INTEGRATED DESIGN ARCJETS FOR HIGH PERFORMANCE

G. Aston* and M. B. Aston**
Electric Propulsion Laboratory, Inc.
Monument, CO  80132

Abstract

Arcjets incorporating multiple, exotic design features have been manufactured and operated with high performance in the 500 W to 15 kW input power range. The integrated arcjet design represents the culmination of several years of technology evolution based on the experimental evaluation of approximately sixty arcjet engine configurations. Specific exotic design features include an arc energy recovery chamber, hot gas heat exchanger, an extensive regenerative propellant heat recovery configuration, by-pass gas flow, and the effective implementation of performance enhancing cathode shape changing features. Arcjet design enhancements are discussed in terms of exploiting the thermal environments in an arcjet engine. Data are presented for several integrated arcjet engines operating on varying blends of hydrogen and nitrogen gases. Miniature 500-700 W arcjets have achieved specific impulse levels of 525 s, with hydrazine-like gas blends, while weighing only 264 g. Similarly, 8-14 kW arcjets weighing only 1,300 g have achieved 850 s of specific impulse with ammonia-like gas blends, and 1,350 s of specific impulse with hydrogen.

Introduction

High performance arcjet engines are attractive for a wide range of earth orbital missions. The relative simplicity, small volume and mass of arcjets, coupled with their benign plume characteristics and high thrust-to-power, make these engines relatively straightforward to integrate into many spacecraft designs. These important features are enhanced by the high input power handling capability of arcjets. High power handling, and hence thrust, allows engines of modest size to orbit-raise satellites weighing several thousand kilograms, with relatively short trip times.

To fully realize the arcjet mission benefits, including reduced cost of space access, increased operation flexibility, and space survivability, arcjets must be capable of delivering high performance for the varying input powers and gas flow conditions which may be encountered during a mission. Interest in arcjet development for the 10 - 15 kW power range has resulted from the potential for this class of arcjet as a high specific impulse upper stage for existing launch vehicles. The availability of such a stage would permit launch vehicle downsizing and thereby result in more cost-effective spacecraft orbit positioning and/or transfer. Similarly, arcjets in the power range 0.5 - 2.0 kW are useful for spacecraft orbit maintenance functions where their high specific impulse enables longer on-station lifetimes.

For ammonia, conventional arcjets provide about 600 to 700 s of specific impulse at 32-35% efficiency at 10 kW, and for specific powers in the range 60-70 MJ/kg. The Electric Propulsion Space Experiment (ESEX) ammonia arcjet, scheduled for space flight testing, achieves a specific impulse of about 800 s at 30% efficiency and 26 kW for a specific power of 108 MJ/kg. For hydrogen propellant, conventional arcjet designs achieve specific impulse levels in the range of 1,000-1,200 s, at efficiencies of about 40-35%, at 10 kW, and for specific powers of 180-200 MJ/kg. These low specific impulse and efficiency levels are inadequate to enable significant performance advantages with such arcjets when compared to chemical propulsion systems which have inherently much lower mass, albeit with larger propellant load requirements.

This paper describes the results of an extensive research effort to significantly increase the performance of arcjet engines, and to achieve an arcjet engine design...
which maintains high performance with varying input power. Of principle concern to this effort were techniques which could increase arcjet performance at a given specific power level, and techniques which would allow arcjet engine operation at higher specific power levels without engine damage. Engine designs were evolved which radically depart from conventional arcjet design practices.

**Thermal Power Control Regions**

Arcjet performance can be maximized by consideration of the various energy transfer reactions and heat flow paths in this type of electrothermal propulsion engine. In a very real and useful way, an arcjet can be thought of as comprising three regions of thermal power control which encompass the spatial regimes of the macroscopic, to the microscopic. Figure 1 shows a schematic of these three power regimes. Each of these regions were examined in detail during this development program, and each region contributed significantly, and in a cumulative way, to major gains in arcjet engine performance.

**Macroscopic**

In Region I the propellant is used to capture heat that would otherwise have been lost during engine operation. This macroscopic propellant regenerative heat recovery process is significant in improving arcjet performance since returning heat energy to the propellant flow reduces electrical input power requirements to the arcjet. At the start of this development effort various experimental and analytical approaches were investigated to quantify the benefits of different regenerative heat recovery schemes, and to manufacture such geometries into arcjet engines. Figure 2 reproduces a numerical evaluation of the temperature distribution in a regeneratively cooled arcjet design from this early work, which also includes a nozzle radiation fin for additional macroscopic thermal power control. Some of the early developmental arcjets incorporating such propellant regenerative heat recovery systems are shown in Fig. 3

**Microscopic**

Region II is the microscopic thermal power control region where power densities can be of order 3-$10$ kW/mm$^3$. This region includes the cathode electrode tip, the arc column, and the arc attachment location on the anode nozzle. While it may be possible one day to completely analyze the many processes that occur during the brief passage of time that the propellant gas passes through this region, such analysis is more likely to assist in better understanding the geometrical effects which have already been noted from simplified analyses and careful parametric empirical studies. Specifically, Region II was studied extensively during this development effort by the use of modular arcjet engines of the type shown in Fig. 4. Major geometrical changes to Region II were readily examined by assembling various combinations of tungsten and molybdenum disc parts as shown in this figure. In addition, these early modular test bed arcjets allowed for the assembly of different propellant injection schemes for the investigation of gas mixing and arc column

![Fig. 1 Thermal power control regions crucial to arcjet engine power design.](image-url)
stabilization phenomena.

Fig. 2 Finite element heat transfer analysis was used to verify the efficacy of various regenerative heat recovery and radiative heat transfer schemes for arcjet thermal control.

Fig. 3 Early developmental arcjets incorporated different types of regenerative heat recovery and radiative thermal control schemes.

Fig. 4 Test bed arcjets incorporating modular constrictor, nozzle, and gas passage sections were useful in identifying engine geometrical parameters key to enhancing performance.

Macroscopic/Microscopic Interface

Region III is the macroscopic/microscopic interface thermal power control region which enables the important processes occurring in Region I and Region II to occur without damage to the engine, and at the highest possible arcjet specific power, thus maximizing thruster performance. To achieve high specific power operation without engine damage, it is necessary to incorporate a heat exchanger in Region III as shown schematically in Fig. 1. Multiple functions are performed by this heat exchanger and include the following: rapid heat removal from the cathode tip, constrictor, and arc attachment locations in Region II; presentation of a large area high temperature surface to the flowing gas from Region I for maximum convective heat transfer; and elimination of a direct heat conduction path to the arcjet outer body surface. This latter feature effectively regulates the thermal power transfer from Region II to Region I such that propellant regenerative heat recovery is maximized, and radiative thermal loss from the arcjet engine outer body is minimized.

Performance Enhancement
Geometrical Configurations

Many arcjet engine configurations were fabricated and operated to verify the sensitivity of arcjet performance to specific geometry changes. This work was guided by a general appreciation of the three thermal
control regions, and the power transfer interplay between these regions. The following sections review some of this development effort, and identify several specific arcjet engine geometries which offered significant arcjet performance enhancements.

Energy Recovery Chamber

Early development work using variants of the modular arcjet concept shown in Fig. 4 identified improved arcjet performance with an energy recovery chamber. This chamber was immediately downstream of the constrictor and created an intermediate pressure between the constrictor and nozzle, which allowed additional transfer of energy from the arc to the propellant. Figure 5 compares a conventional arcjet constrictor and nozzle geometry with a dual cone angle design and the energy recovery chamber design. The dual cone angle design was developed very early in the program. Since that time, other workers have developed similar designs which are called bi-angle nozzles. Figures 6a and 6b compare operation of a modular test bed arcjet on simulated ammonia (75% H2/25% N2) using each of the constrictor nozzle designs shown in Fig. 5. As can be seen from these data comparisons, the energy recovery chamber design resulted in superior performance over the specific power range investigated.

The energy recovery chamber captures a large fraction of the frozen flow losses in the propellant gas. This chamber allows the gas flow and arc column to expand very rapidly from the constrictor, whereupon gas expansion is essentially halted in the large diameter, and constant cross sectional area, of the energy recovery chamber. The fairly constant gas pressure in the energy recovery chamber is less than in the constrictor, but still much greater than if the gas were allowed to expand directly into the nozzle. As a consequence of this intermediate pressure regime, and the extended length of time the gas flows in this chamber, there is significant conversion of the various excitational mode energy of the arc column heated propellant gas back into kinetic energy of the gas flow. Also, because of the lengthening of the arc column by forced arc flaring, the arc voltage for a given input power is significantly increased. Similarly, the flared arc attaches to the large surface area in the energy recovery chamber and, consequently, the heat loading at the arc attachment location is significantly decreased. These latter effects are very important for increased arcjet efficiency and longevity.

It should be noted that the energy recovery chamber results in 25%-50% higher arc voltage operation, for a given input power, than operation of a conventional arcjet without an energy recovery chamber. This is an important effect since higher voltage operation means lower arc currents, which generally means lower heat loading on arcjet engine surfaces surrounding the arc column. Typically, such heat loading reductions will increase arcjet component longevity.

It is possible to continually increase the operating voltage of an arcjet to very high levels by the use of
various geometrical modifications both upstream and downstream of the constrictor. During this development program, stable arcjet operation was achieved with arc column lengths which were of order ten times the constrictor diameter. But, it was found that the high operating voltages of such arcjets, up to twice that of conventional arcjets, resulted in excessively high voltage stress levels, and very high power loadings at the cathode tip and the anode nozzle arc attachment location, with subsequent rapid damage to the engine.

**Hot Gas Heat Exchanger**

The heat load on engine surfaces surrounding the arc column of an arcjet must be controlled so as to prevent these surfaces from attaining temperatures which would promote rapid evaporation, or even melting, of engine components. Traditional approaches to this heat loading problem have included high emissivity coatings for the arcjet’s exposed exterior surfaces, and regenerative cooling passages through the nozzle and near the constrictor. The importance of efficient regenerative heat recovery schemes was recognized from the start of this program and such cooling schemes were used in all of the arcjets developed and tested during this effort. High emissivity coatings were not used on these arcjets since such coatings offer only a small performance gain, and, any advantageous coating could be readily added as a final fabrication step.

It was determined early in the program that there was a practical limit to the amount of heat transfer which could be accommodated by traditional regenerative heat recovery schemes. A hot gas heat exchanger was conceived as an effective method of significantly increasing the heat transfer from the critical engine surfaces surrounding the arc. As noted in Fig. 7, the heat exchanger functions to remove heat as rapidly as possible from the highest heat loading regions of the arcjet. These regions are as follows: the entrance to the constrictor, whose heat load comes primarily from the arc emitting from the white hot tip of the nearby cathode; the constrictor, whose heat load comes primarily from the extremely hot arc column passing through it; the energy recovery chamber, whose heat load is generated by the attachment of the hot arc; and the initial portion
Projected Maximum Constrictor Temperatures

Fig. 7 Hot gas heat exchanger functions to remove heat loading from Region II.

of the diverging expansion nozzle, whose heat load comes from the collisional processes occurring in the hot gas flow as the kinetic energy of the propellant flow is ordered into a well directed plume.

The heat exchanger concept is remarkable in that the actual heat exchanger device is effectively thermally isolated from significant thermal conduction paths to the rest of the arcjet body. At first it would seem that anything which prevented radial heat conduction from the arc column region to the outer arcjet body surfaces would only promote further interior engine heating, and the earlier onset of thermal overload damage. This is not so. Figure 8 plots numerically derived maximum constrictor/energy recovery chamber temperature projections for an arcjet with, and without, a Region III heat exchanger. For these calculations a fraction of 10% or 15% of the total input power into the arcjet was assumed to be incident upon the interior surfaces of the constrictor/energy recovery chamber. The effectiveness of the heat exchanger concept in mitigating dangerously high temperature extremes is evident in these analyses by comparing the much higher surface temperatures experienced without a heat exchanger present.

Thermally isolating the heat exchanger forces it to operate at a high, relatively uniform temperature, which promotes more effective convective heat transfer to the gas stream. Moreover, due to the very low radial temperature gradient of the heat exchanger, there is little thermally induced radial mechanical stress which, in conventional arcjets, can cause significant creep of the anode material and gradual closure of the constrictor.

Regenerative Cooling

While early arcjets developed during this program used extensive regenerative propellant heat recovery geometries, inclusion of a heat exchanger resulted in significant changes to the propellant flow path. Basically, the more work performed by the propellant flow in recovering arcjet engine heat energy, the greater the impedance to the propellant flow through the engine. An increased flow impedance creates an increased pressure drop in the engine, which in turn
reduces the effectiveness of the propellant flow in vortex stabilizing the arc column in the constrictor. Increasing the propellant supply pressure to compensate for this flow impedance effect is usually not a useful option. Generally, the propellant supply pressure cannot be easily increased. This is especially the case with most common arcjet propellants which are stored as liquids, such as hydrazine and ammonia, or propellants which are stored as cryogens, such as hydrogen. With the addition of a sophisticated heat exchanger assembly, the regenerative heat recovery scheme had to be configured so as to recover the maximum amount of heat with the minimum amount of impedance to propellant flow.

The dual, thin walled arcjet body tube design (Fig. 1 - Region I), was retained with the modified regenerative heat recovery system, but the swirl motion imparted to the propellant flow in the early arcjets as it passed between these tube sections was replaced with an axial flow. This axial gas flow was allowed to continue to the arcjet engine tip by designing the anode nozzle as an essentially hollow structure. The axial gas flow path was then reversed 180° before entering the heat exchanger. Figure 9 shows this axial propellant flow path which should be compared with the multiple helical propellant flow paths shown previously in Fig. 1. Heat transfer to the axial propellant flow was maximized by incorporating multiple ridges machined normal to the flow direction, as shown in Fig. 9, on both the surfaces of the thin walled body tube sections and the thin walled nozzle sections.

**Axial flow**

![Axial flow path and surface ridges](image)

**Fig. 9** Axial flow path and surface ridges minimized engine pressure drop and maximized heat transfer.

### Bypass Flow

It is advantageous, from a mission perspective, to have the capability of increasing arcjet thrust significantly to perform rapid maneuvering functions. With a constant arcjet input power, thrust increases are possible by increasing the propellant flow rate, which lowers the specific impulse, and increases the thrust. However, in a practical manner, there is only a small thrust increase which can be realized by this technique due to the rapid rise in required arc voltage as the constrictor flow rate is increased from its nominal design value. If allowed to continue however, this rise in engine arc voltage can result in propulsion system shut down as the power conditioning system output voltage limit is exceeded. Thus there is a practical limit to the thrust increases, at constant input power, which can be obtained by increasing the propellant flow in a conventional arcjet.

During this development program, several auxiliary propellant injection schemes were investigated for their effect on arcjet performance. As noted previously in Fig. 4, the modular arcjets were designed to enable assembly of several engine components which were often times machined with additional flow paths. Auxiliary propellant flow was injected upstream of the constrictor, in the constrictor and energy recovery chamber, and downstream of these regions to determine relative performance effects during modular engine tests. In all cases, except the downstream injection experiments, the additional gas flow paths were counter-productive to enhancing arcjet engine performance, either as a result of destabilizing the arc column and causing excessive erosion, or because of undesirable arc voltage effects.

Figure 10 shows several arcjets developed to provide a high thrust mission capability without incurring arc column destabilization or voltage changes. Figure 11 shows a schematic view of how the downstream micro-nozzles shown in the arcjets in Fig. 10 were integrated into the overall arcjet operating concept. Briefly, the by-pass flow arcjet design has two separate propellant flow paths that enter the engine. As noted in Fig. 11, one propellant flow path passes through the constrictor region, while the second flow path bypasses propellant around this region to exit into the main anode nozzle via micronozzles embedded into its surface. These micronozzles exit downstream of the constrictor region of the arcjet, and their exhaust adds to the total
Several arcjets were fabricated using by-pass flow micro-nozzles embedded in the main nozzle to provide thrust and specific impulse control at constant input power.

![By-pass flow arcjet schematic.](image)

Since the bypass propellant flow does not interact with the arc column to become ionized, the heat energy transferred to the bypass flow from the constrictor region heats the gas without incurring frozen flow energy losses. Although the bypass gas flow temperature cannot exceed the materials temperature limits of the heat exchanger and micro-nozzles, the efficiency of this heat transfer process can be very high. As a consequence, the performance of the arcjet with the micro-nozzles is a combination of the high thrust, high efficiency, relatively low specific impulse of the bypass gas flow, and the lower thrust and efficiency, but much higher specific impulse, of the gas flow passing through the constrictor and interacting directly with the arc column. Thus, balancing the gas flow between these two flow paths allows for great control of arcjet total thrust and specific impulse for a constant input power.

Cathode Geometry

The cathode electrode in an arcjet must provide tip electron emission currents levels of the order of several tens of ampere/mm² or more, for mission lifetimes of 500 - 2000 hours. High electron emission current densities result in high tip temperatures, which can result in significant cathode tip evaporation. If the cathode tip is allowed to recede significantly from the constrictor entrance region, the arc voltage may rise to unacceptably high levels as the overall arc column length is increased.

During this program, efforts were made to develop cathode designs which resulted in increased arc column stability, increased heat transfer from the cathode, and increased plasma density for enhanced thermonic emission. Both a helix design, and an axially slotted cathode design, were developed and tested successfully and are shown in Figs. 12a and 12b respectively.

The design rationale for the helical cathode was that the gas flow swirl imparted by the propellant upon injection into the plenum is strengthened and maintained by the gas flow being forced to follow the helix, which is machined to ensure a common direction of swirl. Strengthening and prolonging the gas flow swirl with the cathode tip helix increases the axial dimensional stability of the arc column, which enables lower gas flows to be used in the arcjet for a given input power level, which in turn enables higher specific power operation of the arcjet and higher performance. In addition, the helix effectively increases the surface area of the cathode tip, and this results in a greater amount of convective heat transfer from the cathode tip to the gas flow. This additional heat energy input to the gas flow further increases arcjet performance, and also reduces cathode tip erosion by enhancing heat removal from this high current density electron emission site.

The design rationale for the axial slot cathode was that the gas flow swirling around the cathode tip tends to stagnate in the axial slots, creating a high gas and high plasma density within the region of the axial slots closest to the usual electron emission portion of the cathode tip. This high plasma density in these axial slots makes the slots function as hollow cathodes, with...
electron emission occurring from the surfaces of the axial slots. Because of the plasma sheath voltage gradient, the intense electric field effectively lowers the electronic work function of the axial slot surfaces due to the Schottky effect. The result is that the axial slot surfaces add to the usual emitting portion of the cathode tip, increasing the cathode's total electron emitting surface. This enhanced electron emission process enables higher arc currents for a given input power and flow rate.

The effectiveness of these above described cathode geometries can be appreciated by noting that the cathode diameters used in the larger arcjet engines developed during this program, which were operated at arc currents up to 70-100 A, had diameters of about 3 mm. By contrast, more conventional arcjet designs use cathode diameters of order 6-7 mm for operation in this arc current range.

**Fabrication**

Considerable effort was spent on developing fabrication techniques which allowed the implementation of the exotic arcjet engine design features described above into practical, low mass, arcjet engines. A combination of welding techniques were implemented to join the various engine components. Figure 13 shows several 8-14 kW class arcjets, and 500-700 W class arcjets, fabricated using the integrated arcjet design approaches developed during this program. The larger engines weigh 1,300 g, while the smaller engines weigh only 264 g. The larger engines were manufactured using primarily electron beam joining techniques which did not give completely satisfactory sealing performance in critical joint areas. By contrast, the smaller engines were fabricated after the larger engines and represented a more refined mechanical design. Most importantly, fabrication of these smaller engines took advantage of an advanced vacuum welding technology which became available towards the end of the program.

![Fig. 13](image-url) Two high power, 8-14 kW class, integrated design arcjets surrounding four similar internal geometry low power, 500-700 W class, integrated design arcjets.

Both sizes of engines shown in Fig. 13 incorporate identical geometrical performance enhancement features.
Also, both engine sizes utilize a rear flange assembly containing a metal seal ring which enabled disassembly and inspection of interior engine components during performance testing. Eliminating this metal seal and flange assembly for flight engines would further reduce their mass.

Test Facilities and Procedures

During the course of this development effort the vacuum test chamber, gas flow control system, thrust stand, and data collection and analysis techniques gradually evolved to accommodate the increasing demands of the arcjet engines under test. Some of the early data collection and test facility descriptions are contained in previous publications.\textsuperscript{5,13,14}

For performance evaluation of the engines shown in Fig. 13, and for engines incorporating similar integrated performance enhancement features, all testing was performed in a 0.59-m diameter x 1.83-m long stainless steel and aluminum chamber. Arcjet exhaust gas pumping was provided by a system of multistage blowers and mechanical displacement pumps. The pumping capability of the vacuum facility was aided by exhausting the test arcjet plume directly into a diffuser, which also functioned as an accurate beam power calorimeter. Vacuum chamber background pressures were of order 150 mTorr for operation at 10 kW on simulated ammonia, and 200 mTorr for operation at 10 kW on hydrogen. This chamber was fitted with a movable bulkhead on which the thrust stand, arcjet, electrical connections, and diagnostic instrumentation were located. The thrust stand used a horizontal swing arm deflection principle, and was fabricated from carbon-carbon composite material and dense graphite for dimensional stability. Swing arm motion was transmitted to a thin carbon-carbon flexure of near perfect spring constant and was sensed by a linear voltage differential transformer. Passive magnetic damping controlled spurious vibrations, and a remotely controlled test mass system allowed for thrust stand calibration during test arcjet operation. Thrust stand accuracy was determined to be better than $\pm3\%$, with a resolution of 1 mN.

Thrust stand data were corrected for facility background pressure effects, although these effects on measured thrust were typically less than 2%. Propellant mass flow rate was calibrated using a direct gas bottle weighing technique, and by secondary tests using a volume bleed-down technique. Mass flow rate measurements were accurate to $\pm2\%$ for all gases investigated.

This development program was not concerned with long term endurance testing, but the identification and implementation of key exotic engine design features which would cumulatively add significantly to overall arcjet engine performance. Due to the many arcjet geometrical features investigated during this program, it was determined at the start of the effort to perform all engine starts using argon, at low voltage and power, with transition to the test gas of choice. This procedure helped to avoid the possibility of engine damage during start-up, which was very important since even very small dimensional changes could effect the relative performance characteristics of the specific geometrical feature being investigated. In addition to start-up on argon, a unique high frequency gas breakdown procedure, and low current arc ramp-up procedure were developed early in the development effort to ensure that even the most exotic engine geometries could be brought up to full power operation without engine component damage.\textsuperscript{5,9} It should be noted that following completion of this development effort, direct start-up on typical arcjet propellants was demonstrated using state-of-the-art arcjet power conditioning systems.\textsuperscript{17}

Integrated Arcjet Performance

Summary

Figures 14a and 14b plot the specific impulse and efficiency variations with specific power for operation of the large integrated arcjets shown in Fig. 13 on simulated ammonia propellant. For comparison purposes, test results from refs. 18 and 19 are also presented. From the data trends in these figures it is clear that incorporation of the performance enhancement features developed during this program into an integrated arcjet engine design offers much greater performance than more conventional arcjet engines. Extrapolation of the data in Fig. 14a suggests that the integrated arcjet engine design should be capable of 900 s specific impulse at a specific power of about 100 MJ/kg. This specific power operating point corresponds to an input power of about 15 kW. Similarly, the data in Fig. 14b indicate that an efficiency of 0.40 could be expected from the integrated arcjet operating at this same 100 MJ/kg specific power.
As noted in Figs. 14a and 14b, integrated arcjet operation with the helical cathode produced the best performance. Many tests were performed to validate this performance advantage over the standard cathode geometry. The results of these tests showed that for integrated arcjet operation at the same simulated ammonia propellant flow rate and specific power, the specific impulse increased by an average of 5.1%, and the efficiency increased by an average of 7.7% using the helical cathode geometry. Similarly, the helical cathode tended to increase the arc voltage by about 3% when compared to arcjet operation with the standard cathode geometry. The measured arcjet axial length temperature distribution remained unchanged during arcjet testing with either the standard or helical cathode geometry.

One of the key features of the integrated arcjet design is the ability of the engines to operate at a relatively constant specific impulse and efficiency, over a wide power throttling range. Figures 15a and 15b document this useful performance characteristic. For these data, the integrated arcjet was operated in a mode where specific power decreased with increasing input power to obtain a relatively constant specific impulse and efficiency level.

Fig. 14a Specific impulse performance of high power integrated arcjets operating with simulated ammonia compared with more conventional arcjet designs.

Fig. 14b Efficiency performance of high power integrated arcjets operating with simulated ammonia compared with more conventional arcjets.

Fig. 15a High power integrated arcjets gave relatively constant specific impulse over their 8-14 kW design range.
Fig. 15b High power integrated arcjets gave relatively constant efficiency over their 8-14 kW design range.

Figures 16a and 16b show performance of the integrated arcjet engines using simulated hydrazine propellant (67%H$_2$/33%N$_2$). The low specific power data point was from testing of the miniature 500-700 W class integrated arcjets shown in Fig. 13. The other data points in Figs. 16a and 16b correspond to operation of the larger integrated arcjets shown in Fig. 13. As can be seen from these data, the similarity of design features in these two very differently sized engines resulted in virtually identical performance trends, with all of the data following essentially a straight line variation with increasing specific power.

The exception to this linear trend was the drop in performance noted at the highest specific power where a significant decrease in engine pressure was also noted. Inspection of the arcjet engine following this last data point revealed a circumferential crack in one of the downstream engine body electron beam welds. This crack caused the engine pressure drop, which decreased arc voltage leading to the observed reduction in measured performance. Extrapolating the data in Fig. 16a, without this last data point, shows that a specific impulse of 800 s could be realized with simulated hydrazine by operating the integrated arcjets at a specific power of about 80 MJ/kg. It should be noted that no engine cracks developed during extensive testing of the miniature arcjets shown in Fig. 13. As discussed previously, these low power arcjets were fabricated using an advanced vacuum welding technology which was not available at the time the larger, high power engines were manufactured.

As noted in Figs. 16a and 16b, the axial slotted cathode geometry was evaluated against the helical cathode geometry during integrated arcjet operation using simulated hydrazine propellant. For the same flow rate and specific power, the axial slotted cathode tended to reduce the arc voltage by about 13% compared to operation with the helical cathode geometry. This effect resulted in a higher arc current requirement to attain the same arc power level, which caused slightly higher arcjet temperatures. There appeared to be little performance difference between the two exotic cathode geometries, with perhaps a slight arcjet efficiency increase associated with the axial slot cathode.
The ability of the axial slot cathode to emit electrons more efficiently was part of the rationale for this particular cathode design. However, higher arc currents for the same input power operating point have traditionally increased cathode erosion rates. The apparent increase in electron emitting efficiency from the axial slot cathode design may mitigate these potential increased erosion rate effects at high arc currents. However, long-term cathode life testing would be required to verify this process. Nevertheless, higher arc currents do increase the arc attachment heat load on the arcjet, which does increase arcjet operating temperatures. Primarily for this latter reason, the axial slot cathode was deemed inferior to the helical cathode, although superior to the standard cathode design.

Although the larger integrated arcjet engines shown in Fig. 13 were fabricated for operation on simulated ammonia propellant, these engines were also operated successfully with hydrogen propellant. Figures 17a and 17b plot the measured specific impulse and efficiency variations, respectively, as a function of specific power for hydrogen propellant operation. Also

Fig. 16b Both the low power and high power integrated arcjet engines gave high efficiency performance on simulated hydrazine and followed similar performance trends with specific power.

Fig. 17a Integrated arcjets gave high specific impulse performance with hydrogen.

Fig. 17b Integrated arcjets gave high efficiency performance with hydrogen.
plotted in Figs. 17a and 17b are data from an earlier integrated arcjet design which was fabricated to produce more optimal performance with hydrogen propellant for input powers of order 5 kW.\textsuperscript{20} It should be noted that all of the data shown in Figs. 17a and 17b were obtained using a standard cathode geometry and thus show lower performance than would be expected if a helical cathode geometry were used. These test results indicate that an integrated arcjet with a nozzle and constrictor size optimized for hydrogen propellant, and using a helical cathode, would achieve a specific impulse of about 1,500 s, with an efficiency of about 50% for operation at an input power of 15 kW, and at a specific power of 250 MJ/kg.

An integrated arcjet utilizing a bypass propellant flow scheme, with four micro-nozzles embedded in the anode nozzle, was operated successfully during this program. In these preliminary tests, the measured arc voltage only increased from 163 V to 165 V as the simulated ammonia propellant flow through the bypass channels and micro-nozzles was increased from zero to 50% of the total engine input propellant flow. These tests also demonstrated both a substantial thrust, and efficiency, increase during by-pass flow integrated arcjet operation.

Finally, the heat recovery capability of the regenerative propellant flow scheme in the integrated arcjet engines was demonstrated by completely insulating the outer body of a test arcjet with a 2-cm thick thermal blanket which extended to 1.5 cm upstream from the nozzle exit plane. A polycrystalline mullite fiber was used to blanket the engine, and this insulation material was covered by a thin titanium vented shroud. Arcjet operation was sustained at an input power of 8 kW using simulated ammonia propellant with no damage to the interior engine components. During these tests, only the small exposed nozzle tip area was visibly radiating, while the remainder of the arcjet titanium shrouded outer body surface was essentially at room temperature.

Conclusion

Exploiting the physical processes, and subsequent thermal environments, important to arcjet operation has resulted in the successful development and implementation of several significant performance enhancing arcjet geometrical features. These design features included an energy recovery chamber, hot gas heat exchanger, novel regenerative heat recovery schemes, by-pass gas flow systems, and exotic cathode geometries. Arcjets manufactured utilizing these advanced engine features incorporated into an integrated system have achieved performance significantly greater than conventional arcjet engines.\textsuperscript{21} Further development of the integrated arcjet engine concept can be expected to yield further performance gains as the designs are fully optimized.

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1949-1962.


