracted, and cooperative efforts were undertaken to address these issues to the extent possible in ground-based experiments.

To understand plume impacts on communications, a number of experiments were performed at LeRC to determine the electrical characteristics of arcjet plumes. Electrostatic probes were used to measure both electron number densities and temperatures.[12-14] Typical results are shown in Figure 8. These data were used in two separate analytical assessments of plume impacts on communications. The first of these models was developed by Carney at LeRC.[15] Far field plume characteristics were estimated using a source flow model and the plume was modeled as a plasma slab. Both attenuation and phase shift of a 4 GHz communications signal were estimated and results indicated that impacts on transmission would be negligible for realistic spacecraft configurations. A second, more inclusive, study was undertaken at the University of Texas at Austin (UTA). This group used the previously generated plume data and a cold plasma model to approximate plume characteristics and then applied a ray tracing method to determine the impacts of the plasma on transmission signals. A worst case configuration, in which the signal was directed through the near field plume, was chosen and plume electrical characteristics were varied over a wide range. As in the earlier study, results indicated that kW-class arcjet plumes should not adversely impact communications satellite signals.[16] The UTA model was later exercised by industry using a realistic spacecraft configuration with a similar result.

In addition to the in-house and grant efforts described above, the NASA program supported a large scale arcjet system integration test at TRW, Inc. (with RRC as a subcontractor). This Arcjet System Integration Demonstration (ASID) was designed specifically to demonstrate arcjet/spacecraft compatibility for the benefit of potential users.[17,18] One of the flight-type arcjet systems from the hardware development program was installed near a qualification model FLTSATCOM satellite in TRW's 30 foot diameter space simulation chamber (Figure 9). The arcjet was operated on hydrazine propellant and was powered by a FLTSATCOM battery simulator. Several antennas and probes were used to measure conducted and radiated EMI. An array of calorimeters and radiometers were positioned at various locations to provide information on convective and radiative thermal loads. Finally, witness plates were mounted on the solar panel used in the tests and at various stations in the arcjet exhaust. In order to use the spacecraft as a diagnostic, several critical subsystems were powered and telemetry was monitored throughout the experiment. Radiated emissions measured during the ASID test were generally within accepted limits in frequency ranges above 500 MHz and this indicated that arcjet systems should not affect high frequency communications links typically used on modern communications satellites. Significant broad and narrow band signals were observed in the ASID testing at frequencies below 500 MHz. Some of this noise was directly attributable to the PPU and this was addressed by industry in a follow-on program to develop flight hardware for a specific program. The calorimeter data were provided to industry for thermal management assessments. After three hours of testing under high vacuum conditions, visual inspections and weight measurements of the witness plates revealed no build-up of non-volatile materials. No interference was observed in any of the telemetry signals.

Shortly after the completion of the ASID program, arcjets were baselined for NSSK on General Electric's (now Martin Marietta) 7000 Series spacecraft and these spacecraft were selected for AT&T's Telstar communications satellite series. These arcjet systems operate at a nominal mission average of 500 s specific impulse and are descendants of the flight-type devices developed under the government/industry program. Several integration issues remained open at that time, however, and most of these were addressed through a cooperative program (Space Act Agreement) with General Electric's Astro-Space Division (GE), the spacecraft manufacturer, and RRC, the arcjet supplier.[19,20] The objective of the test was to retire risks perceived both by GE and AT&T. Concerns centered on plume impacts on spacecraft surfaces, electrostatic discharge phenomena, and EMI. Samples of typical spacecraft materials were supplied for the test by GE along with experimental equipment for electrostatic discharge tests. GE also made available a flight-type brassboard PPU which was developed under their program with RRC. RRC provided arcjet hardware and support. The testing was performed in the large space propulsion testbed at LeRC (Figure 10) with an array of antennas for radiated EMI measurements installed. Spacecraft materials samples were arranged so that exposure to the plume would approximate on-orbit conditions. Detailed comparisons of pre- and post-test measurements of critical physical properties of the spacecraft materials samples showed that no significant degradation resulted from plume exposure during the test. Similarly, the effects of electrostatic discharge phenomena were found to be negligible. As in earlier testing both at LeRC and TRW, EMI levels in regions of important to the commercial satellite user community were within acceptable limits. EMI above standard limits was still measured in low frequency ranges and this remains an open issue. While not a major concern with modern commercial communications satellites, the issue may need to be addressed if arcjet systems are considered for some military applications.

As a result of the joint industry/government arcjet development effort, kW-class arcjets reached operational status on the Telstar 401 satellite earlier this year and are baselined on several additional communications satellite series. Given this, the NASA program has now redirected efforts to meet the technical challenges related to next generation arcjet systems.

Program Directions

At present, the NASA hydrazine arcjet program includes the development of 1) high performance (600 s), 2 kW-class arcjet technology for future commercial, geosynchronous comsats[21] and 2) low power ($P_e < 1$ kW) systems for power limited spacecraft.

To increase mission average specific impulse, the arcjet must be run at specific power levels substantially above those used in SOA arcjet systems. In early testing it was found that increasing specific power using SOA arcjet designs and materials led to closure of the anode throat. This phenomenon, illustrated in Figure 11, severely limits arcjet life at the required performance levels. To mitigate this issue, several alternative design approaches, Figure 12, were examined. Most successful was the use of high temperature materials in the critical throat region and the program focused on the use of several advanced refractory materials developed in previous NASA programs. Initial tests of one of these proved very encouraging as sustained operation was achieved at anode temperatures approximately 700°C above those typical of SOA systems. Material availability was an issue, however, and the program provided support to (re)develop a source of the material. Other design improvements, such a redesigned cathode to reduce long term degradation, were also implemented under the NASA program. At this writing, a flight-representative thruster had been assembled and over 450 hours of a qualification level life test (scheduled for 1000 hours) were complete. As noted above, this technology will be transitioned to the commercial sector if the development effort is successful. Beyond this, it NASA's intent to push the performance limits of the technology and to this end, several high temperature materials are under evaluation. Starting at the very low flow rates required for operation at mission average specific impulses above 600 s is also expected to be a problem. To address this issue, two starting techniques are under development. The first involves modifications to PPU control circuitry to limit current levels in the period before the arc transitions to its steady state position.[22] The second employs a pressure pulse technique to facilitate rapid transition to the steady state operating condition.[23] Both of these techniques may also be applicable to the low power systems discussed below.

A market for low power arcjets is also emerging and NASA program is accelerating efforts to develop this technology for several potential applications. These applications include insertion, orbit maintenance, and deorbit for proposed low- and mid-Earth orbit systems and NSSK for power limited geostationary spacecraft. For both of these targets it appears that a system operating at approximately 500 s mission average specific impulse would provide significant advantages over SOA systems. In anticipation of these applications, NASA has maintained a low level, in-house program over the past several years. Hardware, including a breadboard PPU[24] and modular, low power thrusters, have been developed and tested to obtain performance estimates and to explore issues related to starting and steady state operation at low power levels.[25,26] Following the example of the kW-class program, the program is now initiating a contracted effort aimed at development of flight-type hardware.

Concluding Remarks

Arcjets are now operational for NSSK on commercial satellite systems as a result of joint NASA/industry efforts between the inception of the program in 1984 and initial flight in 1993. The NASA program philosophy was to support the technology from initial feasibility demonstrations through operational application. While technology insertions are often program specific, several of the lessons learned appear to have general applicability. The experience gained suggests that in the development of a new system, all critical elements must be considered from the start. This recommendation extends to subsystems, like the arcjet gas generator, with prior flight history at different operating points. It is likely that integration issues (thermal, electrical, plumes, EMI) etc.) will be an overriding concern of decisionmakers and will drive design details. For this, intense and sustained interactions with potential users are required in order to determine both hardware requirements and perceived risks as they arise. Industrial sources of flight-type hardware are critical and hardware developed must be verified over qualification envelopes covering known application requirements. Finally, support is often required even beyond initial acceptances as new user concerns arise. These approaches are now being applied in follow on programs aimed at the development of both high performance 2 kW-class and subkW-class arcjets.

Acknowledgements

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STATE-OF ART IMPACTS

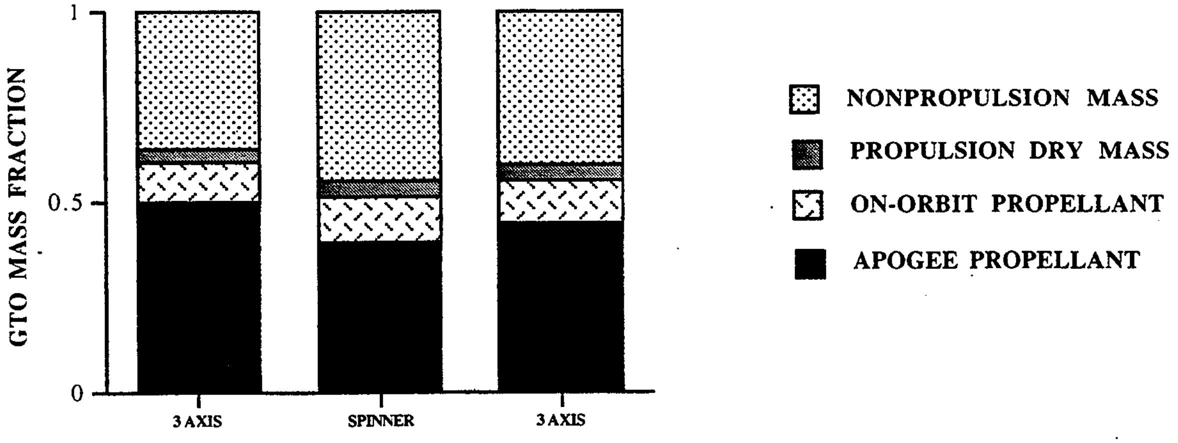
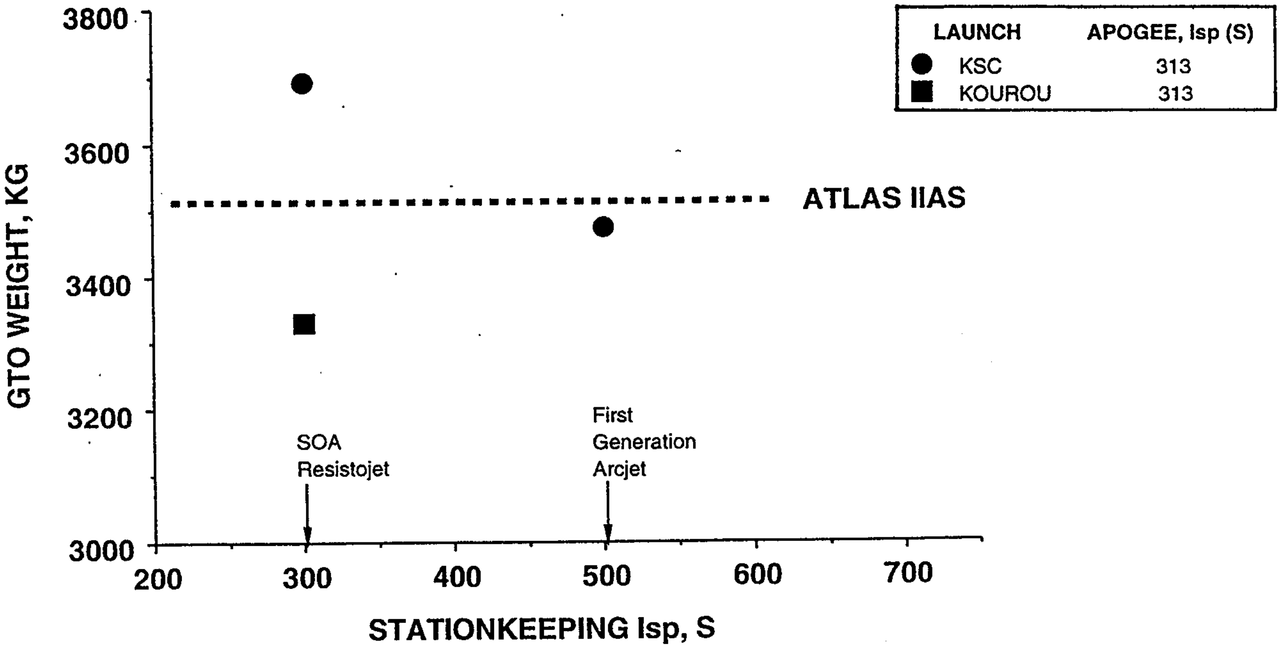


Figure 1. Mass Fractions for Recent Commercial Communications Satellites.



HIGH PERFORMANCE STATIONKEEPING PROPULSION

- REDUCES GTO REQUIREMENTS
- MITIGATES LAUNCH SITE IMPACTS

Figure 2. Hydrazine Arcjet System Impacts.

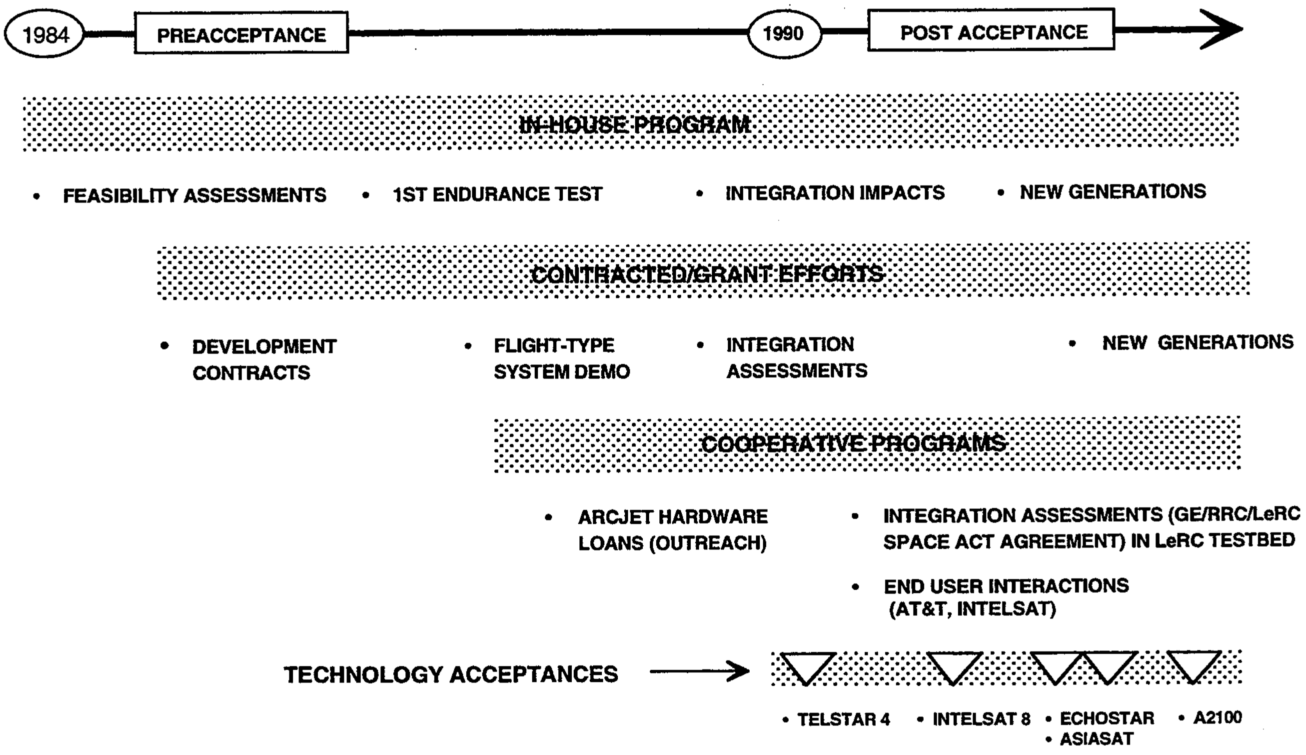
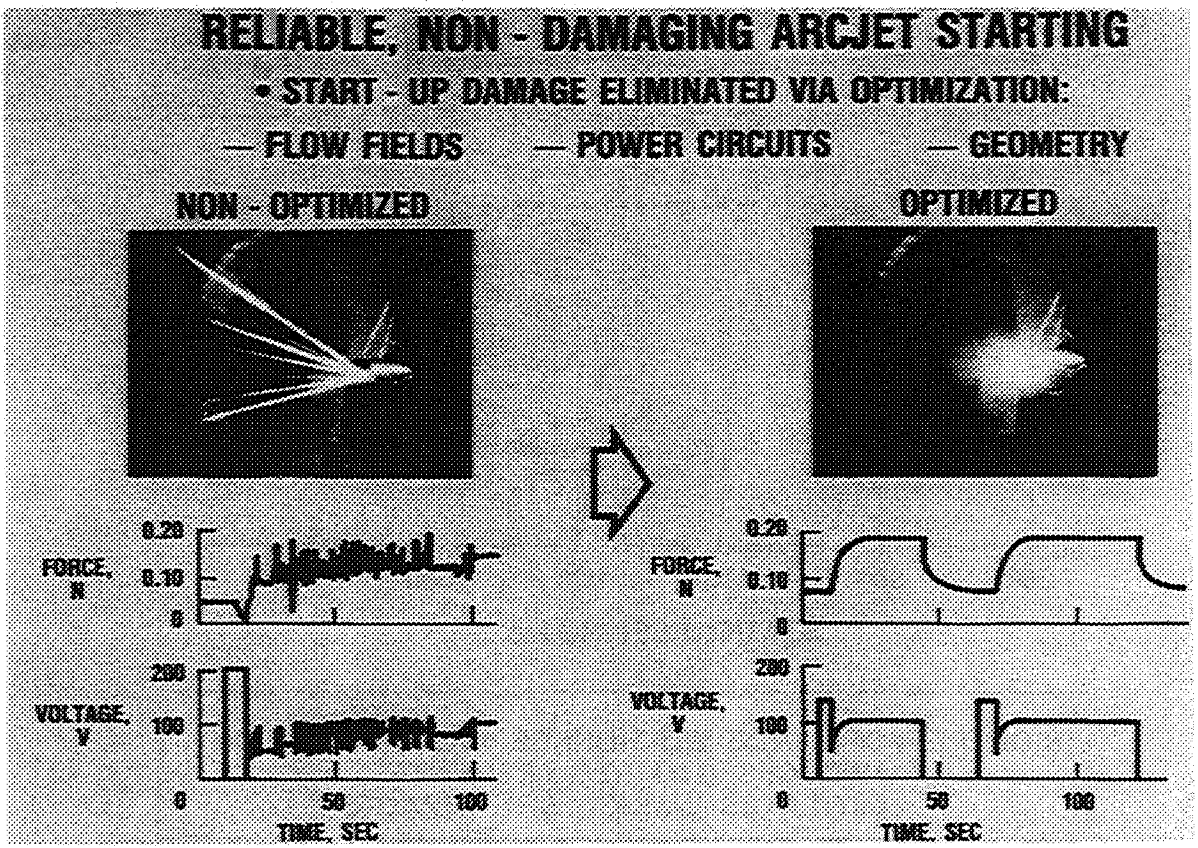


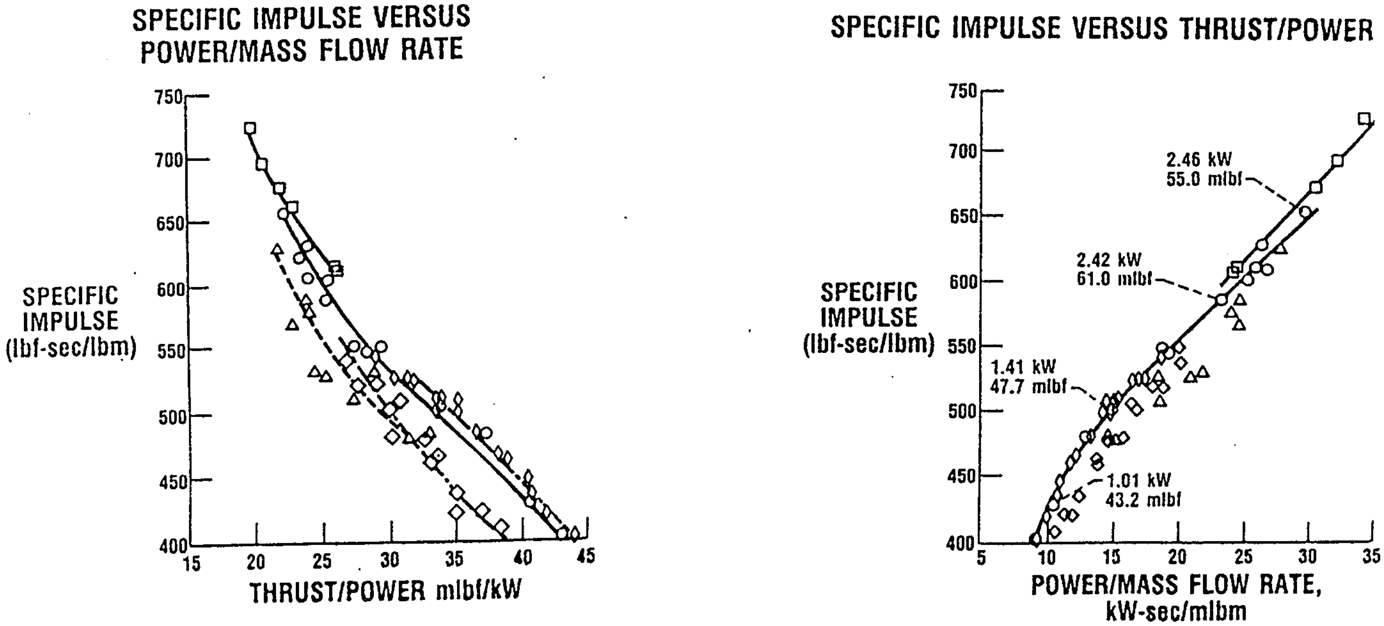
Figure 3. Hydrazine Arcjet Development Program Description.



RELIABLE, NON - DAMAGING ARCJET STARTING

- START - UP DAMAGE ELIMINATED VIA OPTIMIZATION:
  - — FLOW FIELDS — POWER CIRCUITS — GEOMETRY

Figure 4. Arcjet System Feasibility Demonstrations.



SPECIFIC IMPULSE VERSUS POWER/MASS FLOW RATE

SPECIFIC IMPULSE VERSUS THRUST/POWER

Figure 5. Hydrazine Arcjet Performance Assessments.

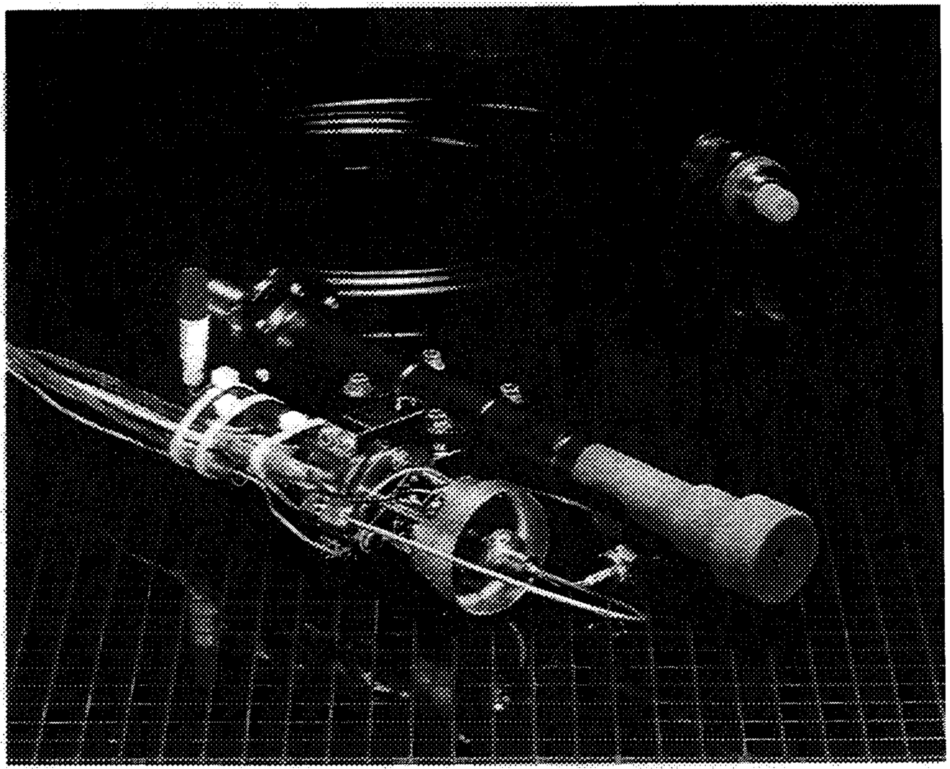
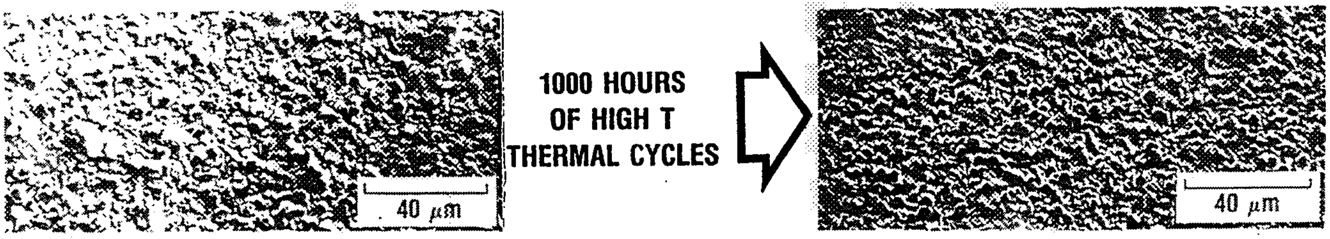


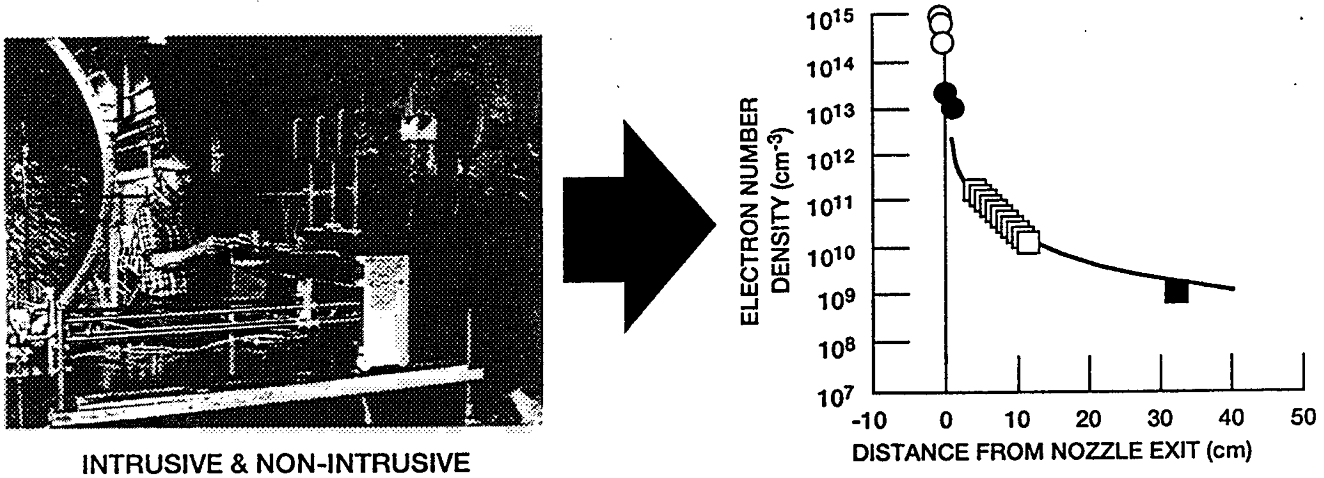
Figure 6. Flight-Type 1.4 kW Arcjet Thruster.

THERMAL/MECHANICAL INTERFACES



- **STABLE, HIGH ϵ COATINGS VERIFIED**
- **THERMAL INTERFACES MET**
  - **CONDUCTED HEAT < 10 WATTS**
  - **CONNECTOR TEMPERATURE < 140 °C**

Figure 7. High Emissivity Coating Development.



INTRUSIVE & NON-INTRUSIVE PLUME DIAGNOSTICS

PLUME ELECTRICAL PROPERTIES (Ne,Te)

Figure 8. Arcjet Plume Electrical Characteristics.

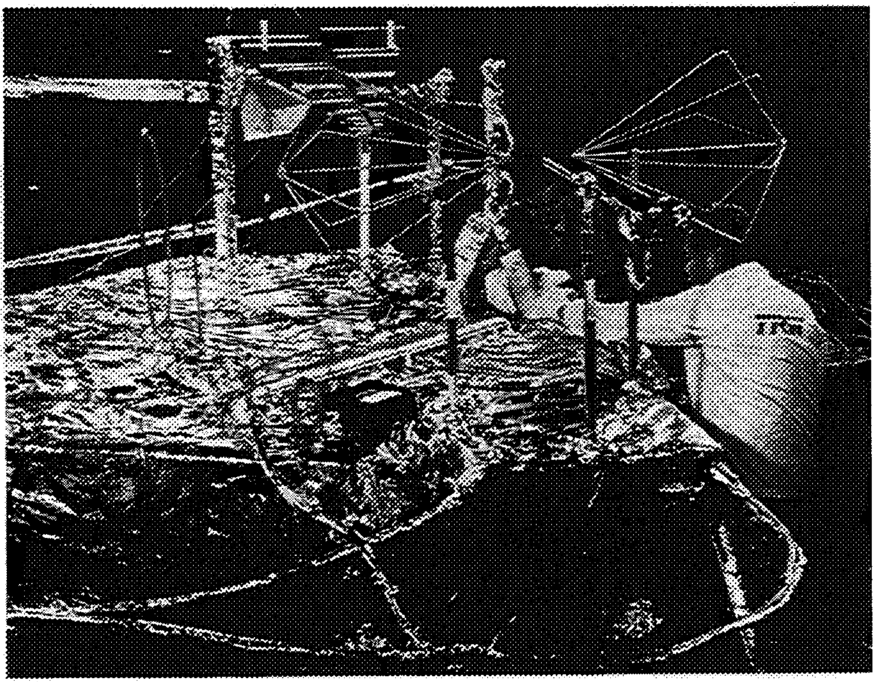


Figure 9. Arcjet System Integration Demonstration (at TRW).

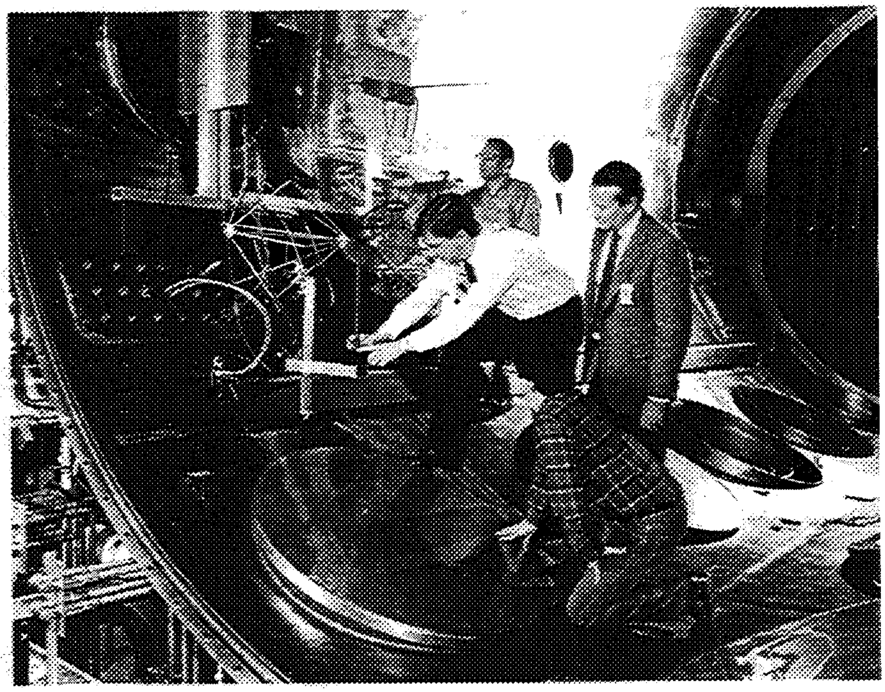


Figure 10. GE/LeRC/RRC Integration Testing (Space Act Agreement).

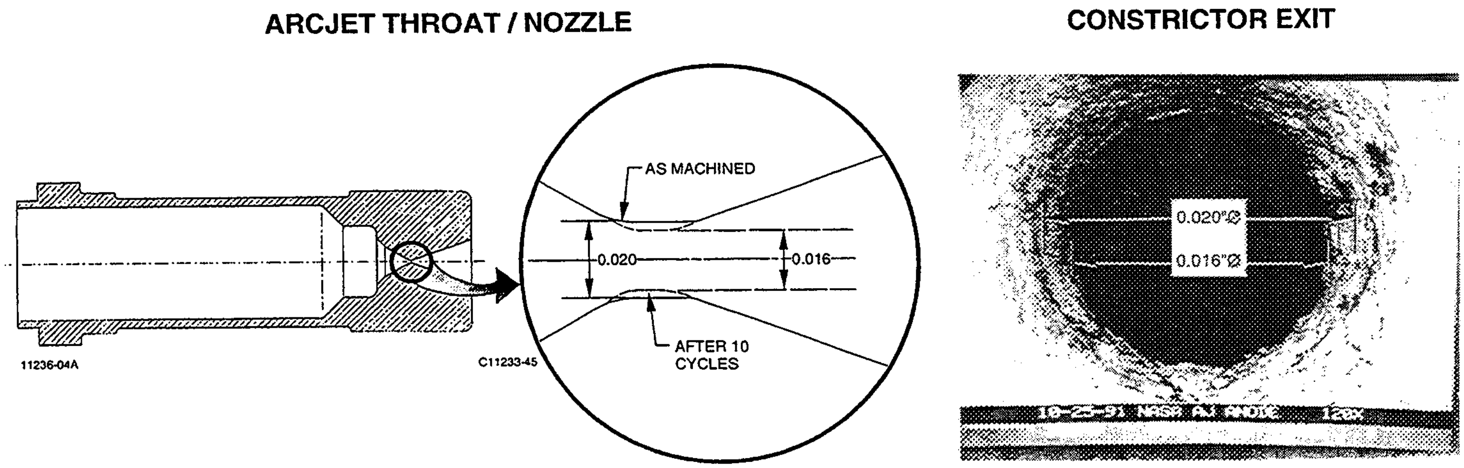


Figure 11. Arcjet Throat Closure Phenomenon at High Temperature with SOA Materials.

MULTIPLE OPTIONS CONSIDERED

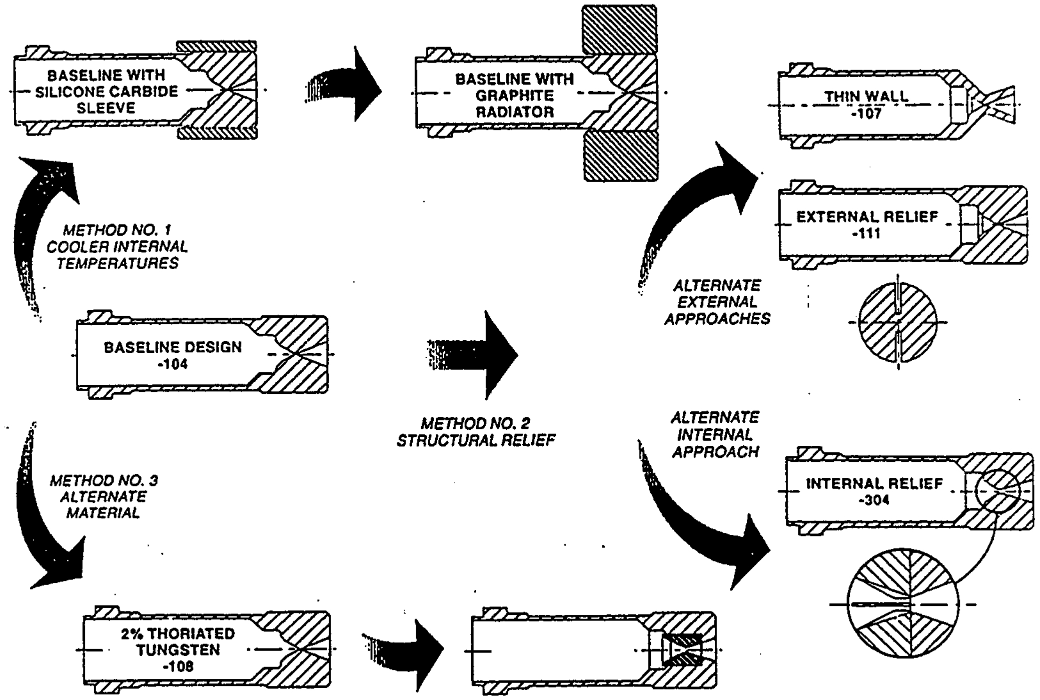


Figure 12. High Performance Arcjet Design Approaches.

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13. ABSTRACT *(Maximum 200 words)*

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19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT