HIGH SPECIFIC POWER AMMONIA AND HYDROGEN ARCJET DEVELOPMENT

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Abstract

A review of advanced ammonia and hydrogen arcjet development programs at EPL is presented. Rationale for specific arcjet design features are discussed in the context of fabricating engines which may be readily qualified for near term flight applications. A standardized arcjet engine design is presented which weighs only 1.5 kg and which is sized for variable input power operation up to 15 kW.

Introduction

High performance arcjet engines are attractive for a wide range of Earth orbit missions. The relative simplicity, small volume and mass of arcjets, coupled with their benign plume characteristics, make these engines fairly straight forward to integrate to existing spacecraft designs. These important features are enhanced by the large input power handling capability of an arcjet. This power handling capability allows for engines of a size which can be comfortably hand held, and yet which are potentially capable of orbit raising satellites weighing thousands of kilograms.

Most arcjets presently under development can trace their design heritage to extensive high power ammonia and hydrogen arcjet test programs performed during the sixties.1-3 At present, no arcjet has yet flown in space. However, a first north/south station keeping communications satellite application of a 1.8 kW hydrazine arcjet system is expected soon.4 Beyond this initial low power application, a test flight is scheduled for verification of the environment surrounding a battery powered 26 kW ammonia arcjet.5

For arcjet orbit raising applications, significant economic benefits must be derived from the use of arcjet propulsion to justify its selection over traditional chemical rocket systems.

Typically, these cost benefits, as identified by analyses6-8, are reduced launch vehicle size and cost when an electric orbit transfer vehicle (EOTV) is selected for satellite orbit insertion, as compared to larger, higher cost launch vehicles coupled with a chemical rocket transfer stage.

These EOTV cost benefit trade studies identify required arcjet performance levels which exceed those attained by conventional arcjet designs.9-15 In recognition of these performance limitations, the Air Force Phillips Laboratory, and McDonnell Douglas Aerospace, initiated separate advanced arcjet development programs several years ago at the Electric Propulsion Laboratory (EPL). For the Phillips Laboratory, the program goals are the development of a flight weight, fully welded arcjet, performance optimized to achieve a minimum specific impulse of 950 sec., and a minimum efficiency of 35% using ammonia propellant while operating over an input power range of 6 - 14 kW. For McDonnell Douglas Aerospace, the program goals are the development of a flight weight, fully welded arcjet, performance optimized to achieve a minimum specific impulse of 1,300 sec., and a minimum efficiency of 40% using hydrogen propellant while operating at a constant input power of 5 kW.

This paper describes the basic arcjet design and test considerations, and the techniques used to investigate critical arcjet geometry changes for performance optimization using both ammonia and hydrogen propellants. Data are presented emphasizing the importance of arcjet designs which are capable of operating at very high specific power without damage.

Specific Power as a Performance Criteria

For an arcjet, specific power is defined as the ratio of the electrical input power divided by the propellant mass flow rate and is usually expressed in the units MJ/kg. This important parameter is useful in comparing the relative performance advantages of different arcjet designs and is usually plotted against the measured arcjet specific impulse and efficiency. Generally, arcjet specific impulse increases with increases in specific power, with the rate of increase in specific impulse tending to decrease as the engine is pushed to its maximum specific power. This maximum specific power limit is usually reached when, for a

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given fixed input power, the propellant mass flow rate has been leaned to the point where further leaning would cause unacceptably high constrictor erosion rates due to excessively high operating temperatures. An excellent presentation of the pursuit of higher arcjet specific impulse, by incremental specific power increases in a conventional ammonia arcjet engine, is presented in Ref. 9.

Power throttled operation of an arcjet is required during a typical orbit raising mission as a result of solar array degradation during passage through the radiation belts. To achieve maximum performance from the arcjet during throttling, it is desirable that as the input power is reduced, the propellant mass flow rate also be reduced to maintain constant engine specific power. This throttling scenario results in continued arcjet operation at approximately the same thrust-to-power ratio, while causing only gradual linear reductions with power of the arcjet specific impulse and efficiency.

The design challenge of building arcjets with performance suitable for orbit transfer applications is then two fold. First, the engine must be capable of long term operation at specific powers significantly in excess of conventional arcjet designs to achieve the required gains in specific impulse and efficiency. Second, the engine must not be damaged, or excessively eroded, during reduced input power operation while maintaining this high specific power.

Arcjet Design Considerations

In evolving an advanced, high performance arcjet design, the approach taken to meet the requirement of long term high specific power operation has been guided by the additional objective of developing a flight qualifiable engine for near term use. The following sections summarize the results of various design, fabrication and analysis programs which contributed to critical arcjet design features.

Power Handling Capability

For orbit raising missions with launches planned in the next ten years, available spacecraft solar array power levels of a maximum of a few tens of kW's can reasonably be assumed. While arcjet input powers of 25 - 40 kW have been examined in recent test programs9,11,15, and a battery powered 26 kW ammonia arcjet test flight is planned12, practical considerations of redundancy, lifetime, power throttling requirements, and spacecraft integration, suggest maximum arcjet input power levels of 15 kW would satisfy most foreseeable EOTV missions.

Similarly, for EOTV applications, arcjet operation at reduced input powers during throttling need not be extended to arbitrarily low power levels. Severely throttling engines designed for operation at input powers of 25 - 30 kW, to power levels of 3 - 5 kW results in relatively poor engine performance and also potentially unstable arc column formation and operation.16 These considerations, the anticipated degradation of a nominal 30 kW EOTV solar array, and redundancy requirements, suggest a 15 kW arcjet design should be throttled to a minimum power of about 5 - 6 kW.

The arcjets developed by EPL for either ammonia or hydrogen operation are all sized, with minimal external differences, to this general requirement of maximum input power operation of 15 kW and a throttling range of about 3:1.

Mechanical Integrity

During orbit raising, an arcjet propulsion system will be turned off during Earth shadowing of the solar arrays since it is impractical to oversize the arrays and provide additional storage batteries for continuous operation during eclipse. The thermal stress attendant to this cyclic operation, and the extreme sensitivity of internal arcjet pressure changes on engine performance, put severe requirements on the arcjet mechanical integrity.

Initial EPL arcjet development efforts investigated a variety of arcjet sealing techniques.17 As result of this and later work, all EPL arcjets use a combination of electron beam welds, TIG welds and high temperature brazing to ensure various engine components remain leak tight during thermal cycling. Over the several years of EPL development testing, no failure of any weld joint has occurred.

The basic EPL arcjet design consists of two portions; a front assembly and a rear assembly. Figures 1a and 1b show these major components for a hydrogen arcjet prior to assembly and testing. Briefly, the arcjet rear assembly contains the cathode, cathode holder, propellant distributor, hermetically sealed cathode and anode insulator assembly, the anode support barrel and half mating flange. Similarly, the arcjet front assembly contains the expansion nozzle anode, constrictor and critical support components, propellant distribution paths, thermal barrier tubes, and half mating flange.

Assembly of the arcjet sections shown in Figs. 1a and 1b, is accomplished by the use of a solid nickel seal into which the knife edges machined into the respective front and rear assembly half flanges are compressed. This compression is
mal barrier tubes for limiting arcjet axial heat conduction from the hot tip to rear portions of the engine; (2) active propellant cooling techniques using propellant flow passages (this active propellant cooling can also be thought of as regenerative heat recovery and as such it is accurate to state that all EPL arcjets are regeneratively cooled designs); (3) arcjet tip shaping to enhance radiative heat exchange to the surrounding space environment.

**Mass Distribution**

Due to heat conduction thermal barrier requirements, and the necessity to provide spacecraft radiation heat shielding, flight arcjet designs tend towards geometries which have a large body length-to-diameter aspect ratio. The EPL arcjet is 30 cm long and mechanical mounting of the arcjet is performed by attachment to the mating flange which is close to the axial center-of-mass of the engine. This is an important consideration since arcjets tend to be tip heavy due to the use of tungsten for constrictor/nozzle manufacture.

The primary metals used in the manufacture of the EPL arcjet are stainless steel, molybdenum and tungsten. These metals are assembled using the aforementioned welding techniques in composite structures which are arranged to take advantage of the strength, durability and density of each metal type. In this way, metal choices are made for the thermal and mechanical stress requirements peculiar to each location in the arcjet. This composite assembly technique results in light weight engine structure and an EPL arcjet mass of approximately 1.5 kg.

**Test Facilities**

An important consideration in any arcjet development program are the test facilities. These facilities must be adequate to support the goals of the arcjet operational test program. The following sections describe the EPL test facilities and procedures as they have evolved during the past several years of arcjet development.

**Vacuum chambers**

Arcjet testing at EPL can be performed in two vacuum test environments. Most engine operating tests are conducted in a mechanical blower pumped stainless steel tank 0.59 m dia. x 1.83 m long. Approximately 1,650 l/s of blower capacity supports arcjet operation in this tank. These blowers are backed by a staged train of appropriately sized mechanical pumps. Figure 2a shows background pressures in this facility during arcjet operation on a blend of 25% N₂/75% H₂ to simulate the
mechanical blower pumped arcjet test facility is that the arcjet exhausts into a diffuser which is shown in Fig. 3. This diffuser promotes significant arcjet plume pressure recovery, in addition to providing the straight forward function of literally guiding the rapidly moving plume gases to the inlet throats of the blowers. Figure 4 shows operation of a test arcjet with simulated ammonia propellant and high lights the direct arcjet plume injection into the diffuser throat. The diffuser also functions as a plume calorimeter for measurements requiring estimates of the arcjet plume power and this function has been discussed in a previous paper.18

![Fig. 3](image3.png)

**Fig. 3** Diffuser/calorimeter used by EPL to augment pumping of arcjet plume in the mechanically pumped arcjet test facility.

![Fig. 4](image4.png)

**Fig. 4** Arcjet plume being captured by diffuser during arcjet operation on simulated ammonia propellant. Diffuser entrance is to right and arcjet is shown at left enclosed by thermal radiation shroud.

The principle reason for the excellent pumping capability of the EPL arcjet decomposed products of ammonia, and Fig. 2b shows background pressures for arcjet operation on pure hydrogen. This facility is capable of maintaining background pressures in the sub-Torr range during arcjet operation at engine power levels up to 15 kW. Should additional blower capacity be required, the pump room supporting this facility is provided with hook-ups to accept an additional blower of approximately 1,500 l/s capacity.

![Fig. 2a](image2a.png)

**Fig. 2a** Pumping capability of EPL mechanically pumped arcjet test facility for arcjet operation using simulated ammonia propellant.

![Fig. 2b](image2b.png)

**Fig. 2b** Pumping capability of EPL mechanically pumped arcjet test facility for arcjet operation using hydrogen propellant.
The second vacuum test environment available for arcjet testing and performance evaluation at EPL, is a diffusion pumped test facility with a total length of 8.3 m. This diffusion pumped facility comprises three separate EPL diffusion pumped vacuum chambers joined together along their long axes. During normal operation these chambers are separately pumped and are used to support various experimental test programs. For arcjet testing, lightweight adapter collars are fitted between the chambers, and the arcjet and thrust stand bulkhead are relocated to the largest chamber which has a diameter of 1.3 m. These changes take only a couple of hours. The resulting combined facility is capable of maintaining a background pressure environment of $5 \times 10^{-4}$ Torr during arcjet operation at input powers up to 5 kW. This high vacuum test capability is particularly important for investigating nozzle flow expansion effects, and background gas convective cooling effects such as described by Sankovic et al.\[19\]

**Propellant Flow System**

Accurate propellant mass flow rate readings are critical to ensuring that arcjet performance figures are reliable. All propellant gases used at EPL for arcjet testing are ultra pure carrier grade with a 99.999% purity specification and an oxygen content less than 1.0 ppm. Where premixed gases are required, such as for hydrogen and nitrogen gas blends simulating the decomposed products of ammonia, each bottle is individually certified and the variance in blend ratios is not more than 0.2% of the gas bottle volume.

Electronic mass flow controllers of the thermal sensing type are used to monitor arcjet propellant flow rates. Primary calibration of these flow controllers is maintained by a direct gas bottle weighing technique. Figures 5a and 5b show typical flow controller calibration results for simulated ammonia and pure hydrogen propellants. In addition to direct bottle weighing, the flow system has a sample bottle in-line with the arcjet which can be bled down in pressure, while maintaining arcjet operation at constant conditions. This in-situ bleed down calibration technique estimates flow rates which differ by less than 1% from the direct bottle weighing approach.

**Arcjet Start-up**

During past arcjet and related development programs, EPL developed an arcjet power supply system which has proven to be extremely capable of non-destructively starting any arcjet constrictor and nozzle test configuration.\[20-22\] Two key features of this laboratory power system are the use of high frequency gas break down and soft start arc initiation. These start techniques are pertinent to present arcjet power conditioning unit development activities and are described in more detail in the following sections.

In starting any arcjet there are three basic steps which must be performed sequentially. The first requirement is to break down the propellant gas so that free electrons and ions are present in great enough numbers to support an arc. At EPL this break down is accomplished by applying a continuous ringing voltage to the cathode-to-anode constrictor gap.
The frequency of this applied voltage is of order 1 MHz, and the peak-to-peak open circuit voltage is about 2 kV. This starting voltage waveform is generated by a Tesla coil circuit whose air coupled secondary winding is in series with a soft start arc initiation supply. The step-up transformer to this Tesla coil circuit is supplied by 60 Hz laboratory power and has a maximum rating of 50 VA. EPL has applied this starting circuit to several dozen different arcjet test geometries with great success. Gas breakdown always occurs, and does so without regard for whether the arcjet cathode has been recently exposed to air, or the specific test geometry under investigation. The average power transferred to the cathode during this gas breakdown is so low that the starting circuit can be left on for long time periods with no measurable cathode erosion.

Following gas break down, the second arcjet starting requirement is to establish a low current arc discharge. This arc discharge current is regulated to not exceed 4 A and is left on for a few seconds during which time the high frequency gas breakdown circuit is switched off. The purpose of this soft start arc initiation procedure is to allow sufficient cathode tip heating to occur so as to thermally condition the cathode for high current operation.

With the cathode thermally conditioned, the third arcjet starting requirement is to establish the desired test arc current. The high power run supplies are switched across the arcjet with an initial current of typically 20 A, after which the soft start arc initiation supply is turned off. At this point, arcjet start-up has been fully effected and the operator can adjust the arc current to the test value desired while the engine is allowed to thermally equilibrate.

The above described starting system is used at EPL with argon gas, with switch over to simulated ammonia, or hydrogen, after the high power run supplies have been activated. The use of argon gas is simply a laboratory technique which allows relaxation of the insulation tape requirements around the engine electrical and gas feeds, and thus significantly speeds up the turn around time for testing different arcjet configurations. For space flight applications, arcjet start-up would be performed directly on ammonia or hydrogen propellants.

Figure 6 shows a close-up photograph of a cathode tip after this cathode was used to thoroughly test twenty five different arcjet engine configurations on simulated ammonia and pure hydrogen propellants. The number of starts on this cathode was well in excess of one hundred, and this cathode was exposed to air at least fifty times. The round and blunted cathode tip reflects initial shape preparation prior to its use.

![Fig. 6 Cathode tip condition after more than one hundred arcjet starts, and repeated air exposures, during testing of twenty five different arcjets.](image)

**Thrust Stand**

The EPL arcjet thrust stand is flange mounted and bolted to one end of the arcjet vacuum test facility. To expedite engine inspections, and the turn around time required for engine geometry changes, the thrust stand and arcjet are removed as a unit from the test chamber. This arrangement also allows for ready relocation of the arcjet to the front bulkhead of the three coupled EPL diffusion pumped vacuum chambers when very low background pressure arcjet testing is desired.

Figure 7 shows a hydrogen arcjet mounted to the EPL thrust stand prior to testing. The thrust stand design is of the swing arm type with the flexure vertical so that the arcjet is free to swing in the horizontal plane. This swing arm assembly, which contains the arcjet mounting insulators, is securely bolted to a 3 cm thick graphite plate, which in turn is securely bolted to a stress braced aluminum support cradle, which in turn is bolted to the vacuum tank mating flange.

A load cell, mounted at the flexure location, provides a signal proportional to the arcjet thrust. Thrust stand calibration is performed in-situ during arcjet operation by sequentially adding three accurately known weights. Thrust measurements are taken after the test arcjet has reached thermal equilibrium.
Fig. 7 Hydrogen arcjet shown mounted to EPL swing arm thrust stand.

**Early Arcjet Tests**

The first arcjet tests performed at EPL were with early regeneratively cooled engine designs using hydrogen propellant during 1989/1990. Figure 8 shows nozzle and constrictor design details for the three fully welded front arcjet assemblies used in this program. These initial engine designs investigated enhanced nozzle heat removal by the use of a radiation fin and also a bi-angle nozzle for investigating nozzle energy expansion processes.

**Modular Geometry Optimization**

Based upon the results of initial arcjet design, fabrication and test programs, arcjet optimization studies were performed for both simulated ammonia and hydrogen propellants. These optimization studies were carried out using a special test bed arcjet which allowed for modular build-up of virtually any constrictor and nozzle geometry. Figure 9 shows a test arcjet constrictor and nozzle geometry assembled using modular tungsten sections, extras of which are shown in the rear of the photo.

This test bed arcjet was used to investigate the relative performance of eighteen different arcjet geometries using simulated ammonia propellant. Figure 10 reproduces a few results of this investigation and shows plots of the variation in thrust-to-power as a function of specific power for various arcjet test geometries. Similar investigations were performed using hydrogen propellant.

**High Voltage Geometries**

Of the many arcjet geometries investigated using the test bed arcjet, certain configurations showed promise of achieving high specific power, and performance, at high voltage. The importance of achieving high voltage arcjet operation cannot be understated for practical application of high power arcjets to EOTV applications. Simply stated, a 15 kW arcjet operating at an arc voltage of 100 V requires a current feed of 150 A, whereas an arcjet optimized for 200 V operation requires only 75 A of arc current. For mission application, this current reduction can mean the difference between using a relatively simple flexible current feed, or a more complicated rigid current feed as has had to be designed into the ESSEX flight arcjet.
Fig. 9 Test arcjet constrictor and nozzle geometry assembled from modular components.

Fig. 10 Significant changes in arcjet performance were noted in Ref. 22 during testing of novel arcjet designs. Data are for simulated ammonia propellant.

Recent tests at EPL have investigated several new arcjet engines designed to further improve ammonia arcjet performance. These engine designs are based on the most promising geometries derived from the earlier modular configuration test programs described above. Figure 11 compares the voltage characteristics of one of these developmental arcjets with a reference arcjet design which has a conventional constrictor and nozzle geometry. It is significant to note that both arcjet geometries in Fig. 11 had identical diameter constrictors, identical cathodes, and identical cathode-to-constrictor entrance gap settings.

At this time of writing, preliminary performance parameter space mapping for these three arcjets has been performed on only the engine shown in Fig. 11. Significant changes in arcjet performance were noted in Ref. 22 during testing of novel arcjet designs. Data are for simulated ammonia propellant.

High Specific Power Hydrogen Arcjet

The McDonnel Douglas Aerospace supported hydrogen arcjet development effort at EPL has recently begun performance testing three flight weight arcjet engines. These engines have been designed for long term testing at 5 kW. One of these engines is shown on the EPL thrust stand photo included previously in Fig. 7.

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Summary

A discussion of arcjet performance and design considerations has been presented. Emphasis has been placed on reviewing the approaches taken by EPL in the development of advanced, flight weight, regeneratively cooled ammonia and hydrogen arcjet engines. The results of these on-going development efforts, which have been underway for several years, are standardized ammonia and hydrogen arcjet engines. These engines weigh approxi-
Hydrogen

Flow Rate = 0.02488 g/s

Fig. 12a Preliminary data for EPL fully welded hydrogen arcjet showing general impedance behavior at low propellant flow.

Hydrogen

Flow Rate = 0.02488 g/s

Fig. 12b EPL fully welded hydrogen arcjet is designed for operation at 200 MJ/kg with an input power of 5 kW.

Flow Rate = 0.02488 g/s

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