AIAA-95-3065

Current Status of the Microwave Arcjet Thruster

Sullivan, D. J., Kline J., Philippe, C., Micci, M. M.

Propulsion Engineering Research Center
Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA 16802, USA

31st AIAA/ASME/SAE/ASEE
Joint Propulsion Conference and Exhibit
July 10-12, 1995/San Diego, CA
Current Status of the Microwave Arcjet Thruster

D. J. Sullivan†, J. Kline‡, C. Philippe§ and M. M. Micci‡

Propulsion Engineering Research Center
Department of Aerospace Engineering
The Pennsylvania State University
University Park, PA 16802, USA

Abstract

The microwave arcjet thruster uses microwave energy to create a free-floating plasma discharge within a microwave resonant cavity. This discharge absorbs the input microwave power and converts it to thermal energy which is then transferred to the flowing propellant gas. The thruster can be operated in a fixed configuration where neither the cavity geometry nor the tuning mechanisms are adjusted; optimization of this geometry for a given propellant results in power coupling in excess of 97%. The prototype has demonstrated its ability to operate in this fixed configuration within a vacuum tank facility where it has been extensively tested using both N₂ and NH₃. The current design is capable of efficient operation over a wide range of power levels and mass flow rates resulting in representative specific powers of 6.5 MJ/kg for N₂ and 77.2 MJ/kg for NH₃. Current work is focused on development of a compact power supply, redesign of the current prototype to allow for high temperature operation, and design of a low-mass prototype design which mates the magnetron supply directly to its power coupling probe.

Nomenclature

- $a$: cavity radius
- $d$: distance from the load to the stub position
- $E$: electric field vector
- $E_z$: z-component of $E$
- $E_\phi$: azimuthal component $E$
- $E_r$: radial component of $E$
- $f_r$: resonant frequency
- $h$: resonant length
- $J_e$: electric current density
- $m$: mass
- $n_e$: electron number density
- $P$: instantaneous power
- $P_{ave}$: average power
- $q$: unit of electric charge
- $R_L$: real component of impedance
- TM: transverse magnetic
- $z$: z coordinate
- $Z_L$: complex load impedance
- $Z_0$: characteristic impedance of transmission line
- $jX$: complex component of impedance (i.e. reactance)
- $\varepsilon$: permittivity of medium
- $\mu$: permeability of medium
- $\rho$: radial coordinate
- $\sigma$: conductivity
- $\nu_m$: collision frequency for momentum transfer
- $\omega$: radian frequency of the applied microwave field
- $\chi_{01}$: first zero of the $J_1$ Bessel function

† Graduate Research Assistant, Student Member AIAA
‡ Visiting Research Assistant, Student Member AIAA
§ Visiting Research Assistant, Student Member AIAA
‡ Associate Professor of Aerospace Engineering, Senior Member AIAA

Copyright © 1995 by the American Institute of Aeronautics and Astronautics, Inc. All rights reserved.
Introduction

For the past decade, the development of a microwave powered electrothermal thruster has been pursued by a number of researchers utilizing both experimental and numerical methods. The experimental work conducted at Penn State has explored the viability of thruster configurations which have incorporated either rectangular or cylindrical waveguides, or cylindrical resonant cavities as their central components. Results of early studies have indicated that a design based upon a cylindrical conductive cavity operating in the \( \text{TM}_{011} \) resonant mode would be best suited for thruster applications. An electrothermal thruster of this type uses microwaves to form and maintain a free floating plasma discharge within the cavity; cold gas passes through the cavity, is heated by the plasma source, and passes out of the device through a nozzle to produce thrust.

Motivation for electric propulsion

The space community has been launching satellites into earth orbit ever since the launch of Sputnik I on October 4, 1957. The decades following saw rapid growth and change in both the use, size, complexity and cost of these satellites. More recently, entire new industries have been or are being created which have satellite networks as their central component. The International Telecommunications Satellite Organization (INTELSAT), the Global Positioning System (GPS), the proposed global satellite phone systems (e.g. Motorolla's Iridium, TRW's Odyssey, etc.), and direct broadcast systems (e.g. Hughes Communication's DirectTV) are but a few of the major investors in these new markets which have profit potential in the hundreds of millions.

As these markets expand, the satellites themselves are required to do more and be more economical at the same time thereby echoing the smaller, cheaper, better concept which has become the catch phrase of the space industry in the 1990's. The goal of these satellite manufactures has been to maximize both the revenue from the satellite (i.e. increase the amount of onboard electronics) as well as the satellite lifetime, while at the same time reduce the overall satellite volume so as to allow the use of the smallest, and thus cheapest, launch system available. For those satellites which have station-keeping requirements, typically the GEOsats and MEOsats, the most obvious system to target for achieving these goals is the on-board propulsion system.

The propulsion system for a geosynchronous satellite is required to perform many missions and is typically a very complex subsystem which accounts for a large fraction of the total launch mass, and though less commonly acknowledged the propulsion subsystem is also responsible for the majority of satellite failures. The past decade has seen the industry move toward three-axis stabilized platforms which has forced the evolution of propulsion subsystems of increasing sophistication. With these changes have come concerns over the complexity of these systems as well as the desire to make them more efficient. These motivations have resulted in incremental improvements in the propulsion systems. One such improvement has been the incorporation of electric propulsion into the subsystem.

Mission analyses have shown that significant mass savings can be accomplished by using more efficient electric propulsion systems to accomplish the task of north-south stationkeeping (NSSK) which, not including apogee insertion, is the maneuver having the greatest propulsion requirements\(^1\). The fuel savings from the use of an electric propulsion (EP) system for NSSK can be used in several ways. Additional payload can be installed on the satellite, or the payload can be left alone, taking the savings in launch costs. Finally, the launch mass can be held fixed, and a part, or all, of the chemical propellant can be replaced with an electric system and its propellant to increase the maneuver lifetime of the satellite. Since many commercial communication satellites in orbit today were still operational when they ran out of maneuvering fuel, the increased capacity could extend satellite life by a number of years\(^2\).

Microwave Arcjet vs. Conventional Arcjet

Arcjets and microwave thrusters increase the thermal energy of the propellant gas in similar manners. Both these devices use electrical energy to generate high temperature plasmas which in turn heat a flowing propellant gas. Unlike chemical systems which are limited by the amount of energy which is liberated in the combustion process, these devices can impart large amounts of power into relatively low mass flows of propellant. This results in specific impulses which are considerably higher than chemical systems. A second advantage is the flexibility of propellant choice. Since combustion is not necessary, these systems can use low molecular weight propellants resulting in a more efficient use of propellant. The flexibility of propellant choice also allows these devices to be integrated more easily into existing satellite propulsion subsystems without greatly
increasing the risk of system failure. For example the hydrazine arcjet (Figure 1) replaces a monopropellant hydrazine thruster on the Telstar IV satellite. Thus incorporation of this electric propulsion device did not require additional valving or extensive redesign of the propulsion subsystem’s propellant feed system.

The microwave electrothermal thruster (Figure 2) is similar to the arcjet in operation and its performance (e.g. \(I_{sp}\) versus \(P_s\)) is also expected to be similar. The motivation for developing the microwave thruster has been to develop a system which will be more efficiently than the arcjet while at the same time be more reliable, less complex, and less prone to erosion.

The arcjet (Figure 1), as its name implies, is characterized by a dc plasma arc which forms at the tip of a concentrically located cathode and is terminated at an anode which forms the diverging section of the nozzle. Between cathode and anode, the arc passes through a constrictor section where the bulk of the heating process occurs. The heated gas then exits the device through the diverging nozzle.

Two primary problems which arcjets have encountered have been arc stability within the constrictor and erosion of the cathode tip. The stability problem has been successfully addressed by using a vortical flow of gas through the constrictor. The erosion problem is inherent to the device; at present, flight ready hardware is designed such that propellant supply rather than cathode erosion is the lifetime limiting factor. As mission complexity increases past that of satellite stationkeeping, the overall importance of the effects of cathode erosion will become more critical.

The microwave resonant cavity thruster, i.e. the microwave arcjet (Figure 2), is characterized by a free-floating ac plasma discharge. The location of the discharge, which forms at regions of maximum power density, is determined by the electric power density distribution within the cavity. Proper cavity design produces a power distribution which results in an axially located plasma which is positioned directly upstream of a nozzle incorporated into one end of the cavity. Operation in this configuration has the net effect of producing a flow constriction between the plasma discharge and the nozzle inlet. It is in this constricted region that the bulk of the heating process occurs.

In regard to conceptual operation as a thruster, the microwave device does not differ greatly from the arcjet. However, he major differences become apparent in the details of operation. Since the microwave thruster does not use electrodes, the plasma discharge never contacts and thus never causes erosion of a critical electrical component as is the case with the cathode of the arcjet. The power supply of a microwave thruster is a magnetron based microwave generator. Proper design will allow the generator to operate at a single power level; the technology required to accomplish this is mature and very reliable. So while this aspect of power conditioning for the microwave thruster has not been extensively addressed, initial studies indicate that it should be less complex and more reliable than that used by arcjets. A power processing option which is available to the microwave arcjet is to use a single microwave generator which could supply microwave power to a pair of microwave thrusters. For a double redundant NSSK system comprised of four thrusters, this scheme would only require two independent power processing units.

**Background and Theory**

The breakdown mechanism which produces a microwave plasma is similar to the steady field breakdown which produces the dc arc in a conventional arcjet. However, at microwave frequencies the period of the applied field is on the same order as the breakdown process which is typically completed in intervals of \(10^{-6}\) to \(10^{-8}\) seconds. When this is the case, a condition is reached such that electrons produced by electron collisions will not be able to reach an electrode before the field direction reverses. These electrons will oscillate in the gap, undergoing collisions with the gas particles until breakdown occurs. This process occurs without the participation of any electrodes. The microwave arcjet takes advantage of this phenomena.

The details of the breakdown process are well known, but a few of the more important details of high frequency discharges are presented here for clarity. The conductivity, \(\sigma\), of the discharge is given by the ratio between the instantaneous values of the current density and applied electric field

\[
\sigma = \frac{J_e}{E} = \frac{n_e q^2}{m} \frac{v_m - j\omega}{m(v_m^2 + \omega^2)}
\]

In order to ionize atoms or molecules, an electron must be able to transfer energy from the a.c. field to the neutral particles. This can happen only when \(v_m\) is nonzero and is comparable with \(\omega\).
The power per unit volume of the breakdown discharge supplied by the field can be determined by application of the Poynting vector which results in:

\[ P = \frac{n_e q^2}{m (v_m + j\omega)} E \cdot E = \frac{n_e q^2}{m (v_m + j\omega)} E^2 e^{j2\omega t} \]  

(2)

The average real power over one cycle, or multiples thereof, is

\[ P_{ave} = \frac{n_e q^2 E^2}{m} \frac{v_m}{v_m^2 + \omega^2} \]  

(3)

This is the average power gained by all electrons present in the gas. Thus the plasma acts as an ohmic heating source, and the power absorbed by the plasma is proportional to the square of the electric field. Also note that since the plasma conductivity is complex, the load impedance in the cavity due to the plasma will be complex.

Gas breakdown will occur and the plasma discharge will be maintained when the production of newly ionized particles barely exceeds the rate of their loss by all deionizing processes, including diffusion, recombination, and attachment. For microwave plasmas recombination and attachment can usually be neglected with respect to diffusion. For most circumstances encountered in practice, a plasma can be maintained as...
long as the ratio of \( E/p \) can be maintained high enough that ionization is ensured. The rate of diffusion is not generally a controllable parameter.

**Description of the TM\(_{011}\) Resonant Cavity**

A conducting enclosure which has the geometry of a right circular cylinder can, under proper conditions, act as a cavity resonator; the theory which describes this has been described elsewhere\(^4\) and will be summarized here. For the purpose of an electric propulsion device, the TM\(_{01p}\) resonant mode is of interest, and the following discussion will deal primarily with the TM\(_{011}\) mode. The electric field components describing this resonant mode are given in cylindrical components as:

\[
E_z = E_{01p} J_0 \left( \frac{\lambda_0 a}{a} \right) \cos \left( \frac{p \pi z}{h} \right) \quad (4)
\]

\[
E_\phi = 0 \quad (5)
\]

\[
E_p = E_{01p} \frac{p a}{\lambda_0 h} J_1 \left( \frac{\lambda_0 a}{a} \right) \sin \left( \frac{p \pi z}{h} \right) \quad (6)
\]

The geometry of the cavity, i.e. its radius, \( a \), and its length, \( h \), are related to the resonant frequency by the equation:

\[
(f_{01p})^2 = \frac{1}{2 \pi \sqrt{\mu_0}} \sqrt{\left( \frac{\lambda_0 a}{a} \right)^2 + \left( \frac{p \pi}{h} \right)^2} \quad (7)
\]

where \( \lambda_0 \) has an approximate value of 2.405.

As stated earlier, a primary parameter of interest for plasma production and power absorption is the electric energy density. The electric energy density is proportional to \( |E|^2 \) and it is in the regions where this quantity is maximum that a plasma can be expected to form. Thus

\[
\text{Electric Energy Density} \propto E_p^2 + E_\phi^2 + E_z^2 \quad (8)
\]

For the TM\(_{01p}\) mode, equation (5) states that \( E_\phi = 0 \) and the electric power density is dependent upon \( E_p^2 \) and \( E_z^2 \) only. Even though the power density is dependent upon both \( E_p^2 \) and \( E_z^2 \), the amount that each component contributes is determined by the geometry of the cavity. This geometric dependence is derived from the \( E_p^2 \) term and has the form

\[
(p \pi a)^2 / (\lambda_0 h)^2 = A \left( \frac{p a}{h} \right)^2 \quad (9)
\]

Note, the constant terms have been collected into \( A \). As can be seen from equations (4), (6) and (9), when the geometry of the cavity is such that \( p a/h < 1 \), \( E_p^2 \) becomes the dominant component. When this is the case the energy within the cavity is concentrated on the axis of symmetry and the plasma which forms tends to from and remain on the axis.

A contour plot of the electric energy density for a TM\(_{011}\) cavity with the geometry used in the current thruster prototype is shown in Figure 3. The prototype cavity has a radius of 5.08 cm and a resonant length of 15.87 cm yielding a geometric ratio of \( p a/h = 0.320 \). The plot has been generated assuming a resonant frequency of 2.45 GHz. Note that each contour represents the electric power density on a cutting plane which is parallel to and passes through the axis of symmetry of the cavity; because the TM\(_{01p}\) mode does not have a \( \phi \)-dependence, all such cutting planes are identical.

**Power Coupling**

A resonant cavity with imperfectly conducting walls containing a lossy plasma, and the coupling mechanism which connects it to the transmission line, can together be considered as the terminating load which has a complex impedance \( Z_L \). If this load impedance can be matched to the impedance of the transmission line, then the maximum amount of power will be absorbed by the cavity/plasma system.\(^5\)

The power from the microwave generation source is coupled into the microwave arcjet resonant cavity through the use of a linear probe which is orientated so that its length is parallel to the electric field lines in the waveguide. The probe is the termination of the coaxial power transmission line and it enters the cavity such that it is aligned on the axis of symmetry. This process is usually referred to as electric field coupling.

The development by Collin\(^4\), the details of which are omitted here, show that by proper choice of the probe length into the cavity and the proper adjustment of the resonant length, the real part of the impedance of the antenna/cavity system can be matched to the characteristic impedance of the coaxial line \( Z_0 \), and the imaginary part can be adjusted to cancel the part of the input reactance produced by the antenna. With such a choice of parameters, \( Z_L = Z_0 \), and all the incident
power is coupled into the cavity. This type of manipulation is referred to as active coupling.

As will be described in the following section the prototype thruster has the capability of varying both the coupling probe insertion depth and the resonant length of the cavity. As will be discussed, these adjustments, in accordance to the theory just described, allow for almost perfect coupling of microwave power into the plasma discharge.

**Stub Tuning**

As long as the impedance of the transmission line $Z_L$ is a real quantity (which is true if surface effects are neglected) any load which has a real impedance ($Z_L = R_L$) can be matched to the transmission line using a quarter-wave transformer. However, it is usually found in practice that the load impedance is seldom a purely real quantity and is usually complex.

A stub tuner is a device which can be used to transform a complex impedance to a real quantity. The technique uses a single short circuited length of transmission line (a "stub"), connected to a transmission feed line at a certain distance from the load. In single stub tuning, the two adjustable parameters are the distance $d$ from the load to the stub position, and the value of the reactance provided by the stub, The distance $d$ is selected so that the impedance seen looking into the line at a distance $d$ from the load is of the form $Z_L + jX$. Then the stub reactance is chosen as $-jX$, resulting in a matched condition.

A single-stub tuner is able to match any load impedance (as long as it has a non-zero real part) to a transmission line, but suffers from the practical disadvantage of requiring a variable length of line between the load and the stub. In order to avoid this problem, a multiple-stub tuner can be utilized. While the theory of a single-stub tuner is relatively straightforward, the mathematical complexity increases for the multiple stub case. The interested reader is referred to the text by Pozar.

It has been shown in this and the proceeding section, that it is possible to match the transmission line to a load which has a complex impedance thereby obtaining maximum power transfer to a system. Whether the choice of tuning is to use stub tuning or adjustable antenna coupling, or some combination of both depends upon the particular application. As will be discussed, both tuning methods have been used successfully during the course of testing.

**Design of Microwave Arcjet**

A full description of the microwave arcjet prototype has been given elsewhere. The prototype's
design was formulated by examining the experimental results of a number of researchers.\textsuperscript{8-13} Their results coupled with a better understanding of the theoretical basis governing this type of resonant cavity/plasma interaction resulted in a design which has been able to produce stable microwave discharges which possess exceptional axial stability and a desirable location near the axially located nozzle inlet. A cross-sectional view of the current prototype design showing the approximate location and shape of the plasma discharge is presented in Figure 4.

The geometry of the device is adjustable such that the impedance characteristics of the plasma cavity system can be varied. Note, however, that the geometry of the cavity is fixed when the thruster is being tested.

The thruster geometry can only be varied between tests. The fixed configuration allows the device to be operated at high pressure which in turn allows for high power operation.

The microwave arcjet device is inherently safe and does not require any special precautions or electrical isolation during operation. The only high voltage power present is contained within the housing of the microwave generator and access to this is not required during the normal course of testing. During operation of the device, there is no danger presented from being in close proximity of the device. This allows easy access for viewing both the plasma (through the optical access window located in the upper half of the cavity) and the exhaust plume.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4.png}
\caption{Current design of the microwave arcjet prototype. Design allows cavity geometry to be varied between tests. Flexible graphite (Grafoil) gaskets provide pressure seals at elevated operating temperatures. Plasma discharge position and approximate size are also indicated.}
\end{figure}
Recent changes in the propellant feed system have reduced the amount of small leaks within the system. This has allowed a better vacuum to be achieved in the nozzle half of the cavity during start-up. This improvement in the system operation has greatly improved the repeatability of performance and has allowed for the creation of plasmas formed from various gases at relatively low powers (300 W - 500 W) at pressures of approximately 0.01 kPa (~0.1 Torr).

Both high density graphite and stainless steel have been utilized as nozzle materials. During lab testing when the device was exhausted into the lab only a nozzle with a converging portion was used. Current testing is being conducted within a vacuum facility which is using a stainless steel conical converging-diverging nozzle which has an inlet half angle of 30 degrees and a diverging half angle of 20 degrees.

**Previous Results**

Previous testing has shown that the device can be successfully operated with both helium and nitrogen for extended periods. Isentropic estimates of performance from measured parameters of cavity stagnation pressure, propellant mass flow rate and nozzle diameter have yielded promising results. Representative results for calculated vacuum Isp and thermal efficiency versus input specific power are shown in Figure 5 and Figure 6, respectively. As expected, helium has better performance characteristics due to its lower molecular weight.

Testing which was conducted at NASA LeRC clearly indicated that a microwave device could repeatedly produce H$_2$ plasmas but raised concerns about the heat transfer to the structure of the device due to the high thermal conductivity of the hydrogen propellant. This observation has been corroborated by limited testing of both H$_2$ and NH$_3$ with both the current prototype device and with another TM$_{011}$ cavity of slightly different geometry.

Nitrogen testing conducted with the fixed geometry version of the cavity indicated that the plasmas formed could be brought to a high-power / high-pressure condition without requiring adjustment of the three-stub tuning device if the cavity geometry was set such that it produced maximum impedance matching at the high power condition. This proper cavity geometry was determined by iteratively adjusting the cavity geometry between tests. After approximately twelve tuning iterations a cavity geometry was found which would allow both plasma formation and transition to high power (~2200 W) and high pressure (300 kPa - 600 kPa) with coupling typically greater than 98% without recourse to any tuning mechanism. Start-up proved reliable and the thruster could be operated for hour periods. The low thermal conductivity of N$_2$ kept the temperature of cavity relatively cool even during these extended periods of operation. Testing of the device was never terminated as a result of system failure. The proper tuning of the cavity removed the need for three-stub tuning. This removed the power loss associated with the standing wave on the transmission line between tuner and cavity, and the power transmission waveguide remained cool during even the extended periods of operation.

Use of helium propellant within a cavity optimized for N$_2$ operation showed that coupling of power into the system was greatly compromised. This is indicates that the different electrical conductivities of the test gases result in plasmas of which have different characteristic impedances. Since helium was not of great interest the cavity was never optimized for use with this propellant; it was found that the three-stub tuner could be used to increase the power coupling whenever necessary.

Both graphite and stainless steel nozzles were utilized during N$_2$ operation. During the course of testing, it was found that neither nozzle material suffered any appreciable erosion. Some additional testing, however, was also conducted with N$_2$ plasmas which were seeded with approximately 1% - 5% per mass of H$_2$. During this operation, it was observed that the high density graphite nozzle experienced severe erosion. It is suspected that the erosion resulted from a chemical reaction as the temperature of the nozzle material increased due to the increased thermal conductivity of the exhaust gas. Operation of the device with the stainless steel nozzle resulted in some minor erosion of the nozzle throat, but it was not as severe as that which was encountered with the graphite nozzle insert.

**Current Testing**

**Nitrogen-Hydrogen Plasmas**

Testing conducted over the past year included a study directed at characterizing the velocity of the exhaust of the H$_2$-seeded nitrogen plasmas. This work was attempted using the spectroscopic techniques of both emission velocimetry and LIF velocimetry. The work tried to measure the Doppler shift of the emission from the hydrogen which was present in the exhaust. The
Figure 5: Representative performance results of calculated vacuum $I_{sp}$ as a function of specific power for the microwave arcjet prototype.

Figure 6: Representative performance results of calculated thermal efficiency as a function of specific power for the microwave arcjet prototype.
The configuration of the thruster within the vacuum tank is shown in Figure 8.

The initial testing was conducted with N₂ propellant. This was done to characterize both the operation of the thruster and to familiarize the use of the vacuum system. During these tests the vacuum tank was pumped using only the mechanical pump; under typical flow conditions the tank back pressure was on the order of 0.1 kPa (1 Torr). N₂ testing showed that the thruster could be operated autonomously and that it could be operated for extended periods (approximately one hour) without any major damage. During this early testing, some erosion of the stainless steel nozzle was encountered; first to the throat of the converging nozzle (1 mm diameter), and then to a full converging diverging nozzle. The damage was primarily a result of buoyancy forces which resulted in the plasma contacting the nozzle plate which was, due to the orientation of the thruster, not at right angles to the gravity vector. This behavior is shown in Figure 9.

The effect of buoyancy has been partially alleviated by increasing the injection velocity of the gas by reducing the diameter of the injectors and by maintaining a constant 350 kPa pressure differential across the flow controller which feeds the injector...
Figure 8: Diagram showing orientation of thruster prototype within vacuum tank. The orientation of the tank is such that the thruster is rotated 11.25 degrees from the vertical. The microwave circuit shown is capable of supplying the cavity with approximately 2500 W; the 3-stub tuner allows for active impedance matching of the circuit during thruster operation. The front flange of the tank (not shown) contains a 15 cm diameter viewing window.
With the vacuum system running and tank pressure at approximately 0.03 kPa (≈ 0.2 Torr), an $N_2$ flow rate was initiated. When the pressure was such that the probe side of the cavity was at 1 atm, the shunt valve was closed and the $N_2$ flow was stopped. The microwave power was turned on to a preset level (usually 1000 W) and the pressure in the nozzle side of the cavity slowly reduced as it equalized to the ambient tank pressure. Plasma formation was indicated by a sudden decrease in reflected power. Once formed, the mass flow was reinitiated and increased to the desired operating condition. Once the three-stub tuner had been set for a desired operating condition (i.e., power level and mass flow rate), it did not require any adjustment during the start-up process just described. While the above procedure is not truly autonomous, it does indicate that the entire start-up procedure could be easily automated.

**Ammonia Plasmas**

The most recent testing has concentrated on the operation of the thruster with $NH_3$. The primary purpose of this testing is to verify that the thruster can indeed operate with a propellant of interest. This operation also gives indication that the device can be successfully operated with a number of molecular propellants and can easily create and maintain plasmas from them. As previously discussed, the device has been tested with mixtures of $N_2$ and $H_2$, though at $H_2$ levels lower than that for simulated hydrazine testing. However, the results are promising, and it is intended that testing of the thruster with $N_2$-$H_2$ concentrations which simulate the products of hydrazine decomposition from a catalyst bed will be pursued in the near future.

**Nitrogen Testing**

The nitrogen plasmas formed can absorb 98% of the full output of the microwave generator (2200 W). The three-stub tuner is required because the different orientation of the microwave transmission system resulted in a change in the impedance characteristics of the system; this was an expected occurrence. Due to the difficulty involved in making iterative adjustments of the cavity geometry while it is mounted in the vacuum tank, the 3-stub tuner was utilized to fine-tune the system. The thruster operated at relatively high flow rates and pressures up to 800 kPa. At the high pressure operation, the plasma exhaust jet appeared to be very stable and did not exhibit any noticeable rotational motion. The visible portion of the exhaust plume extended approximately one meter from the exit plane of the stainless steel nozzle. During this testing, the specific power ranged from 4.5 MJ/kg to 6.5 MJ/kg, and coupling efficiencies were typically greater than 98%.

The system was operated in the following manner.

With the vacuum system running and tank pressure at approximately 0.03 kPa (~ 0.2 Torr), an $N_2$ flow rate was initiated. When the pressure was such that the probe side of the cavity was at 1 atm, the shunt valve was closed and the $N_2$ flow was stopped. The microwave power was turned on to a preset level (usually 1000 W) and the pressure in the nozzle side of the cavity slowly reduced as it equalized to the ambient tank pressure. Plasma formation was indicated by a sudden decrease in reflected power. Once formed, the mass flow was reinitiated and increased to the desired operating condition. Once the three-stub tuner had been set for a desired operating condition (i.e., power level and mass flow rate), it did not require any adjustment during the start-up process just described. While the above procedure is not truly autonomous, it does indicate that the entire start-up procedure could be easily automated.

**Ammonia Plasmas**

The most recent testing has concentrated on the operation of the thruster with $NH_3$. The primary purpose of this testing is to verify that the thruster can indeed operate with a propellant of interest. This operation also gives indication that the device can be successfully operated with a number of molecular propellants and can easily create and maintain plasmas from them. As previously discussed, the device has been tested with mixtures of $N_2$ and $H_2$, though at $H_2$ levels lower than that for simulated hydrazine testing. However, the results are promising, and it is intended that testing of the thruster with $N_2$-$H_2$ concentrations which simulate the products of hydrazine decomposition from a catalyst bed will be pursued in the near future.

**The results of the $NH_3$ testing have thus far been very promising.** The cavity has been used to repeatedly form $NH_3$ plasmas and it has proved possible to couple 2200 W of power into the device as well as operate it at pressures of up to 1 atm for periods up to an hour. The heat loading of the device has proved to be much more severe than that encountered during $N_2$ operation. The high temperature operation has resulted in damage to the stainless steel nozzle which suggests the need for a higher temperature nozzle material, possible tungsten or molybdenum. The high temperature environment has also resulted in the melting and subsequent failure of a number of silicone o-rings. This has prompted the replacement of these rings with graphite (Grafoil) gasket material (refer to Figure 4). At present, these replacement seals work fine, but the indication is clear that the cavity

Figure 9: The orientation of the thruster prototype within the tank results in the plasma discharge preferentially heating one side of the nozzle inlet. This is a result of buoyancy effects on the discharge. The effect can be minimized by increasing the injection velocity of the incoming propellant flow.
is now at a stage were the design should be carefully examined to examine modifications which would remove the need for the many seals.

The current test for NH$_3$ has also utilized the three-stub tuner for the same reason as that given for the N$_2$ vacuum tank testing. Representative performance numbers for the ammonia operation are as follows:

| Mass flow rate | $2.33 \times 10^{-5}$ kg/s |
| Incident power | 2055 W |
| Power coupling (unoptimized geometry) | 90% |
| Specific power | 77.23 MJ/kg |
| Cavity stagnation pressure | 135 kPa |

At present, the total run time of the prototype with ammonia has been limited to a dozen tests with the longest of these lasting approximately 50 minutes. The harsh operating conditions have resulted in considerable wear on the prototype. Current work is focused on improving the overall design, especially in the area of pressure seals, in order to pursue a more vigorous research program with both NH$_3$ and simulated hydrazine.

**Work in Progress**

Up until this point, the only method for estimating the performance of the microwave arcjet thruster have been one-dimensional isentropic calculations such as those shown in Figure 5 and Figure 6. While these calculations only estimate the actual thruster performance, the continuous improvements in both the thruster design and operation have yielded results that indicate that these calculations are no longer appropriate; e.g. current calculations result in thermal efficiencies which are in excess of 100%. For these reasons, a more direct means of assessing the thruster performance has become necessary. The most recent work with the microwave arcjet has begun to address this issue.

**Development of Compact Power Supply**

The prototype testing described above has utilized a microwave power circuit similar to that shown in Figure 8. For the early stages of this development program such robust system has been helpful, however, an actual flight device will require a much more compact power processing unit.

The first step towards this goal has been to design and manufacture a high voltage power supply which is capable of operating a medium power magnetron. Such a system has been designed, built and tested with the current prototype. The preliminary testing conducted at this time have shown that the prototype using this compact power processing unit can repeatable form helium plasmas, and limited success has been achieved with both nitrogen and ammonia propellants.

The electrical hardware used to manufacture this system have been taken from a conventional 1000 W microwave oven, the circuit diagram for the unit is shown in Figure 10. The following is a brief description of the power supply circuit. One of the requirements of the present device was that it should provide a variable power level. While this will not be the case for the design of the final power supply, this flexibility was deemed desirable for the first of these power supply circuits. The power adjustment on a typical microwave oven is achieved by simply turning off the ac line voltage to the magnetron power supply every few seconds to yield a lower average power output. This was not deemed an acceptable solution for the present problem because the plasma would extinguish each time the magnetron was cycled off.

Typical operation of a magnetron requires a low-voltage high-current ac filament supply and a high-voltage low-current dc cathode supply. The microwave power output is directly related to the dc input power. In order to produce the variable power output, a second transformer has been included in the power supply design; it should be stressed that this second transformer will not be required in the eventual single power level supply. The power supply as designed supplies a constant ac current to the magnetron filament while allowing for an adjustable level of dc voltage to be applied to the magnetron cathode. The magnetron used in this unit was taken from a conventional microwave oven; it is manufactured by Toshiba (Model 2M248J). The specifications for this unit indicate that a 15 kV$_{dc}$ cathode potential (input F) and a 4.4 V$_{ac}$ filament voltage (i.e potential between leads F and FA) should result in the production of 1100 W of microwave power at a frequency of 2.45 GHz. Varying the dc voltage to the magnetron cathode allows this power level to be varied over a limited range.

The magnetron itself is connected to a waveguide
Prototype Redesign And Thrust Measurements

The full advantage of the compact power supply will be realized when it is integrated with a newly designed prototype which is currently being fabricated. The new design is very similar to that which is described in this paper. The major differences are that it is constructed of aluminum, thus making it low-mass, and that it will allow the magnetron to be mated directly to the microwave cavity; this is essentially the design indicated in Figure 2. This design will then remove the requirement for the extensive microwave transmission circuit. However, in doing this the system is also removing the ability to actively tune the system as well as monitor the levels of incident and reflected power. The primary goal of this stage of the development program will be to optimize the cavity geometry to produce efficient power coupling at a set operating condition.

LIF Velocimetry within Vacuum Facility

One of the goals of the prototype testing described in this paper was the measurement of the exit velocity of the exhaust plume produced during operation with ammonia propellant. Unfortunately the harsh thermal operating conditions made extended operation of the prototype impossible. For this reason, it was not possible to conduct the desired LIF-based velocimetry measurements of the exhaust plume. As stated, the prototype is being re-engineered to allow for extended high temperature operation. Once this is achieved, velocimetry measurements will be conducted.

Conclusions

The microwave arcjet thruster prototype has demonstrated consistent and reliable performance with a number of propellant gases. The device produces a stable well-behaved plasm discharge which exists in the converging section of the nozzle inlet. While the plasma
does exhibit some slight asymmetry due to the effect of buoyancy forces, this is not anticipated to be a concern when the device is operated in the microgravity environment for which it is being developed.

The prototype has demonstrated that it can operate in a fixed geometry achieving greater than 98% power coupling at steady-state operation. Testing has also demonstrated that this optimal geometry is dependent upon both the electrical conductivity of the propellant gas and the actual layout of the microwave power circuit. Testing within the vacuum tank facility has demonstrated that the prototype can be operated in a semi-autonomous manner. The vacuum tank testing has also shown that the exhaust plume is symmetric and well-behaved, i.e. no rotational motion.

Operation with nitrogen has shown that the device can be operated for extended periods of time (i.e. periods exceeding one hour) without any detrimental effects to either the thruster directly or to the microwave power circuit. Extended operation of the thruster with ammonia has proved successful but has also indicated the need for re-engineering the device to allow it to better handle the severe thermal environment which this operation produces.

The developmental program of the microwave arcjet is progressing steadily with the design of both a compact power processing unit and a new prototype currently in development. This effort is directed towards producing a low-mass, compact thruster design which will be used to obtain direct thrust measurements under vacuum conditions.

References
9 - Balaam, P., Experimental Development of a Microwave Resonant Cavity Electrothermal Propulsion Device, Ph.D. Dissertation, Department of Aerospace Engineering, Penn State University.