A Study of a Low-Power Microwave Arcjet Thruster Using Ammonia Propellant

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Abstract

A low-power microwave arjet thruster was studied using ammonia gas as propellant. The purpose of the project was to generate ammonia plasma using a 7.5 GHz magnetron and a cylindrical cavity thruster, which is resonant in the TM_{001} mode [1]. The desired pressure was atmospheric or above while generating a thrust of roughly 20mN and an I_{sp} of about 500s operating at low power (<100 kW).

Introduction/Overview of Electric Propulsion

Two main parameters used to describe a rocket engine are the thrust and the specific impulse (I_{sp}) generated by the rocket. Thrust is an exchange of momentum, momentum from the exhaust is transferred to the space vehicle which allows is to propel through space. Below is the derivation of the basic thrust equation where **P** = momentum, $\mathbf{m}_{dot}$ = mass flow, $\mathbf{v}_e$ = exhaust velocity, and $\mathbf{F}_{THRUST}$ = thrust force.

$$\mathbf{P} = \mathbf{mv}$$
$$d\mathbf{P} = d\mathbf{m}\ \mathbf{v}_e$$
$$d\mathbf{P}/dt = d\mathbf{m}/dt\ \ \mathbf{v}_e$$
$$\mathbf{F}_{THRUST} = \mathbf{m}_{dot}\ \mathbf{v}_e$$

Specific impulse is a performance parameter used for rocket engines, which compares the thrust to the amount of propellant used. The equation for the I_{sp} is shown below where $\mathbf{F}_{THRUST}$ = thrust force, $\mathbf{m}_{dot}$ = mass flow, and g_0 = gravitational constant.

$$I_{sp} = F_{thrust} / m_{dot} * g_0$$

Though most space vehicles currently use chemical propulsive devices, the substantial growth of Earth-orbiting satellites for communication and surveillance has sparked a new and intense interest in electric propulsive (EP) devices [2]. Chemical thrusters generate a greater thrust than EP devices but lose when it comes to I_{sp}. Below in Table 1 you can see a comparison of different propulsion systems and the respective specific impulse they produce.

Table 1 : Comparison of I_{sp} for different propulsion systems

Type	Isp (s)	Thrust duration
Chemical	200-465	minutes
Nuclear	750-1500	hours
Electrothermal	300-1500	years/months
Electromagnetic	1000-10000	years/months
Electrostatic	2000-100000+	months/years

The above table clearly shows that both propulsion and thrust duration of electrical propulsion systems is much better than those of chemical and nuclear thrusters. Aside from their higher specific impulse relative to other propulsive devices Electric Propulsion systems can also be very compact in size and may have low-power capabilities. This makes them suitable for micro satellites, deep space, and low drag missions. Electric propulsion devices are divided into three groups electrothermal, electromagnetic, and electrostatic. All three sub groups will be discussed below.

Electromagnetic Thrusters [2, 3, 4]

Electromagnetic thrusters use the electromagnetic force shown below to accelerate the propellant downstream.

$$\boldsymbol{F_m} = \boldsymbol{j} \times \boldsymbol{B}$$

$\boldsymbol{F_m}$ = electromagnetic force per unit volume of gas (N/m^3)
$\boldsymbol{j}$ = electric current density passing through the gas (A/m^3)
$\boldsymbol{B}$ = magnetic field in gas (T)

In a simplified electromagnetic thruster current flows through a propellant gas from an anode to a cathode. A magnet provides a magnetic field perpendicular to the current and propellant flow (permanent magnet, electromagnet, or a solenoid may provide the magnetic field). The resulting magnetic force accelerates the propellant down stream of the thruster.

A few examples of electromagnetic thrusters are the pulsed plasma thruster (PPT) and the magnetoplasmadynamic thruster (MPD). Most all PPTs use a solid propellant and achieve an I_{sp} between 1000-1500s. PPTs are compact in size and have high power efficiency, they operate in short impulses (~μs) thus making them very suitable for attitude control. MPDs produce a thrust that is proportional to the magnetic pressure inside the cavity and seem to be a promising thruster for the future as they are being heavily researched. Unfortunately no MPDs have achieved efficiencies higher than 35%.

Electrostatic Thrusters [2, 3]

The basic concept behind the electrostatic thruster is that electrical charges attract or repel each other. A source supplies charged particles of either sign into a cavity in which there is an electrostatic field and then they are passed out to a region in which the overall flow is neutralized. Common forms of the electrostatic thruster are the ion engine and the Hall thruster.

The ion engine electrons are produce by a cathode and sent into a chamber along with the propellant gas. The gas is then ionized and an optical grid is used to control the potential difference and accelerate the ions downstream. A Hall thruster is very similar to the ion engine. In a Hall thruster a propellant gas is ionized by counter flowing electrons. These ions are then accelerated by an electrostatic field generated by a negative cathode. The electrons are strongly magnetized and are forced to execute an azimuthal drift known as the Hall current.

Electrothermal Thruster [2, 3, 5]

Electrothermal devices are the most basic type of electric propulsion. Electrothermal thrusters use electrical energy to heat a working gas and then a conventional nozzle is used to accelerate the gas and produce a thrust. Such thrusters include resitojets and arcjets. The current project is a study of an arcjet thruster using ammonia propellant, which is brought to a plasma state by introducing microwaves and operating at low power. Arcjet thrusters can be made in a compact size and with advances in power subsystems they may operate at low-power making them very useful for micro satellites. Figure one below shows the microwave thruster firing. In this figure you can easily see the plasma inside the chamber and the resulting plume leaving the nozzle.

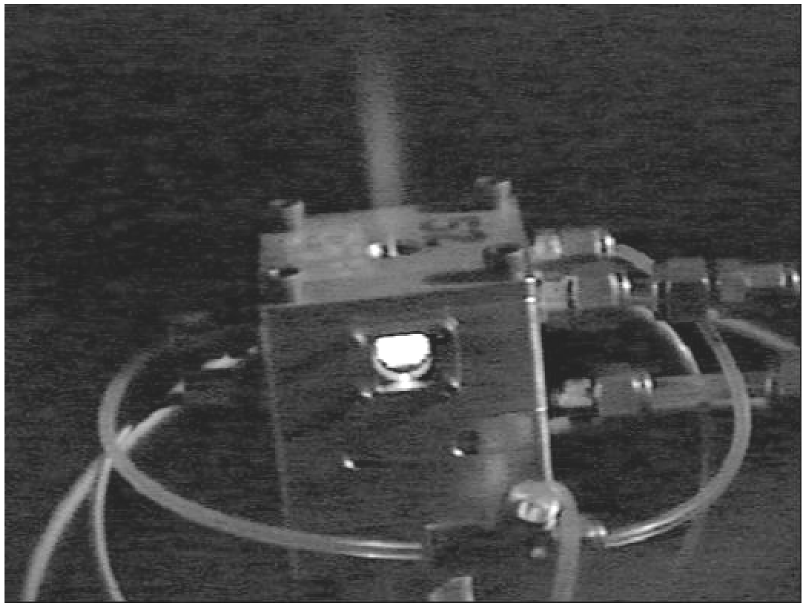

Figure 1 : 7.5 GHz thruster firing helium in vacuum conditions

For the missions in which the microwave thruster is intended for, we need to operate at very low power. Thus for the current experiment low power is defined at less than 1kW. Low-power thrusters were researched and compared to our theoretical assumptions of the microwave thruster performance. Table 1 shows all the thrusters that were researched and compares thrust, I_{sp}, input power, mass flow, efficiency, specific power, and specific thrust (the current study is listed last as NH3 microwave). We have estimated an I_{sp} of 500s and a thrust of 20mN. Figure 2 shows a graph of all the thrusters shown in Table 2, it is a plot of specific impulse versus efficiency. Here one can see that the microwave thruster has a high efficiency for the desired I_{sp}, only three other thruster have a higher efficiency but with lower I_{sp}. For this study and the future use of the microwave thruster an I_{sp} of 500s or greater is desired thus making this device the optimum thruster for the micro satellite missions it was designed for.

Table 2 : Comparison of low-power thrusters

	Thrust	Isp	Input Power	Mass Flow	Efficiency	Specific Power	Specific Thrust
	mN	sec	W	mg/s	P[I] / P[J]	J/mg	mN/W
Mark-IV Resistojet H2O	50.0	180	100	66.000	0.441	1.515	0.500
Pulsed Plasma Thruster	1.0	1500	100	0.068	0.074	1470.000	0.010
Helium Pulsed Arcjet	28.7	290	68	10.100	0.600	6.733	0.422
Teflon Pulsed Plasma	2.9	745	100	0.392	0.104	255.280	0.029
CIT 3-cm Ion Thruster	0.5	3703	24	0.014	0.377	1746.579	0.021
RUS 5-cm Ion Thruster	1.6	2900	72	0.056	0.316	1278.900	0.022
GRC 8-cm Ion Thruster	3.6	1760	100	0.150	0.310	666.667	0.036
GRC Colloid Thruster	0.20	390	0.5	0.051	0.700	10.706	0.366
Busek Hall Thruster	12.4	1346	207	0.940	0.395	220.213	0.060
Stanford Hall Thruster	11.0	544	277	2.063	0.106	134.249	0.040
Fakel Hall Thruster	4.7	1000	94.5	0.480	0.244	197.043	0.050
KeRC Hall Thruster	5.7	895	109	0.600	0.229	181.667	0.052
PPL Annul Hall Thruster	3.5	1086	98	0.400	0.190	245.000	0.036
PPL Cylind Hall Thruster	3.7	1136	103	0.400	0.200	257.500	0.036
NH3 Microwave (Est)	20.0	500	120	4.082	0.408	29.400	0.167

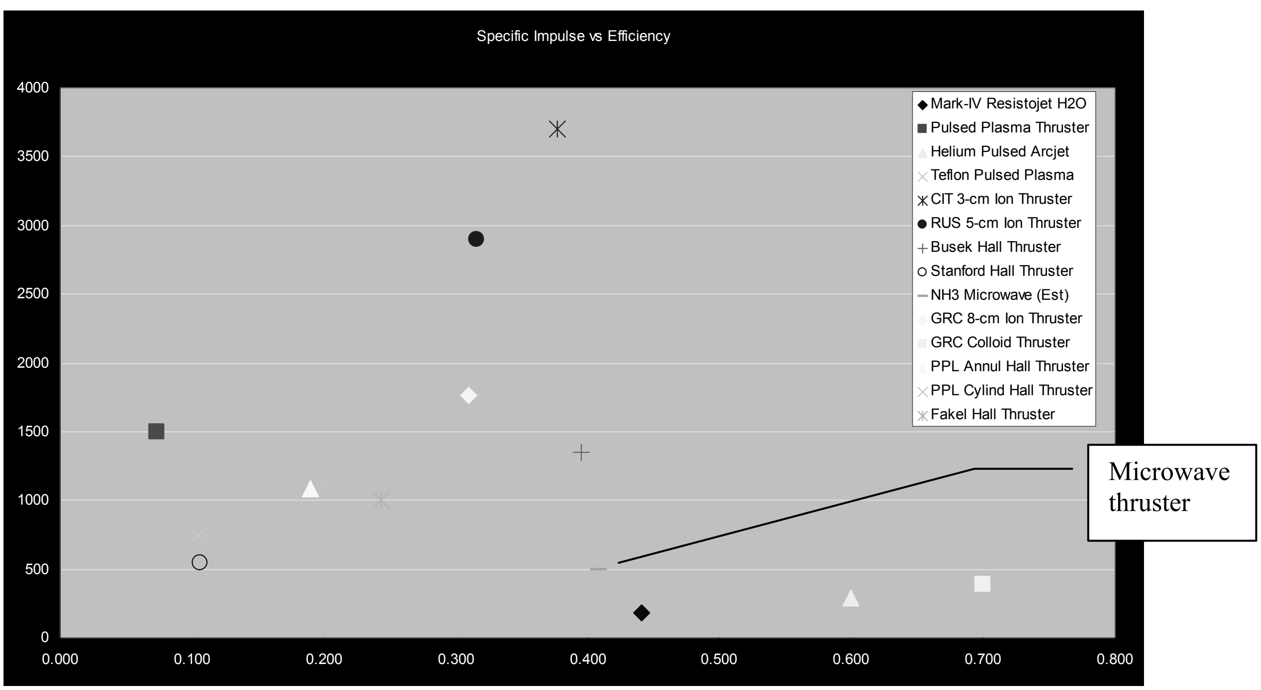

Figure 2 : plot of I_{sp} vs. efficiency of thruster from table 1

Experiment

The thruster is made up of a cylindrical cavity shown in Figure 3. A 7.5 GHz tunable magnetron is used to introduce microwaves into the cylindrical cavity which is resonant in the TM_{001}. The chamber is divided by a quartz plate for its dielectric properties and the propellant is injected tangentially. The propellant is introduced into the plasma chamber tangentially for two reasons; one is to cool the chamber walls and help maintain the temperature at the proper range, this also helps to maintain the radial stability of the plasma [5].

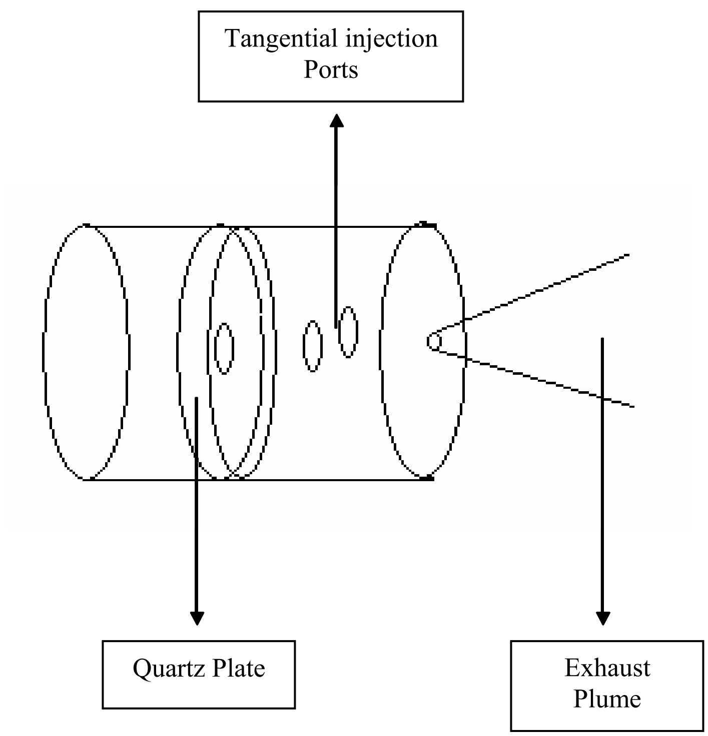

Figure 3 : Thruster Cavity

Fields inside a microwave cavity are governed by Maxwell's equations; a microwave cavity is resonant at many frequencies where there is a solution to Maxwell's Equations [1]. The frequencies at which a solution is met are the modes of the cavity resonator. The microwave cavity used in this experiment is resonant in the TM_{001} mode (first transverse magnetic mode). The geometry of a cavity with radius *a*, and length *h* is described by the following equation.

$$(fr)_{001}^{TM} = \tfrac{1}{2}\pi \, [\, (\mu\varepsilon) * \sqrt{(x_{001}/a)^2 + (\pi/h)^2}\,]^{1/2}$$

The experimental setup of the thruster on the thrust stand is shown in Figure 4. Here the thruster is hanging freely connected to the Narda dual-directional power coupler at the thruster cavity antenna which in turn is connected to the magnetron tube antenna. The power coupler is connected to two Hewlett-Packard 432A power meters by attenuator cables in order to measure both the incident and reflected power, which is being put into the system. The magnetron is a 7.5GHz 100 W tunable magnetron by Mictron and is powered by a Mictron power-conditioning unit. Figure 4 also shows the LVDT force transducer which will be used in future works. Pressure was read by a transducer which was affixed to the chamber cavity via a porthole.

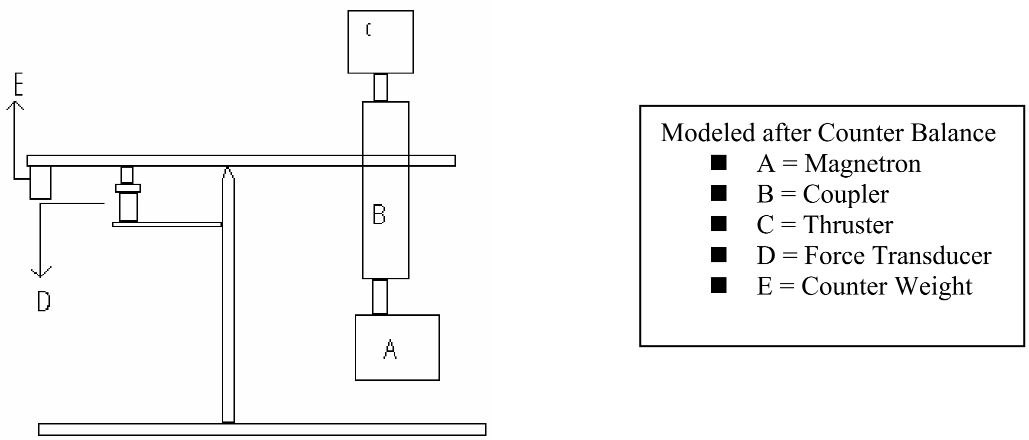

Figure 4 : Thrust stand setup

Testing and Results

For testing we first ignited helium gas in the thruster and then would close off the flow of helium and switch over to ammonia. Ammonia was able to be ignited but was unable to be maintained at desired pressures over the course of the project. Below in tables 4 and 5 are the results for both helium and ammonia gas. Shown in the tables is both forward (incident) and reflected power, anode voltage, anode current, filament voltage, filament current, control voltage, pressure, and mass flow (as a %).

Table 3 : Results for helium gas

arcet thruster	Helium							
Forward Pwr.	**Reflected Pwr**	**VA**	**IA**	**VF**	**IF**	**VC**	**psi**	**mdot**
0.52	0	4474	27	2.2		3515	1.03	4
0.5	0	4472	27	22		3573	1.27	5.5
0.5	0	4473	27	2.2		3574	0.98	4
0.5	0	4473	27	2.21		3572	1	4
0.66	0	4360	38	2.2		3442	15.9	70.1
0.66	0	4359	38	2.2		3442	16.05	70.1
0.62	0	4393		2.21		3467	15.96	70.1
0.68	0	4310	36	2.2	5	3392	14.98	70

Table 4 : Results for ammonia gas

Arcjet Thruster	NH_3							
Forward Pwr.	Reflected Pwr	VA	IA	VF	IF	VC	psi	mdot
0.48		4336	28	2.2		946	0.55	4
0.485		4484	29	2.2		948	0.57	4.1
0.46		4420		2.21		943	1.2	6.6
0.4		4410	32	2.21		950	1.76	8.4
0.4		4648	43	2.21		950	0.84	4.8
0.34		4628	38.5	2.2		962	1.02	4.8
0.385		4557	36	2.21		945	2.02	7.6
0.38		4556	39	2.19		951	2.03	7.7
0.38		4561	38	2.21		957	2.02	7.6
0.66	0	4386	32.7	2.2		3463	1.7	3.8
0.68	0.01	4373	34	2.2		3454	2.49	7.8
0.52	0.01	4453	28.4	2.2		3514	2.06	6.5
0.66	0.01	4330	36	2.2	5	3422	1.5	6
0.68	0	4346	35.5	2.21	5	3420	0.71	2.9
0.7	0	4330	36.7	2.2	5	3410	0.68	3.1
0.6	0	4392	32.6	2.2	5	3466	0.58	3.1
0.67	0	4322	37.5	2.2	5	3410	0.7	3.1
0.52	0.03	4418	38	2.2	5	3477	2.63	9.1

Atmospheric pressure is roughly about 14.30 psi, Table 3 shows that helium plasma was able to be maintained until atmospheric pressure conditions where met. Unfortunately ammonia plasma was not, with the highest pressure achieved being 2.63 psi. Ammonia plasma was also never cold started. Where as helium plasma could be ignited by itself regularly ammonia was not, helium plasma had to be ignited and then the propellant would be switched over to ammonia. Figure 5 shows the chamber in the horizontal position with the chamber filled with helium plasma.

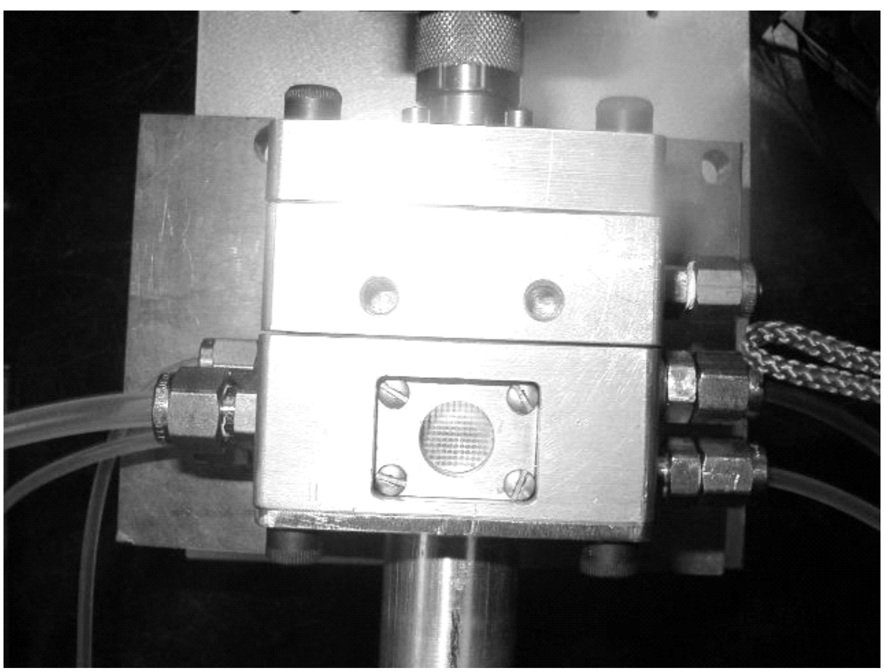

Figure 5: Thruster in horizontal position with helium plasma

Due to the time constraints and technicalities in the laboratory a run with ammonia plasma was never able to meet atmospheric pressure conditions. Also thrust measurements where not able to be taken and the project was not able to move into the vacuum chamber. Fortunately the project will continue through academic year. The working propellant has been switched to nitrogen, and a new in vacuum thrust stand is under works. The ultimate goal is to be able to ignite a helium-ammonia plasma mix and move into the vacuum chamber for further testing.

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References

1. *Roos, C. J. A., Vertical-Deflection Thrust Stand and Measurements of a Low-Power Microwave Arcjet Thruster, MS. Thesis, Aerospace Engineering Dept., Pennsylvania State University., University Park, PA, Aug., 2001.*

2. *Humble, R. W., Henry, G. N., and Larson, W. J., Space Propulsion Analysis and Design, McGraw-Hill Co. Inc., New York, 1995*

3. *Martinez-Sanchez, M., and Pollard, J. E., "Spacecraft Electrical Propulsion – An Overview," Journal of Propulsion and Power, Vol. 14, No. 5, 1998, pp. 688-698*

4. Ziemer, J. K., and Choueiri, E. Y., "Scaling Laws for Electromagnetic Pulsed Plasama Thrusters," *Plasma Sources Science Technology*, Vol. 10, 2001, pp. 395-404

5. Souliez, F. J., Chianese S. G., Dizac, G. H., and Micci, M. M., "Low-Power Microwave Arcjet Testing: Plasma and Plume Diagnostics and Performance Evaluation,"

6. Funaki, I., Kuninaka, H., Toki, K., Shimizu, Y., Nishiyama, K., and Horiuchi, Y., "Verification Tests of Carbon-Carbon Composite Grids for Microwave Discharge Ion Thruster," *Journal of Propulsion and Power*, Vol. 18, No. 1, 2002, pp. 169-175

7. Fujita, K., and Arakawa Y., "Performance Computation of a Low-Power Hydrogen Arcjet," *Journal of Propulsion and Power*, Vol. 15, No. 1, 1999, pp. 144-150

8. Schmidt, D. P., Meezan, N. B., Hargus Jr, W. A., and Cappelli, M. A., "A Low-Power, Linear-Geometry Hall Plasma Source with an Open Electron-Drift," *Plasma Source Science Technology*, Vol. 9, No. 1, 2000, pp. 68-76

9. Bushman, S. S., and Burton, R. L., "Heating and Plsama Properties in a Coaxial Gasdynamic Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 17, No. 5, 2001, pp. 959-966

10. Wilmes, G. F., and Burton, R. L., "Low- Power Helium Pulsed Arcjet," *Journal of Propulsion and Power*, Aerospace Engineering Dept., Pennsylvania State University., University Park, PA, Vol. 15, No. 5, 1999, pp. 440-445

11. Sweetin, M. N., Lawrence T., and Leduc, J., "Low-cost manoeuvres for minisatellites using novel resistojet thrusters," *Proceedings Institution of Mechanical Engineers*, Vol. 213, part G, 1999, pp 223-231

12. Spanjers, G. G., Birkan, M., and Lawrence, Major T. J., "The USAF Electric Propulsion Research Program," AIAA Paper 2000-3146, 2000

13. Rayburn, C., Cambell, M., Hoskins, W. A., and Cassady, R. J., " Development Of A Micro Pulsed Plasma Thruster for the DAWGSTAR Nanasatellite," AIAA Paper 2000-3256, 2000

14. Gorshkov, O. A., Grigo'yan, V. G., and Muravlev, V. A., "Development of the Low-Power Xenon Ion Thruster for Lightweight Satellites," *Journal of Propulsion and Power*, Vol. 16, No. 6, 2000, pp. 1083-1085

15. Souliez, F. J., *Low-Power Microwave Arcjet Spectroscopic Diagnostics and Performance Evaluation*, MS. Thesis, Aerospace Engineering Dept., Pennsylvania State University., University Park, PA, Aug., 1999.

16. Burton, R. L., and Turchi, P.J., "Pulsed Plasma Thruster," *Journal of Propulsion and Power*, Vol. 14, No. 5, 1998, pp. 716-733