Effect of Nozzle and Cathode Configuration on Arcjet Performance

William D. Deininger,* Thomas J. Pivirotto,* and John R. Brophy†
California Institute of Technology, Pasadena, California

Experimental investigations were conducted to evaluate the effects of a bell-shaped contoured nozzle and modified cathode tip shape on 30-kW$_e$-class ammonia arcjet engine performance. The experiments were conducted in a fully instrumented facility which included a thrust stand. The performance data for an arcjet with a bell-shaped nozzle were compared to the performance data of an arcjet that had a 38-deg included-angle, conical nozzle. Thrust improvements of up to 10% were demonstrated which corresponded to a 10% improvement in thrust efficiency and up to a 35-s increase in specific impulse. The modified cathode tip had a reduced diameter and more acute conical tip with respect to the baseline cathode design. A uniform 15% decrease in arc voltage was noted over a mass flow range of 0.175–0.350 g/s using the modified cathode. However, there was no change in the engine performance characteristics.

Nomenclature

A_I = engine arc current
A_V = engine arc voltage
F = thrust
g_0 = mass-to-force conversion constant
I_{sp} = specific impulse
$\dot{m}$ = mass flow rate
M_E = electrode mass loss
M_p = exhausted propellant mass
P_s = specific power ($P_W/\dot{m}$)
P_W = engine input power
η_T = total thrust efficiency

Introduction

ACTIVE research on thermal arcjet thrusters began during the late 1950s and proceeded vigorously until the mid-1960s. This research is reviewed in Refs. 1 and 2. During that period, arcjet engines were being developed for primary propulsion applications where power was derived from a space reactor power system (SRPS). Engines requiring from 1 kW$_e$ to greater than 200 kW$_e$ of input power were examined. Engine operation on a variety of propellant gases was investigated and included H_2, He, Li, N_2, NH_3, N_2H_4, Ne, and Ar. Development of both high-power solar and nuclear power systems (including the SP-100 SRPS program, the space reactor power system at 100 kW$_e$) has renewed interest in using electric propulsion for primary propulsion functions and has led to the renewed development of arcjet engines.

As ammonia arcjet engine was operated for 573 h at approximately 25 kW$_e$ during a recent long-duration test.[3-5] This engine was based on a design originally tested for 50 h, the previous endurance record for ammonia arcjet operation.[6] Tungsten whisker growth on the cathode tip resulting from cathode tip erosion caused a low-voltage condition in the engine, terminating the long-duration test.[5,7] The 573-h endurance test served as a means of reestablishing arcjet engine technology.

This paper describes changes in arcjet engine performance resulting from the use of a bell-shaped contoured nozzle and a modified cathode as compared to the duration test engine. The contoured nozzle performance data were compared to the performance data of the duration test engine, which had a 38-deg included-angle, conical nozzle. Contoured nozzle engine performance was mapped over a power range of 10.0–31.0 kW$_e$ at ammonia mass flow rates between 0.175 and 0.350 g/s. These tests were conducted to determine if the use of a contoured nozzle could improve engine performance.

The ultimate goal of cathode redesign is to minimize cathode erosion and whisker formation in order to lengthen engine lifetime. A first step in the redesign process is to verify that cathode design changes do not degrade the engine performance. Performance characterizations of an arcjet using a modified cathode were conducted using the contoured nozzle engine and compared with the previous contoured nozzle data

Table 1 Design parameters and essential dimensions of the engines used in these experiments

Parameter	Baseline engine	MOD I engine	MOD II engine
Constrictor length, cm	1.07	1.08	1.08
Constrictor diam, cm	0.51	0.51	0.51
Nozzle exit diam, cm	2.41	2.93	2.93
Exit area ratio[a]	23	33	33
Nozzle type	38-deg Cone	Bell	Bell
Plenum chamber diam, cm	2.03	2.03	2.03
Plenum half-angle taper at constrictor end, deg	50	49.5	49.5
Major cathode diam, cm	0.95	0.95	0.95
Minor cathode diam,[b] cm	0.95	0.95	0.70
Cathode tip included angle, deg	60	60	45
Cathode tip radius, cm	0.15	0.15	0.05
Electrode gap[c]	0.21	0.21	0.21
Propellant injection angle, deg	30	30	30
Nominal nozzle diam, cm	5.08	5.08	5.08
Nominal engine length, cm	14.7	16.4	16.4

[a]Ratio of constrictor area to nozzle exit area.
[b]Diameter of cathode immediately behind tip cone.
[c]Axial gap between the cathode cone and corner of the constrictor entrance.

Presented as Paper 87-1082 at the 19th AIAA/DGLR/JSASS International Electric Propulsion Conference, Colorado Springs, CO, May 11–13, 1987, received July 1, 1987; revision received April 20, 1989.

*Member Technical Staff, Electric Propulsion and Plasma Technology Group, Propulsion Section, Jet Propulsion Laboratory. Member AIAA.

†Member Technical Staff, Electric Propulsion and Plasma Technology Group, Propulsion Section, Jet Propulsion Laboratory; currently at Electric Propulsion Laboratory, Inc., Lancaster, CA 93535.

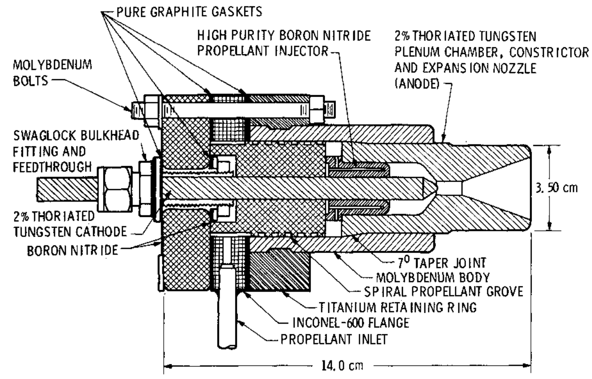

Fig. 1 Schematic of baseline arcjet engine.

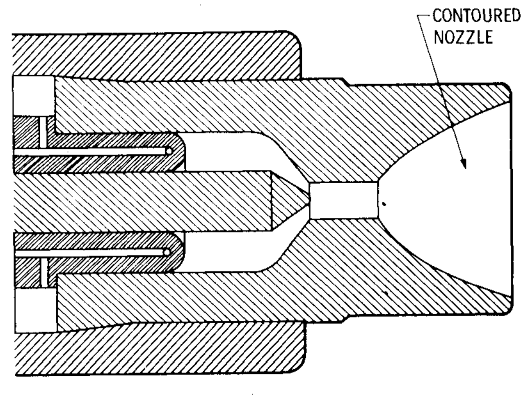

Fig. 2 Baseline MOD I engine.

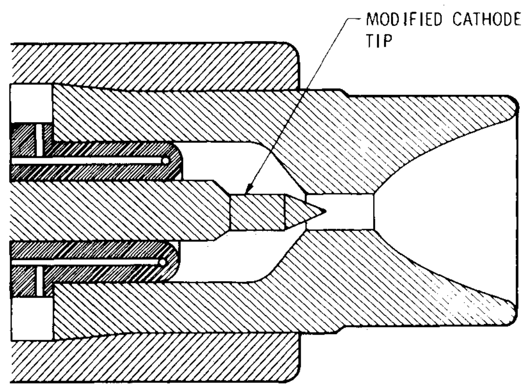

Fig. 3 Baseline MOD II engine.

obtained using the baseline cathode design. Engine performance was mapped at powers of 14.6 and 22.0 kW_e with a range of ammonia mass flow rates of 0.175–0.350 g/s.

Arcjet Engine Design

Several arcjet engine designs were evaluated during this program. The critical parameters and essential dimensions of each are summarized in Table 1. The important variations between the engine designs are discussed in the following paragraphs.

Baseline Engine

The baseline engine performance was taken from the characterizations conducted prior to the beginning of the 573-h long-duration test.[4] The engine is shown schematically in Fig. 1. This engine has a conical nozzle with a 38-deg included angle and a cathode of continuous diameter up to the 60-deg included-angle conical tip. A complete description of this engine can be found in Refs. 4 and 5.

Baseline MOD I Engine

The important features of the baseline MOD I engine are shown in Fig. 2. This engine is identical to the baseline engine except that it has a bell-shaped, contoured nozzle. This nozzle shape was defined by Brophy et al.[8] in an effort to improve the arcjet nozzle efficiency. No techniques for optimizing the nozzle contour for the unusual flow conditions produced by an arcjet have been developed. As a result, an approximate analytical technique was used to generate this bell-shaped contour. This technique was based on the formalism developed by Rao[9] for an optimum inviscid expansion nozzle contour, which was then modified by "adding" the boundary-layer displacement thickness to obtain the nozzle wall contour.[8]

Baseline MOD II Engine

Some electrode erosion is expected during arcjet operation which can limit the useful life of an engine. The area of greatest erosion in engines that were operated for relatively long periods of time was found to be the cathode tip.[5,10-12] It was felt that most of the cathode erosion occurred during the first several tens of hours of engine operation.[5,10-12] Mass losses of up to 1% of the total cathode mass have been noted.[11,12] During a 30-day duration test of a 30-kW_e, hydrogen arcjet, the M_E/M_P ratio was 1.3×10^{-5}.[11] This corresponds to an average electrode erosion rate of 1.2 mg/h. A cathode mass loss of 1.95 g of tungsten was reported at the conclusion of the recent 573-h duration test corresponding to an M_E/M_P ratio of 1.1×10^{-5}.[5] This corresponds to an average tungsten erosion rate of 3.4 mg/h.[5] There is evidence to suggest that erosion rates of this order are primarily due to material evaporation.[7,13]

The MOD II engine, shown in Fig. 3, is identical to the MOD I engine except for the modified cathode tip. The baseline MOD II engine cathode had a cross-sectional area that was reduced to 53% of its original value for a distance of 1.25 cm immediately behind the cathode tip. The tip had a 45-deg included angle with its point radiused to 0.05 cm. This resulted in a more pointed cathode tip. In order to minimize the change in the propellant gas velocity distribution at the constrictor inlet, the new cathode was inserted into the plenum chamber so as to leave the annulus between the cathode cone surface and the corner of the constrictor inlet the same. This forced the tip of the new cathode to move farther downstream in the constrictor channel, as can be seen by comparing Figs. 2 and 3.

The new cathode tip geometry was chosen in an effort to reduce cathode tip erosion. It is felt that, with the baseline cathode design, heat conduction away from the cathode tip is high enough to force the arc root to concentrate onto a small spot to maintain high enough temperatures in a local area to support thermionic emission. This could result in the formation of a small molten pool of tungsten on the cathode tip, which must support thermionic emission and maintain the discharge. The evaporation of this molten pool could result in cathode tip erosion.[7,13] The modified cathode tip design, shown in Fig. 3, should force the entire tip area to a higher temperature by increasing ohmic heating and reducing rearward thermal conduction. An increased overall tip temperature should allow an expansion of the thermionic emission zone, thereby reducing the peak temperature of the cathode tip material. Cathode tip erosion should decrease markedly once the peak temperature drops below the melting point of tungsten. An important step in cathode redesign is ensuring that the changes do not degrade engine performance. The experiments involving cathode design changes described in a later section address this issue.

Facilities and Instrumentation

The tests described in this paper were conducted in a cylindrical, stainless steel vacuum tank 1.2 m in diameter and 2.1 m long. The exhaust plume of the arcjet was collected by a diffuser, 0.16 m in diameter, and pumped by a high-capacity vacuum pumping plant based on a 6.3-m^3/s roots blower. Tank pressures were maintained between 0.04 and 0.07 Torr (5.3 and 9.3 N/m^2) during engine operation.

The engines were mounted on a cantilevered beam-type thrust stand to measure performance. Power was supplied to the arcjet through a coaxial current feed and mercury pools, allowing the engine to move freely. The thrust stand was calibrated before each run using a deadweight technique. Engine performance and the facility were monitored by a computer-based data acquisition and control system (DACS). Detailed descriptions of the test facility, instrumentation, and required data corrections can be found in Refs. 3-5.

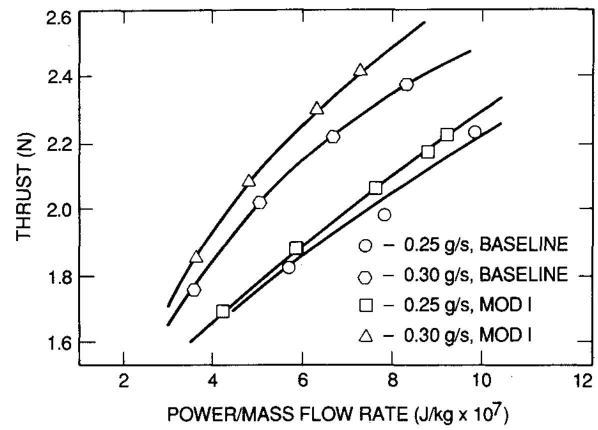

Fig. 4 Comparison of thrust characteristics between baseline and baseline MOD I engines.

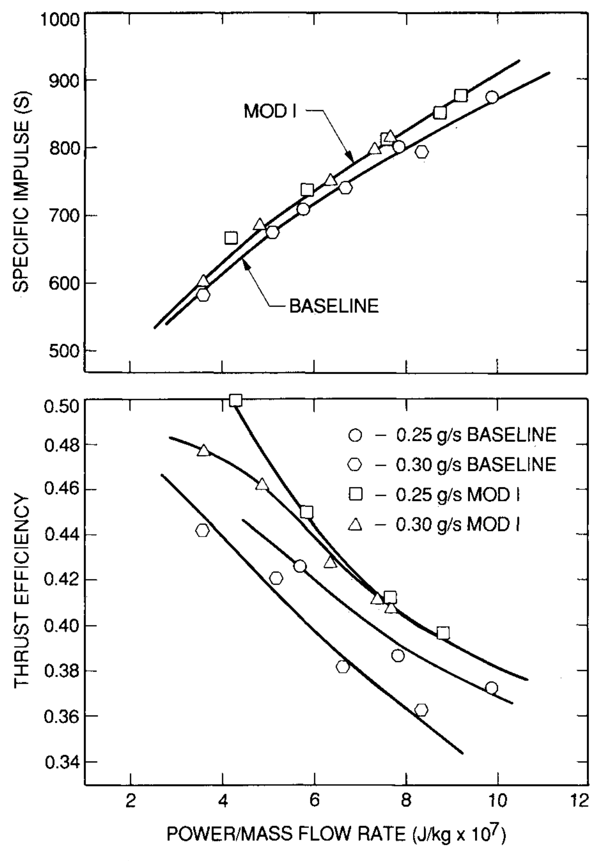

Fig. 5 Comparison of specific impulse and thrust efficiency characteristics between baseline and baseline MOD I engines.

Results and Discussion

At each flow rate and power setting examined, the arc current and voltage, thrust, propellant flow rate, tank pressure, and various facility temperatures were measured. These parameters were recorded every 20 s by the computer-based DACS. This system also computed the input power, specific impulse, and overall efficiency in real time using

$$P_W = A_V A_I \tag{1}$$

$$I_{sp} = F/(g_0 \dot{m}) \tag{2}$$

$$\eta_T = F^2/(2\dot{m}P_W) \tag{3}$$

Only the electrical power is included in the equation for total thrust efficiency [Eq. (3)], since the power represented by the cold gas flow is on the order of 35 W, and the form of Eq. (3) allows a direct comparison to the 573-h duration test data.[4,5] In addition, the effect of nozzle exit pressure and vacuum facility ambient pressure on thrust were ignored, since this pressure times area correction is on the order of 5×10^{-3} N. Once the engine reached steady-state operating conditions, typically 10–15 min, several sets of performance data were recorded, and then operating conditions were changed to prepare for the next set of data. The overall maximum uncertainty in the measured thrust was ±2% (see Refs. 3-5).

Contoured Nozzle Investigation

A comparison of engine thrust, as a function of specific power, is given in Fig. 4 for the baseline and baseline MOD I

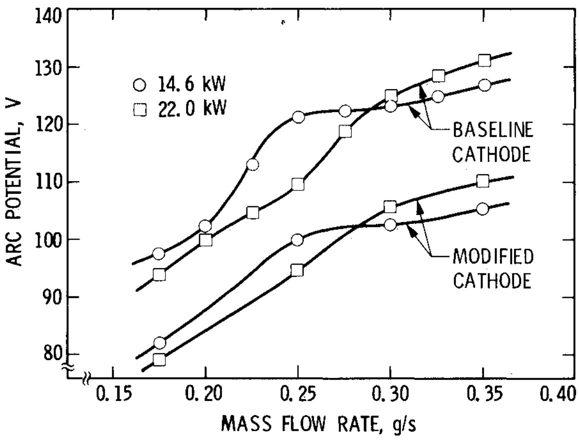

Fig. 6 Effect of cathode location and shape on arc voltage.

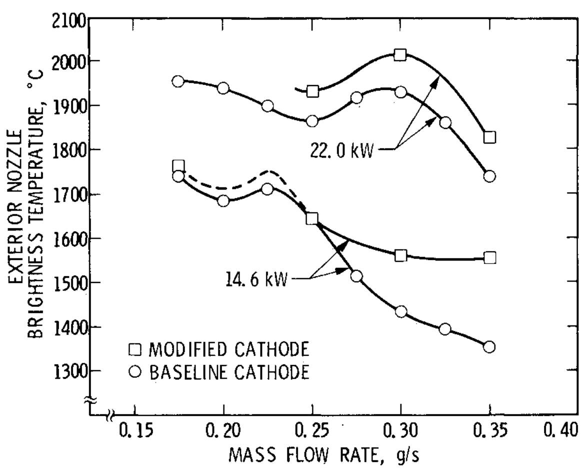

Fig. 7 Effect of cathode location and shape on anode surface temperature.

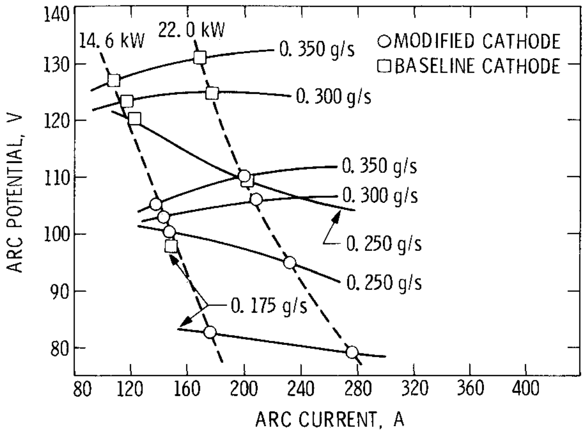

Fig. 8 Comparison of *V-I* characteristics between baseline MOD I and MOD II engines.

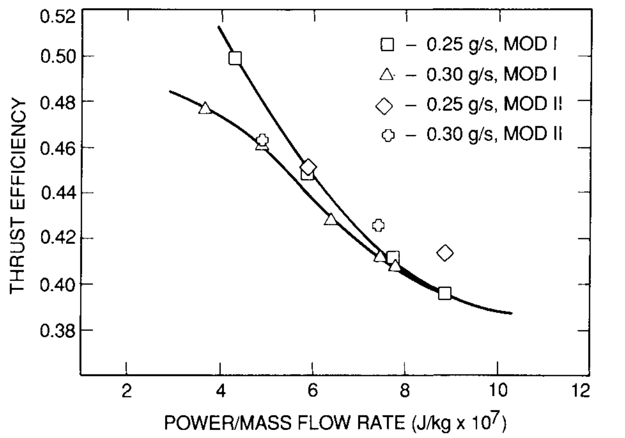

Fig. 10 Comparison of thrust efficiency characteristics between baseline MOD I and baseline MOD II engines.

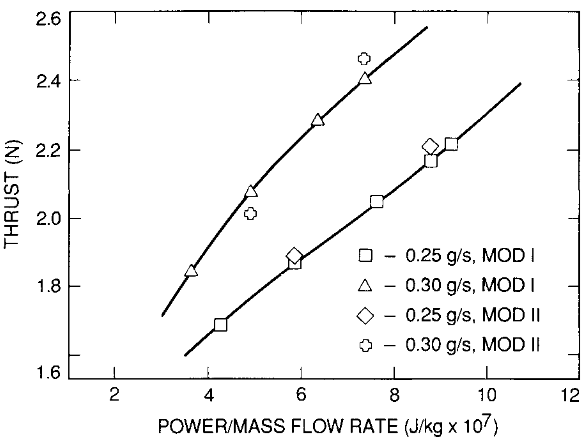

Fig. 9 Comparison of thrust characteristics between baseline MOD I and MOD II engines.

engines. A new baseline cathode was used in both engines for the performance characterizations. For an ammonia mass flow rate of 0.25 g/s, the bell-shaped nozzle provided a uniform thrust improvement, as a function of power, of 0.05 N. At a mass flow rate of 0.30 g/s, the thrust improvement varied from 0.08 N at low power to 0.15 N at 25 kW_e. These improvements correspond to 2–10% improvements in engine thrust as a result of the use of a bell-shaped nozzle.

The specific impulse and thrust efficiency are calculated using the measured values of thrust and mass flow rate through Eqs. (2) and (3). Figure 5 shows these results as a function of specific power. Use of a contoured nozzle led to typical improvements in specific impulse of 35 s. Since thrust efficiency depends on the square of the thrust, this parameter shows a more pronounced difference between the two engine performance characterizations. At 0.25 g/s, typical thrust efficiency improvements were on the order of 5%. However, when the flow rate was 0.30 g/s, the efficiency improved by 10%. It is significant to note that for the baseline engine with the conical nozzle the thrust efficiency decreased with increasing mass flow rate, whereas the efficiency of the baseline MOD I engine decreased with mass flow at low specific powers but was constant with respect to mass flow at higher specific powers. This suggests that the thrust efficiency improvement provided by the contoured nozzle compensates for the thrust efficiency degradation resulting from the increased mass flow rate due to the efficiency's dependence on thrust squared.

Effect of Cathode Tip Geometry

Figure 6 shows arc voltage as a function of mass flow rate and power for both cathode geometries. The cathode placement chosen for the reduced-diameter cathode in the MOD II engine led to a significant decrease in the arc potential compared to the placement of baseline cathode in the MOD I engine. The voltage dropped 15% over a mass flow range of 0.175–0.350 g/s. The cathode placement led to an effective 10% reduction in the geometric arc length. This reduction in operating potential led to a corresponding increase in arc current to maintain the same power level. This resulted in an increase in the overall anode block temperature as shown in Fig. 7. The increased current should have also led to a corresponding increase in the anode losses. These findings are in agreement with previous theoretical and experimental work.[14,15]

The engine voltage-current (*V-I*) characteristics are shown in Fig. 8. The solid lines in Fig. 8 represent constant mass flow, and the dashed lines represent constant power. The *V-I* characteristics exhibit a negative resistance characteristic at low (constant) mass flow rates and a positive resistance characteristic at high (constant) mass flow rates for both cathode geometries. The *V-I* characteristic is negative as a function of power. This behavior can have implications with regard to arcjet power conditioning unit design. The *V-I* characteristics of the arcjet with the modified cathode shifted down along the lines of constant power due to the 15% reduction in engine operating voltage. However, the relative positions of the individual data points within the *V-I* characteristic for each cathode shape were essentially the same.

Although the engine *V-I* characteristics of the arcjet changed dramatically, the performance did not. This is illustrated in Figs. 9 and 10, which show the engine thrust and thrust efficiency as functions of specific power. For values of specific power above 5.7×10^7 J/kg, there was a general trend indicating that the modified cathode provided slightly improved engine performance, though the valves are within the experimental uncertainties.

The baseline MOD I engine contained a cathode that had a total run time of 35,760 s (9 h and 56 min). The MOD II engine cathode was run for 12,120 s (3 h and 22 min). The apparent thermionic emission areas of the MOD I and MOD II cathodes were approximately 0.09 and 0.12 cm^2, respectively. Even though the latter cathode had a shorter run time, it had a larger apparent emission area. This is consistent with the higher operating currents it experienced due to cathode placement and the increased ohmic heating and reduction in rearward thermal conduction.

A hypothesis to explain the different *V-I* characteristics, but similar performance of the two engines, has been proposed.[16] The basic difference in the *V-I* curves is attributed to the geometrically shorter arc length for the modified cathode when compared to the baseline cathode. As noted earlier, achieving a given arc power (*V-I*) required increased current and reduced voltage, which should lead to larger anode losses. The anode losses may be offset by reduced frozen flow in the exhaust.

A shorter arc length implies that the propellant heating time is reduced or that the rate of heating is increased for a fixed power, flow rate, and average exhaust velocity (all of which are readily measurable quantities). A higher heating rate will alter the nonequilibrium state of the propellant.[17] When propellant is heated by conduction at rates higher than vibrational relaxation rates, the energy appears in random thermal motion of the molecules rather than dissociation, excitation, and ionization. If we assume the heating rate was increased, then the propellant is, hypothetically, in a nonequilibrium state that favors more efficient expansion. This, in turn, would allow an arcjet to operate with a higher thrust efficiency (Fig. 10).

Verification of the preceding hypothesis could be critical to the design of a more efficient arcjet. The hypothesis may be examined two ways: 1) by a detailed theoretical treatment that includes the effects of heating, expansion, excitation, dissociation, and ionization rates; and/or 2) by optical diagnostics of the arcjet exhaust to determine the propellant state. Both of these techniques would be desirable from the point of view of developing a more complete understanding of arcjet operation.

Conclusions

A series of experimental investigations were performed to evaluate two arcjet engine design modifications. The engine modifications include the use of a bell-shaped contoured nozzle and a cathode geometry variation. The contoured nozzle demonstrated thrust improvements that ranged from 2 to 10% and depended on the power level and mass flow rate. The thrust increases translated into 3% enhancements in specific impulse and 5-10% improvements in thrust efficiency over a power range of 10.0-30.0 kW_e and a mass flow range of 0.175-0.350 g/s. The new cathode tip design and placement led to a 15% decrease in engine operating voltage with no change in the engine performance characteristics. Therefore, engine performance appears to be more strongly related to engine input power and mass flow rate (or specific power) than cathode shape and location (hence the constant specific power *V-I* characteristic). It is believed that the shortened arc length reduced the frozen flow losses, offsetting the increased anode losses resulting from the higher engine operating current.

Further work needs to be done, both experimentally and theoretically, to better define an optimum arcjet nozzle contour. The combined results of these tests coupled with those of Brophy et al.[9] suggest that the nozzle should have a more pronounced bell shape. It is felt that much work can be done to further optimize the cathode/constrictor geometry for longer life and better performance. Other promising candidate geometries require performance and duration testing. The boundaries, if they exist, of the engine operating envelope where cathode shape and location strongly affect performance need to be investigated.

Acknowledgments

The research reported in this paper was performed by the Jet Propulsion Laboratory, California Institute of Technology, as part of its Innovative Space Technology Center, which is sponsored by the Strategic Defense Initiative Organization/Innovative Science and Technology Office through an agreement with NASA. The authors would like to thank D. Q. King for suggesting the new cathode design; J. Lawless and R. J. Cassady for helpful discussions on cathode physics; and W. R. Thogmartin, A. G. Owens, and R. L. Toomath for facilities and electronics support.

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