ARCJET NOZZLE AREA RATIO EFFECTS

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An experimental investigation was conducted to determine the effect of nozzle area ratio on the operating characteristics and performance of a low power dc arcjet thruster. Conical thoriated tungsten nozzle inserts were tested in a modular laboratory arcjet thruster run on hydrogen/nitrogen mixtures simulating the decomposition products of hydrazine. The converging and diverging sides of the inserts had half angles of 30 and 20 degrees, respectively, similar to a flight type unit currently under development. The length of the diverging side was varied to change the area ratio. The nozzle inserts were run over a wide range of specific power. Current, voltage, mass flow rate, and thrust were monitored to provide accurate comparisons between tests. While small differences in performance were observed between the two nozzle inserts, it was determined that for each nozzle insert, arcjet performance improved with increasing nozzle area ratio to the highest area ratio tested and that the losses become very pronounced for area ratios below 50. These trends are somewhat different than those obtained in previous experimental and analytical studies of low Re number nozzles. It appears that arcjet performance can be enhanced via area ratio optimization.

INTRODUCTION

Demands for high performance systems for auxiliary propulsion on commercial communications satellites have driven an intense effort directed toward the development of kilowatt-class arcjet propulsion systems. The performance improvements that these systems offer over existing resistojet and chemical systems will lead to significant reduction in the north-south stationkeeping propellant mass budget.

In the recent past, arcjet system development has focussed on meeting the technology goals necessary to bring these systems to flight readiness. In many areas, these goals have been met. Stable and reliable operation on hydrazine decomposition products at specific impulse levels between 450 and 500 seconds has been demonstrated (refs. 1-4). Pulse-width modulated power processing units incorporating pulsed, high voltage starting circuits have been tested (refs. 5-7). Extended, cyclic lifetests on both laboratory model (ref. 8) and flight-type (ref. 7) arcjet systems have been completed. Other studies have been performed to assess the impacts of arcjet system integration. Electron number densities and temperatures have been obtained via extensive Langmuir probe surveys of both the near and far field arcjet plume (refs. 9 - 12). The result of these studies have been used to model the effects of the slightly ionized plume on communications signals (refs. 13 and 14). Finally, testing of a flight-type arcjet system on a spacecraft simulator directed toward the documentation of spacecraft/arcjet system interactions has recently been completed (ref. 15).

The efforts noted above have been largely successful in bringing the arcjet system to flight-ready status. It is possible, however, that further arcjet design optimization could yield performance enhancements. Improvements in nozzle design, if possible, would be attractive as they are easily implemented. Many analytical and experimental studies have been performed to achieve a better understanding of nozzle flow phenomena in the low Reynolds number (Re) range characteristic of arcjet thrusters (refs. 16-23). For example, one study showed that the thrust coefficient of a conical nozzle with a 20° divergence angle was maximized for an area ratio of approximately six for heated hydrogen flows at Re near 500 (ref. 16). The effects of nozzle shape, cone angle, and area ratio were studied by Murch, et al., for both hydrogen and nitrogen flows (ref. 17). Experiments and calculations showed that for nozzles with a conical diverging section, a divergence half-angle of 20° provided better performance than divergence half-angles of either 10° or 35°. For the 20° half-angle nozzle, the nozzle efficiency increased with decreasing area ratio to the minimum area ratio tested (20). The study indicated that the optimum area ratio decreases with decreasing Re. Furthermore, over the range of area ratios tested (1-200), performance was found to increase with increasing area ratios for Re greater than 800. For Re below 800, the opposite trend could be observed, i.e. decreased performance accompanied increases in area ratio. It was also found that nozzle shape made a slight difference in performance as a trumpet shaped nozzle out-performed both conical and bell shaped nozzles. A numerical scheme used by Rae to solve the slender channel equations (ref. 18) suggested that small area ratios

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and wide divergence angles were optimal for low Re flows in small rockets. The results of another study (ref. 19) indicated that at low Re the curvature of the throat was important.

The Viscous Nozzle Analysis Program (VNAP) was developed by Cline to calculate flows in gas dynamic lasers (ref. 22). These devices employ nozzles similar to those used in low thrust propulsion devices. This code has been widely applied and, in fact, a derivative was used to optimize the nozzle area ratio on the flight-type thruster (ref. 3). More recently, codes based on both continuum flow (ref. 23) and Direct Simulation Monte Carlo methods (ref. 24) have been reported and these, too, should be useful tools in low Re nozzle flow analyses.

While the noted studies provide significant insight into low Re flows such as those typical of resistojet thrusters, arcjet nozzles are complicated by a number of phenomena that have not yet been properly addressed. These include arc energy addition processes, swirl in the propellant flow field, and arc attachment points or zones. Also, because of the large gradients in temperature, viscosity, and density inherent to the arcjet flowfield, a unique Re cannot be defined. Thus, it is likely that the low Re analyses performed to date will serve only as a starting point for arcjet nozzle optimization. Models describing the arc heating process have been developed by numerous authors (see, for example, refs. 25 and 26). Similarly, constricted arcs in swirling flow fields have been investigated (refs. 27 and 28). Very recently, a sophisticated numerical model has been developed for the arcjet thruster (ref. 29). A test case has been run with nitrogen and compared to experimental results (ref. 30). In this preliminary comparison, the model correctly predicted trends in operating characteristics.

In a recent nozzle design optimization study (ref. 31), a simple conical nozzle was shown to out-perform other classical nozzle shapes. It was clear from this study that more information on the effects of nozzle design would be helpful both in near-term performance optimization and to serve as part of the data base needed for a better understanding of the device. This report details the results of an experimental investigation of the effects of nozzle area ratio on arcjet performance. Conical nozzles, similar to those used in previous tests, were run in a modular, laboratory arcjet assembly on hydrogen/nitrogen mixtures simulating the decomposition products of hydrazine at power levels between 0.6 and 1.4 kW. The nozzle area ratio was adjusted by machining back the length of the divergent section between tests.

APPARATUS

ARCJET THRUSTER

A cross-sectional schematic of the arcjet thruster used in this study is shown in Figure 1 (a). The thruster was modular and similar to thrusters used in many recent tests (refs. 8,31,33) The nozzle/anode is called out in Figure 1 (b) and the dimensions are noted. All nozzles were made from 2 percent thoriated tungsten. Both the converging and diverging sides of each nozzle were conical with half-angles of 30 and 20°, respectively. On each nozzle, the inlet to the converging side was 6.4 mm (0.25 in.) in diameter, and the length and diameter of the constrictor were nominally 0.09 mm (0.0035 in.) and 0.58 mm (0.023 in.), respectively. The nozzle area ratio was adjusted by machining back the diverging section.

The cathode was a 2 percent thoriated tungsten rod 3.2 mm (0.125 in.) in diameter with the tip ground to a 30° half-angle to match the converging section of the nozzle. To avoid the need for long burn-in periods prior to performance testing, a cathode that had been run in prior tests was used. The cathode to anode spacing, or arc gap, was set by moving the cathode forward until it contacted the anode and then withdrawing it 0.58 mm.

A molybdenum injection disk with two tangential inlets, each 0.51 mm (0.02 in.) in diameter, provided propellant swirl. The injection ports were located 6.8 mm (0.27 in.) upstream of the entrance to the constrictor.

TEST FACILITY

All of the tests were performed in a 0.91 m (3 ft.) diameter test section connected to a main vacuum tank through a gate valve. The main vacuum tank was 1.5 m (5 ft.) in diameter and 5 m (15 ft.) in length. The pumping train consisted of four diffusion pumps with a combined capacity of between 48,000 and 60,000 LPS, backed by a rotary blower and two mechanical roughing pumps. At the maximum propellant flow rate, tank pressure was maintained at approximately 0.65 Pa (5×10^{-4} torr). A calibrated displacement-type thrust stand was used to obtain thrust measurements. This stand employed a linear variable differential transformer (LVDT) and has been described in detail elsewhere (ref. 32) The arcjet was mounted on an isolated bracket supported by a water-cooled mount. The stand was surrounded by a water-cooled copper casing to minimize thermal drift from conducted and radiated heat.

PROPELLANT SUPPLY SYSTEM

To simulate the decomposition products of hydrazine, the arcjet was run on mixtures of hydrogen and nitrogen with a 2:1 molar mixture. Thermal conductivity-type mass flow controllers were used to meter the gas. A calibration tank was

incorporated into the flow system to allow periodic, in-situ flow calibrations. Propellant line pressure was monitored upstream of the thruster to give an approximate indication of arc chamber pressure.

POWER PROCESSING AND MEASUREMENT

A pulse-width modulated power processing unit (PPU) was used in the tests (ref. 5). The supply incorporated a pulsed, high voltage starting circuit. A Hall-effect current probe was used to measure the current to the arcjet and an isolated digital multimeter was used to measure arc voltage. A dc power supply and shunt were used to calibrate the current probe.

EXPERIMENTAL PROCEDURE

TEST SEQUENCE

Prior to each test sequence, the arcjet was assembled, leak-checked, and installed on the thrust stand. The test section was then closed, pumped down via a separate roughing pump and then opened to the main tank. The current probe and thrust stand were both calibrated prior to testing and cold flow performance was measured at both of the mass flow rates to be tested (3.11e-5 kg/s and 4.97e-5 kg/s). These two flow rates span the range expected in most commercial applications.

At the higher mass flow rate the thruster was started with the PPU preset to 10 A. The current level was then decreased in 1 A decrements to the 4 amp level. At each current level the thruster was allowed to come to steady state. The 10 A test point was then repeated in order to determine whether significant changes had occured over the course of the test. At the lower flow rate a similar test sequence was used. To avoid damage to the thruster however, the maximum current tested at the lower flow rate was limited to 8 A.

Each test sequence ended with a recalibration of the current probe and thrust stand. In some tests, a slight drift in the thrust zero was observed. In these instances the thrust data was reduced using the average of the pre- and post- test zeroes. The difference between these values and those calculated using the post test zero was always less than one percent.

RESULTS AND DISCUSSION

The objective of this investigation was to obtain an assessment of the effect of area ratio on the operating characteristics and performance of a kilowatt class arcjet incorporating a conical nozzle insert. Two separate inserts of the same nominal design were tested in order to verify the repeatability of the experimental results. These will be referred to as nozzle inserts 1 and 2.

REPEATABILITY AND ACCURACY

Statistical analyses of repetitive test data taken with similar thrusters in this laboratory have shown that the standard deviations in measured values such as voltage and thrust, as well as in calculated performance values, are typically less than 1 percent (see, for example, ref. 33). The repeated data points taken in the course of testing for this report also fell within this range of uncertainty. After preliminary testing, there was some question as to the repeatability of the arc gap setting. To examine this, a number of the performance tests of the thruster using nozzle insert 1 were repeated after the arc gap was reset. The measurements obtained in these tests agreed to within one to one and one half percent. For clarity in graphing, the average data from these tests is presented herein.

OPERATING CHARACTERISTICS

Current-voltage (I/V) characteristics observed with the two nozzle inserts were similar. The I/V values obtained with nozzle insert 1 for the two flow rates are shown in Figures 2(a) and 2(b). These plots show that there was a general trend towards higher voltage as the area ratio was decreased and that this became more pronounced as the current level was increased. The I/V characteristics appeared to fall into groups. For example, The I/V characteristics taken with nozzle insert 1 at area ratios of 283, 188, and 107 were similar, as were those taken at area ratios of 20 and 50. Significant differences were observed between groups at the higher current levels tested. The plots suggest that the groupings are flow rate dependent. While the causes of the observed trends are not currently understood, the groupings suggest modal behavior. In a recent report in which a segmented anode was used to study arcjet anode/nozzle phenomena, it was found that the lowest arcjet operating voltage was observed when the anode attachment was allowed to seat across the entire anode (ref. 34). Artificially forcing the arc upstream or downstream in the nozzle led to increased operating voltages. From this, as the area ratio is decreased by reducing the nozzle length, the voltage would be expected to rise if either the arc remains seated on the diverging side of the nozzle in the higher pressure region near the throat or the arc at some point changed to attach downstream on the nozzle lip and/or on the anode housing.

Visually, a normal arcjet plume was observed in tests of nozzle area ratios of 50 and above. At the 20:1 and 10:1 area ratios, however, the visible plume changed somewhat as two bright regions, distinct from and symmetrical about the central plume, appeared off-axis. An example is shown in Figure 3. These emanated from the vicinity of the nozzle lip and

may have been a visible manifestation of a luminous cone surrounding the axial plume, making an angle of 45 - 50° with respect to the thruster axis. At the 10:1 area ratio, the size of these luminous regions rivaled the core plume. This phenomena is simply noted here for future investigation as spectroscopic data has not yet been gathered to document this phenomena.

PERFORMANCE CHARACTERISTICS

Plots of thrust versus power for nozzle insert 1 tested at various area ratios at each mass flow rate are shown in Figures 4 (a) and (b). Similar data were obtained with the second nozzle insert. The plots indicate that the arcjet performance improved with increasing nozzle area ratio to the highest area ratio tested and that the losses became more pronounced as the area ratio was reduced to below the 50 to 100 range. This is shown more clearly in Figure 5. Here thrust is plotted versus area ratio for both nozzle inserts at a fixed power level of one kilowatt at the upper flow rate and 0.8 kilowatts at the lower flow rate. The similarity between nozzle inserts shows the repeatibility of the data. The data also indicate that similar trends in performance were obtained at both of the propellant mass flow rates tested. The performance trends illustrated in these figures are somewhat different than those obtained in most previous experimental and analytical studies of low Re nozzle flows. The results of the previous studies suggest that viscous losses offset gains due to increased area ratio at very low area ratios. For example, the numerical analyses of Rae suggested that for very viscous flows, nozzle area ratios as low as 10 could be used with no serious degradation in performance (ref. 16). An extensive experimental and analytical study by Murch, et al., indicated that for conical nozzles and Re greater than 800, the performance should increase with area ratio up to about 200. At higher area ratios, however, frictional losses were expected to decrease performance. The experimental work performed by Murch also indicated that at Re below 800 specific impulse would decrease with increasing area ratio in this range. Similarly, the VNAP2 code, designed to model low Re nozzle flows, was recently used to optimize a low power arcjet nozzle (ref. 3) and the results of this analysis indicated that viscous losses offset expansion gains for area ratios above 50:1. Clearly, the experimental results presented in this report indicate that performance improved with area ratio to the maximum area ratio tested for each nozzle insert and it appeared that for each insert, small performance gains could be realized at higher area ratios. The causes for the differences noted between the results of this report and previous analytical and experimental analyses are not fully understood at this time. The differences are significant, however, and they suggest that conventional gasdynamic analysis is not sufficient to fully characterize arcjet nozzle/anode phenomena.

The systems level impacts of increasing area ratio are shown in Figures 6 (a) and (b). Here, specific impulse and efficiency are plotted versus specific power for the set of tests run on nozzle insert 1. Efficiency was calculated as described in Appendix A. Figure 6 (a) shows that across the range of specific power tested, an increase of about 70 seconds in specific impulse was obtained by increasing the area ratio from 10 to 283. Overall, nearly 40 percent of this increase was realized as the area ratio was increased beyond 50. Similarly, Figure 6 (b) shows that the efficiency decreased by a factor of approximately 30 percent over the range of area ratios tested.

In a recent paper on low power arcjets, it was noted that propellant mass flow rate affects arcjet efficiency (ref. 33). In these tests the specific impulse obtained at fixed specific power levels above approximately 17,000 kJ/kg decreased as the mass flow rate was reduced. Similar results were obtained with the higher area ratio nozzle inserts used in the tests performed in this study. As the area ratio was reduced, however, the performance obtained at a fixed specific power level became independent of mass flow rate. An example of this is shown in Figure 7 (a). Here, specific impulse is plotted versus area ratio at a specific power level of 22,000 kJ/kg. As noted in the previous paper on low power arcjet performance (ref. 33), a majority of the input energy not converted to thrust is invested in frozen flow losses, in energy deposited in the electrodes, and in frictional losses. There is currently not enough data available to separate these efficiency loss mechanisms. The plots in Figure 7 (a) also suggest that the maximum value of specific impulse is approached more rapidly at the lower mass flow rate tested. This could, however, be due to data scatter. At higher specific power levels, a similar trend in performance with area ratio was observed and this is shown in Figure 7 (b). In this figure, specific impulse is plotted versus area ratio at a specific power level of 28,000 kJ/kg. Due to the power handling limitations of the thruster system, specific power levels this high were only tested at the lower mass flow rate.

NOZZLE LIP AREA EFFECTS

As the nozzle was machined back between tests, the lip area, or exposed annular surface at the exit plane, increased significantly. Gas expanding around this lip exerts pressure on the surface producing a thrust component related to the lip area. If significant, this thrust component would complicate the interpretation of the area ratio study. To determine the magnitude of the effect, a simple test was performed. After nozzle insert 1 had been tested at an area ratio of 50:1, the insert was machined back so that the lip area was reduced by a factor of approximately 2 so as to equal the lip area of the original 283:1 area ratio nozzle. This insert was then retested under the same operating conditions as the unmodified insert. The I/V characteristics obtained in these tests are shown in Figure 8 (a). The characteristics obtained were very similar. The only significant differences observed occured at the two lowest current settings at the lower mass flow rate. These were just outside of the expected range of standard deviation. Small changes in arcjet performance were observed between tests of the modified and unmodified inserts. This is shown in Figure 8 (b) in which specific impulse is plotted versus specific power for both inserts. From the figure, the nozzle with the reduced lip area produced lower performance across the specific power

range tested. The effect increased slightly with decreasing specific power. The maximum difference in specific impulse observed, however, was only about 10 seconds. As with the voltage, this difference is only slightly above the statistical uncertainty (~ 7 - 8 seconds). If real, the small magnitude of this effect would not alter the gerneral trends observed in performance with area ratio.

CONCLUDING REMARKS

A modular, kilowatt-class arcjet thruster was tested with conical nozzle inserts to determine the effect of nozzle area ratio on arcjet operating characteristics and performance. The diverging sections of the nozzles were shortened between tests to vary the area ratio. For each insert, the performance increased with increasing area ratio to the highest area ratio tested, 283 in one case and 318 in the other. The losses in performance became more pronounced at nozzle area ratios below about 50. These results are somewhat different than those obtained in previous analytical and experimental studies of low Re nozzle flows and suggest that conventional gasdynamic evaluation is not sufficient to fully describe the arcjet flowfield. The results indicate that for arcjets incorporating nozzles with conical diverging sections, performance levels can be optimized by employing nozzle area ratios above 100 if the hydrogen/nitrogen propellant mixture used in this study adequately simulates the decomposition products of hydrazine.

The I/V characteristics observed indicated that the arcjet ran in different modes depending on the area ratio. At a fixed operating point (i.e. mass flow rate and current) the arcjet operating voltage was similar within area ratio groups with step changes occurring between groups. This could indicate some modal behavior in the anode attachment region and/or changes in anode losses and the arc impedence. An interesting change in plume appearance was observed in tests of the very low area ratio nozzles and should be the topic of future spectroscopic investigation.

APPENDIX A

All arcjet efficiency values were calculated using the following equation:

$$\eta = \frac{(1/2)\dot{m}(v_h)^2}{P_a + (1/2)\dot{m}(v_c)^2} \tag{A1a}$$

$$= \frac{(I_{sph})^2}{(2/g^2)(P_a/\dot{m}) + (I_{spc})^2} \tag{A1b}$$

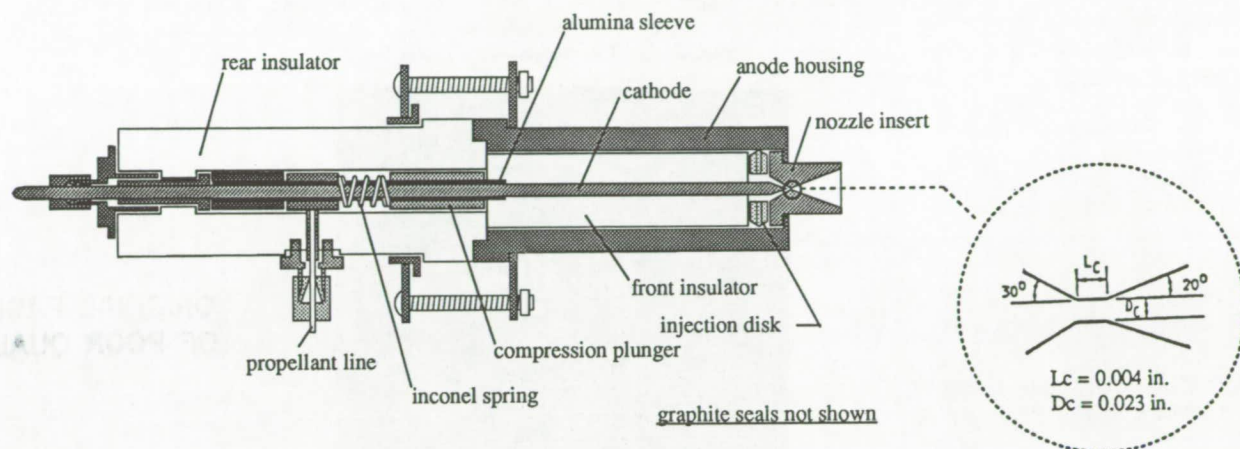For this, the following notation was used:

I_{sp} - specific impulse, sec
$\dot{m}$ - mass flow rate, kg/sec
P_a - arc power, W
v - exhaust velocity, m/sec
η - thrust efficiency.
g - gravitational acceleration, 9.8 m/sec^2
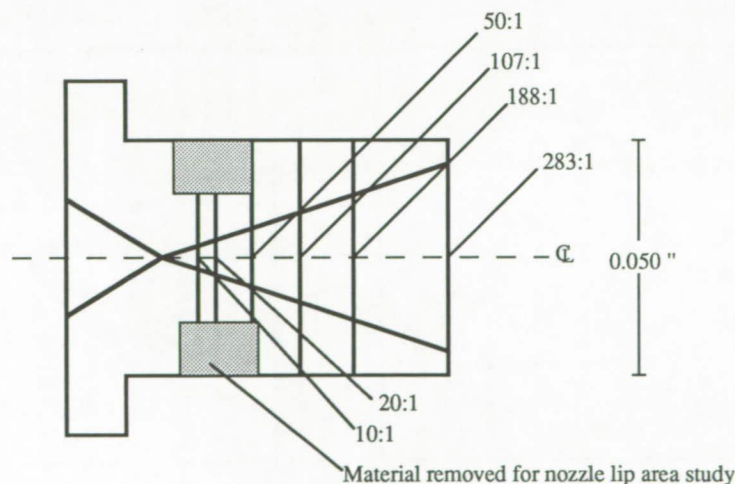h,c - subscripts denoting hot and cold conditions

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a) Cross-sectional schematic of modular arcjet thruster.

b) Cross-sectional schmatic of nozzle insert 1 with area ratio cuts.

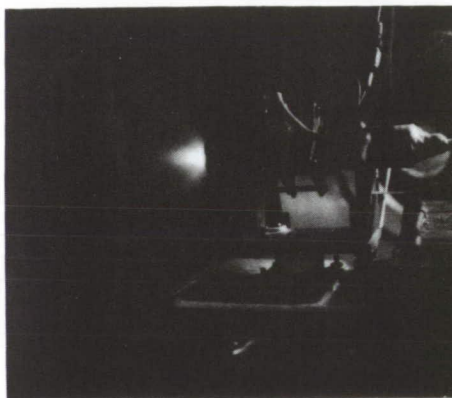Figure 1. Cross-sectional schematics of the modular arcjet thruster and nozzle.

a) Mass flow rate = 4.97 e-5 kg/s

b) Mass flow rate = 3.11 e-5 kg/s

Figure 2. I/V Characteristics - Insert 1.

Figure 3. Arcjet plume observed with low area ratio nozzle.
(10:1 area ratio, ṁ = 4.97 e-5 kg/s, I = 4 A, V = 163 V)

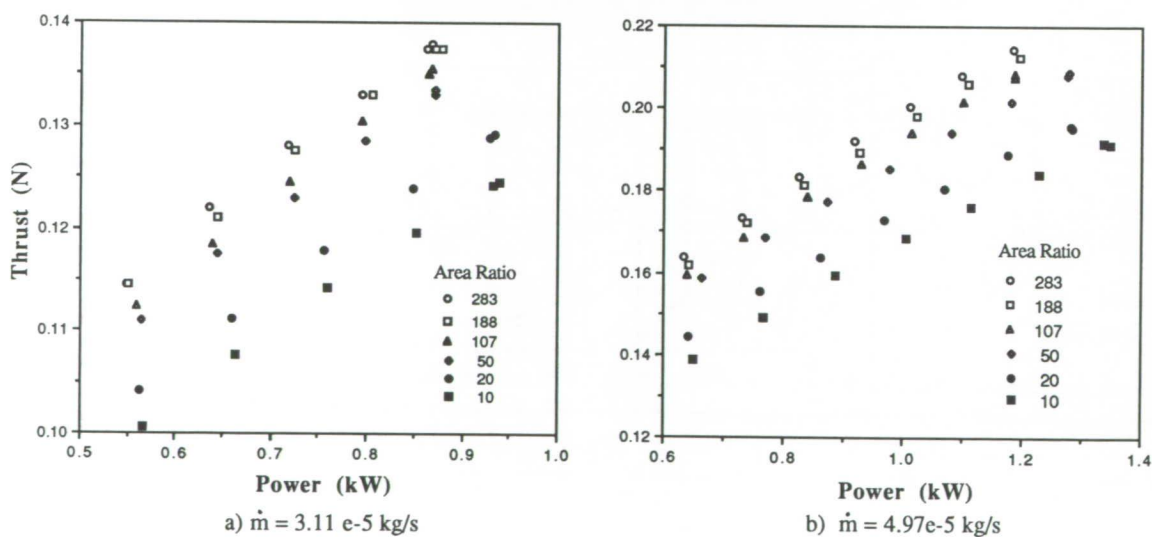a) ṁ = 3.11 e-5 kg/s

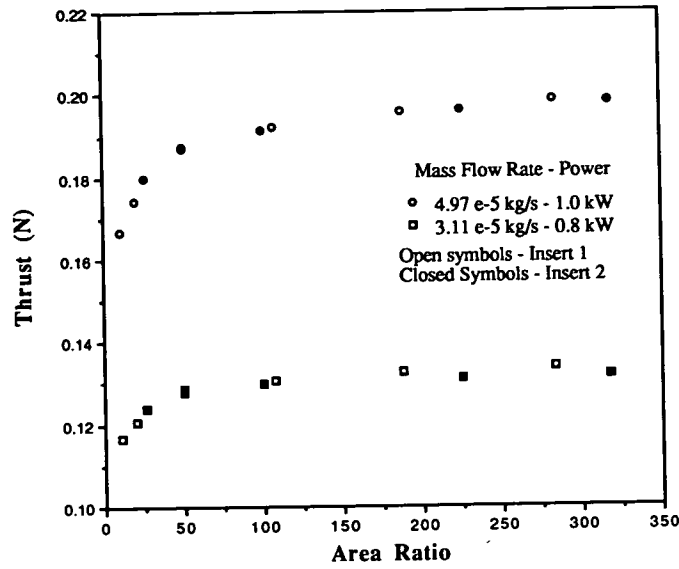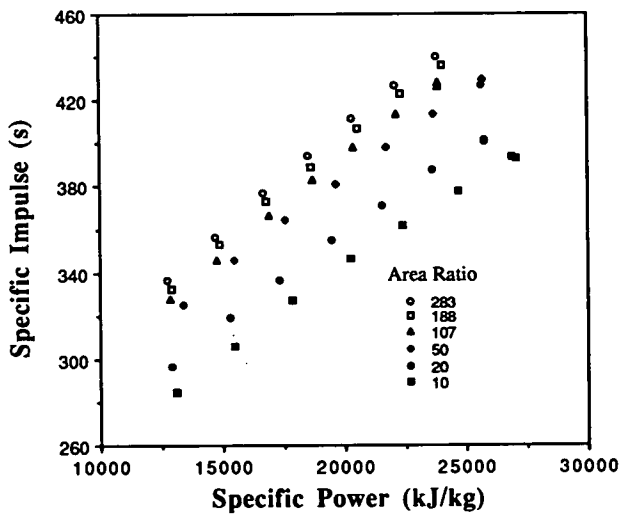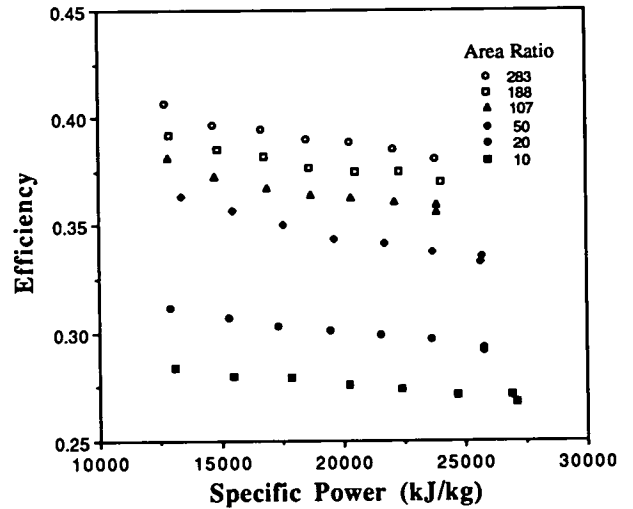b) ṁ = 4.97e-5 kg/s

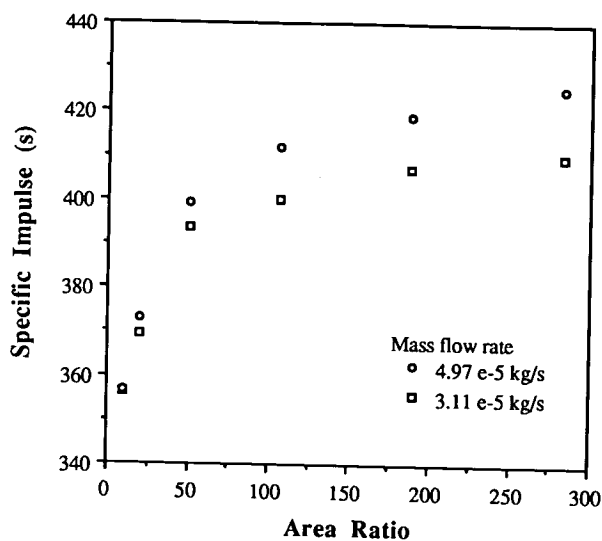Figure 4. Thrust vs power- nozzle insert 1.

Figure 5. Thrust vs area ratio.

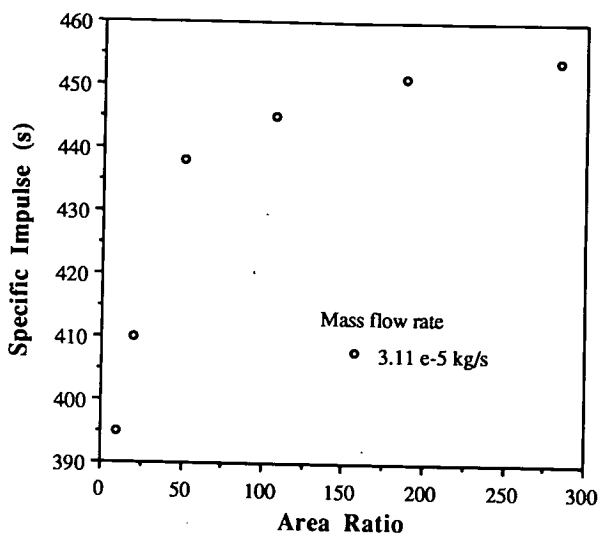a) Specific impulse vs specific power -
nozzle insert 1, ṁ = 4.97 e-5 kg/s

b) Efficiency vs specific power - nozzle
insert 1, ṁ = 4.97 e-5 kg/s.

Figure 6. Specific impulse and efficiency versus specific power - nozzle insert 1.
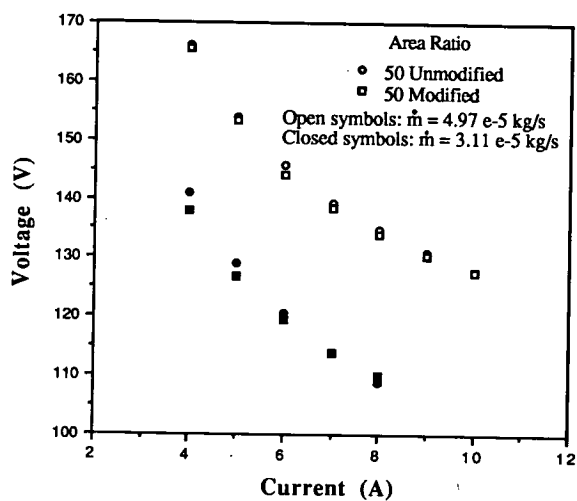
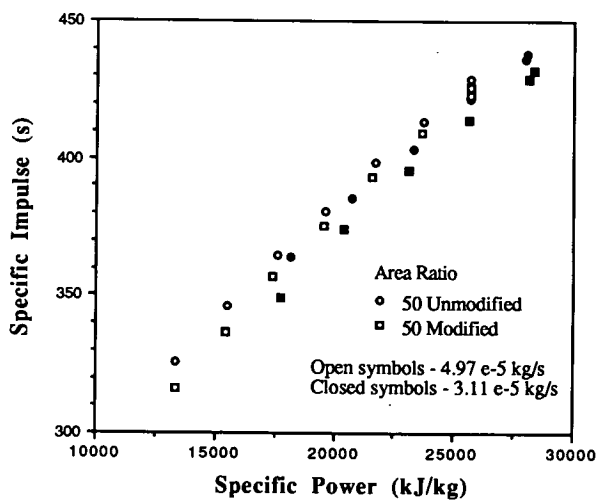a) Specific power = 22,000 kJ/kg   b) Specific power = 28,000 kJ/kg

Figure 7. Specific impulse versus area ratio - nozzle insert 1.

a) I/V characteristics   b) Specific impulse versus specific power.

Figure 8. Nozzle lip area effects - nozzle insert 1.