DEVELOPMENT OF A 500 WATT CLASS ARCJET THRUSTER SYSTEM

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Abstract

Recent work has been conducted at Olin Aerospace Company in support of the NASA sponsored Low Power Arcjet Thruster System Development Program. The program has identified a large application base for an arcjet system in the range of 250 to 1000 watts. The program goal is to develop an arcjet thruster system for this application. As part of the program, OAC has conducted arcjet system trades that determine key areas for development. A propellant feed system study has indicated a flow regulated approach will result in higher overall mission performance than a straight blow down system. OAC intends to develop and demonstrate a flight type arcjet thruster capable of operating through the full power range at optimized specific impulse and efficiency. The thruster is currently in development. OAC has, however, conducted initial investigations with a laboratory model arcjet in the sub-kilowatt power range. This thruster was operated at 500 to 1000 watts through a flow rate schedule consistent with a potential flight application. The thruster, although unoptimized, demonstrated stable, high efficiency operation throughout the operating regime. Specific impulses of 430 seconds at 500 watts and 560 seconds at 1000 watts were achieved. No life limiting processes were identified that would deter this technology from flight qualification. Additional performance enhancement tests and extended duration tests of an engineering development model thruster are planned to assure the flight worthiness of this approach. This paper provides an overview of the system study results and describes the laboratory thruster, test program and preliminary performance test results.

Introduction

In the mid-1980’s, NASA Lewis Research Center (LeRC) and Olin Aerospace Company (OAC) independently saw the need for advanced propulsion for north-south stationkeeping (NSSK) of large geosynchronous communication satellites (GEO Comsats). Both organizations proposed the use of the arcjet thruster for this application. The increased specific impulse (Isp) of the arcjet thruster could reduce the on-board propellant requirements, increase satellite life or increase revenue generating payload over current hydrazine thrusters. In 1984, NASA began supporting both an in-house and a contracted effort to develop an arcjet thruster system. The technical goal of the contracted effort was to develop a flight qualifiable arcjet thruster system design capable of 450 seconds (s) Isp at a power level of 1.4 kW.

The program was successfully completed in 1989 with a 811 hour (h)/811 cycle performance demonstration of an engineering design model (EDM) thruster system including an arcjet thruster, power processor, and a gas generator [1]. This technology became the baseline design for the successful transfer to a commercial satellite application. Lockheed/Martin Corporation (LMC), formerly known as Martin Marietta Corp., contracted OAC to develop a 1.8 kW, 502 s minimum nominal mission average (NMA) Isp. First generation arcjets built by OAC have logged nearly two years of NSSK operation on the first LMC Astro Space Series 7000 satellite.

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In 1991 NASA began a second arcjet technology effort, Arcjet Thruster Development (ATD) Program. The goal of this program was to advance the performance threshold of arcjet technology to greater than 600 s NMA Isp at a thruster input power of 2000 watts. This effort, conducted by OAC under contract to NASA, identified and resolved key life limiting factors of a thruster operating at extremely high performance levels [2]. Unique design approaches were required to resolve low flow start and steady state stability issues [3]. A particular life limiting phenomenon, constrictor closure, required the redevelopment of a high temperature / high strength tungsten alloy and the associated manufacturing and machining processes (2-3). The ATD program was successfully completed with the demonstration of an EDM thruster for over 1000 h/1000 cycles at a NMA performance level of 607s at 2000 watts input power.

In 1994, NASA sought to continue this successful trend by planning the Low Power Arcjet Thruster System (LPATS) Technology Program. The program was awarded to OAC after a competitive procurement and initiated in early 1995. The objective of this effort is to pursue arcjet technology advancement into the next generation. The specific program approach, however, is not to push Isp further, but to maximize performance in the sub-kilowatt range. The approach is consistent with the spacecraft industry trend towards life extensions of existing bus designs as well as size limitation and cost reduction goals for future spacecraft designs [4].

The LPATS program has been divided into three phases. The Phase I initial objective was to investigate the satellite user market to determine the arcjet thruster system power level and performance range appropriate for the broadest set of applications. Determination of the appropriate technical approaches for flight system development was also an objective. The final objective of Phase I was to demonstrate the key arcjet system components required to meet the above specifications.

The three major subsystems of an arcjet system include the arcjet thruster (AJT), the power conditioning unit (PCU) and the propellant feed system (PFS). The objective of Phase II is to demonstrate those key components in a flight-type EDM system configuration. The goal of the Phase III effort, and the goal of the program is to complete the flight design and qualification of a low power arcjet system. Completion of the three phase program will result in the availability of sub-kilowatt arcjet technology for application to the next generation satellite systems.

Part of the Phase I objectives have been met. OAC and NASA conducted a market assessment that indicated a thruster system capable of 400 to 550 seconds mission average specific impulse in a power range of 250 to 1000 watts, would have the widest application base. OAC investigated the current state of arcjet technology and conducted a study of potential system approaches to meet the performance and life goals. The study incorporated current and anticipated low power arcjet performance profiles and determined the resultant mission average performance as a function of various PFS approaches. The study indicated that some flow regulation is required to meet the above goals. OAC has also initiated development of the thruster and propellant feed subsystem hardware. Tests with development thruster hardware have demonstrated over 430 seconds at 500 watts and 560 seconds at 1000 watts of input power.

This paper discusses the results of the propellant feed system study as well as the arcjet thruster development effort to verify and improve the performance of a low power arcjet thruster.

**Propellant Feed System Trade Study**

In the LPATS program, OAC and NASA have taken a overall system view in their attempt to advance arcjet thruster technology. Preliminary investigations indicated that substantial mission performance gains could be achieved just by changing the way propellant was supplied to the thruster. A propellant feed system (PFS) trade study, therefore, was conducted to determine the effects of modifications to the PFS on system benefits.
**PFS Discussions**

Development and flight experience with arcjets has identified technical challenges that must be overcome to provide the best system performance with the smallest spacecraft impacts including:

**Low Flow Gas Generator Life**: Starting with the qualification and flight of electrothermal thrusters [5], the life of low flow gas generators has been limited by nonvolatile residue (NVR) accretion. OAC has made, and continues to make, large advances in the area of low flow gas generator designs [6]. The accretion of NVR continues to be a life-limiting factor for gas generator design that will likely be exacerbated by further decreases in flow rate associated with lower power.

**Large Blowdown Ratio**. Blowdown systems require arcjet operation over a relatively broad range of propellant flow rates. At a minimum, this results in a penalty in NMA Isp compared to the Isp that could be achieved at a constant propellant flow rate. In addition, in some cases reduction in propellant flow rate at the end of life leads to very high temperature operation that can damage the arcjet constrictor.

**Gas Ingestion Effects**. Gas ingestion during propellant loading, decompression of pressurant saturated propellant, and slow decomposition of hydrazine all can produce gas entrained in the propellant. The gas in turn can produce current and voltage fluctuations that may limit the life or operational utilization of the arcjet. PCU modifications minimize the concerns at current operating levels, but the entrained gas may have greater impact at the sub-kilowatt conditions.

Trade studies have been conducted in Phase 1 of the LPATS program addressing each of these technical challenges. A large number of trade options were considered and those meriting further consideration include:

- Changes to the arcjet and gas generator internal design
- Staged repressurization of the propellant supply tank
- Regulate propellant supply pressure
- Separate the gas generator from the arcjet and supply hydrazine decomposition products through a warm gas plenum

Preliminary examination of these trades indicate that changes to the arcjet and gas generator internal design and either a pressure regulation or warm gas plenum appear to best address all the principal technical challenges.

**PFS Trade Study Results**

OAC developed transient models of two arcjet PFS approaches illustrated in Figure 1. Arcjet "A1" is a conventional approach with the addition of a low-flow gas generator. Arcjet "A3" is the warm gas plenum approach. Transient control models of these systems were integrated into Boeing EASY5 software. Three feed systems were also considered that included: B1 – conventional blowdown, B2b – single time repressurization and B3 – regulated feed pressure (Figure 2).

Preliminary results of the study effort indicate there are distinct NMA Isp and total delivered impulse advantages for the Pressure Regulated/Conventional Arcjet (A1B3), and the Warm Gas Plenum Approach. The Blowdown, Conventional Arcjet case (A1B1) is the lowest cost, but also the lowest performance. The Pressure Regulated System and the Warm Gas Plenum with a Blowdown propellant feed (A3B1) are both low weight cases, but weight varies only 2% from the heaviest to the lightest case. Ratios of total delivered impulse to cost and weight were calculated to distinguish between these tightly grouped cases.
This study indicates that there are performance advantages of about 17% to be gained by eliminating the effects of blowdown pressure variation on the arcjet. Both Pressure Regulation and Warm Gas Plenum approaches yield favorable results. Both of these options will be carried forward for a more detailed examination in subsequent phases of the LPATS program.

**Arcjet Thruster Development Effort**

**Apparatus and Test Procedures**

The test effort used a laboratory type arcjet thruster developed at OAC to allow rapid changes of nozzle and thermal design configurations. The tests were conducted at OAC's electric propulsion facilities. The purpose of the tests were to validate the sub-kilowatt arcjet thruster design concepts developed by NASA and OAC over the past few years. The following section is a description of the hardware, facilities and test procedures.

**Arcjet Assembly**

The arcjet thruster test article included an arcjet assembly (Figure 3) and an OAC owned power conditioning unit (PCU). The primary elements of the arcjet assembly include the arcjet thruster, hydrazine gas generator, propellant valves and fluid resistor. The arcjet thruster was a laboratory type, radiation cooled design modeled after a SOA arcjet design. The thruster had modular features, however, to provide easy and reliable exchange of the electrodes and internal components. The anode retaining nut secured the anode assembly to the thruster body with sealing provided by a grafoil ring. The thrusters internal features such as electrode isolation, flow passages and vortex injection techniques were all based on previously successful designs with the exception of additional sealing approaches. The laboratory thruster also had a sealed electrical pass-through. The sealed pass-through was fabricated from commercially available components. The overall thruster thermal design reflects current flight designs. Mo-41 Re heat shielding was added to the anode body to modify thermal design.

The cathode is 2% thoriated tungsten and the anode was fabricated from pure tungsten. The W-4Re-HfC alloy is expected for use in the flight anode configuration because of its superior strength characteristics at extremely high temperatures [2]. Pure tungsten was used, however, to accommodate cost and schedule constraints.

**Electrode Design Approaches**

Sub-kilowatt development work conducted at NASA [7-12] and at OAC [13] over the past 5 years has provided substantial amounts of data and a number of design approaches to meet the above LPATS goals. NASA has investigated both conventional thruster design approaches as well as unconventional approaches such as subsonic arc attachment anodes. NASA has also recently investigated the effects of variable nozzle expansion ratios on the performance of sub-kilowatt arcjets [14]. The results indicated a diminishing return with increasing expansion ratio over approximately 500:1.

OAC has also investigated the conventional designs and the unconventional bi-angle approach. Because of the broad performance goals and power range targeted for the LPATS program, OAC chose to begin their design investigations with variations to the conventional anode design. OAC believes that this approach has the greatest flexibility over low power ranges.

OAC has also investigated variations to the electrode thermal design. In the past, arcjet thermal design was driven by the requirement to minimize thermal energy transfer to the spacecraft and for survivability of anode material. The arcjet design therefore was optimized to radiate thermal energy to space. Energy loss to a sub-kilowatt arcjet is more critical, however. Optimization of the thermal design is expected to result in gains to thruster performance.
OAC has therefore added two specific design variations to the conventional approach, increased nozzle expansion ratio and reduced thermal heat rejection. The thermal variations were tested to observe their quantitative effects on low power performance and operational stability. Expansion ratios and additional thermal improvements will be investigated in future tests.

Test Facility and Instrumentation

Performance characterization of the arcjet configurations was conducted in Cell 10 of OAC's Electric Propulsion Test Facility [5]. The facility includes a low pressure vacuum chamber, a swing arm thrust stand and a helium pressurized propellant delivery system. Power is provided by an OAC owned laboratory type PCU.

Experimental Procedures

Performance characterization consisted of operating the arcjet at multiple flow rates and input power levels. OAC intends to test a full matrix of four nozzle expansion ratio configurations in three different thermal design configurations each. Each of twelve anode configurations will be tested at a minimum of three flow rates and three different power levels. These tests are currently in progress. Table 1 outlines the performance characterization tests that have been completed.

The arcjet was fully instrumented and placed in the test setup as described above. Performance mapping was accomplished by operating the thruster for a minimum of 30 minutes to assure thermal equilibrium. At the end of a operating session, the data was averaged and corrected for any thermal related zero-offsets to assure accuracy. Tests were conducted at three to four discrete flow rates for each power level to establish performance trends. Data was accumulated for 500 to 1000 watts. This data was compared between different test configurations.

Prior to, and after powered operation, a series of unaugmented tests were performed by running the thruster without electrical power until anode temperatures increased less than 1.1°C/minute. Propellant mass flow rate, feed pressure and chamber pressure data were recorded. The purpose of these tests was to provide a reference of thruster health before and after performance testing.

Arcjet Thruster Development Effort Results

Demonstrated Performance

Figures 4 through 6 graphically illustrate the performance characteristics of anode SN 001. Figure 4 indicates that both the shielded and unshielded anode configurations display the expected trends in Isp versus increasing specific power. The shielded anode configurations were expected to significantly show an increase in the performance over the unshielded configuration. It appears that the shielding is not as effective at 500 watts as it is at 1000 watts. This characteristic is evident in thruster efficiency (Figure 5) and thrust power (Figure 6) as well. The reduction in thermal radiation losses resulting from the use of the shields at 1000 watts translates into an increase in thrust efficiency. Thermal analysis of energy savings as compared to the increase in thrust power shows that not all of the thermal energy saved is translated into thrust.

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Some of the energy saved may result in an increase in frozen flow losses. Calculation of the detailed energy distribution profile has not been attempted as part of this task. The total thermal energy recovery may be distributed and lost in other forms, but the net exchange is a positive increase in thrust energy.

**Thermal Characteristics**

Although the use of the radiation shielding may have a positive effect on thruster performance, it also has a detrimental effect on anode temperatures. Figure 7 shows the measured temperature at a nominal anode location versus specific power for the three SN 001 anode configurations. As expected, the anode temperatures are higher for the shielded configurations because of the reduced thermal radiation.

The increase in temperature is acceptable only to the level where it will have a life limiting result. Work conducted on the previous NASA ATD program defined the upper limit for a 2000 watt class thruster [2]. The thermal limitation was manifested in the thermal/mechanical phenomenon of constrictor closure. The problem was resolved with the use of a high temperature/high strength tungsten alloy (W-4Re-HfC). Use of this material on a high performance flight configuration is recommended.

**Operational Characteristics**

Figures 8 and 9 illustrate the operating characteristics of the thruster. The voltage characteristics of the thruster (Figure 8) do not change from the unshielded to shielded configuration. Chamber pressure values, however, correlate with increases in anode temperature. Figure 9 illustrates how chamber pressure increases at the same flow rate as the amount of thermal radiation is reduced. This is anticipated as the result of increased energy input to the gas upstream of the constrictor.

**Conclusions**

The goal of the LPATS program is to develop a sub-kilowatt arcjet thruster system. OAC has conducted a number of activities towards that goal. An investigation of arcjet system technology revealed that propellant feed system design can play a significant role in the overall mission average performance of the arcjet propulsion system. Regulation of propellant flow to an arcjet within a reasonable tolerance band may be required to achieve the high performance goals of the program.

OAC has also investigated arcjet thruster performance in the sub-kilowatt regime. OAC plans to investigate methods to enhance thruster performance by modifying nozzle expansion ratio and anode thermal design. Testing is far from completion, but initial results show that the performance goals are achievable. Performance levels of 430 seconds at 500 watts and 560 seconds at 1000 watts were demonstrated. Thermal design modifications incorporated into the test thruster have shown improvements. Other thermal design approaches and the increased expansion ratios will be investigated further.

No life limiting processes have been observed during the tests conducted. OAC anticipates to observe constrictor closure as higher specific power levels are tested and higher temperatures are experienced. OAC does not anticipate this to be a problem for the flight designs because the high temperature/high strength tungsten alloy, W-4Re-HfC, will be used as the constrictor material.

Improved start technologies will also be incorporated in the flight design to limit possible long term, low flow start erosion. No other life limiting phenomenon were observed. As a result of these efforts OAC and NASA believe that high performance sub-kilowatt technology will be available for flight at the conclusion of the LPATS program.
Acknowledgments:

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References

13. OAC Internal Documentation
Figure 1. Arcjet propellant feed system approaches.

Figure 2. Satellite propellant storage and delivery options.

Figure 3. Arcjet thruster test article.
Figure 4. Specific impulse comparisons

Figure 5. Efficiency comparisons

Figure 6. Thrust comparisons

Figure 7. Thermal characteristics

Figure 8. Voltage current characteristics

Figure 9. Chamber pressure characteristics