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Microwave arcjet thruster sizing and performance evaluation

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MICROWAVE ARCJET THRUSTER SIZING AND PERFORMANCE EVALUATION

A Thesis

Presented to

The Faculty of the Department of Mechanical and Aerospace Engineering

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Steven Michael Carmen

May 2004

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ABSTRACT

MICROWAVE ARCJET THRUSTER SIZING AND PERFORMANCE EVALUATION

By Steven M. Carmen

For approximately 20 years starting with early theoretical proposals in the 1980's through the design and testing of several working models (mid 1980's to present) the concept for a microwave arcjet thruster utilizing a free-floating plasma discharge within a resonant cavity has been explored. All of these studies and designs were based on and utilized macro-scale fabrication techniques and technologies. This evaluation derives a theoretical model / design of the thruster that will support shrinking of the thruster to a much smaller scale (Micro-Thruster, millimeters versus the present Macro-Thruster, centimeters) and proposes that the smaller size thruster when used in numbers will provide superior performance to the larger size thruster that has been examined to date.

Acknowledgments

I would like to thank my Committee members, Dr. Periklis Papadopoulos, Dr. Nikos Mourtos, and Dr. John Siambis, for their guidance and advice on this thesis.

Dedication

This paper is dedicated to my mother, Helen Marie Carmen, and my father, Harris Hyman Carmen, who were responsible for me and thus, they are the parties responsible for everything that I accomplish in my life. Despite their numerous attempts at getting me to accept the responsibility for what I do; as the years go by I realize more and more that their efforts (starting with my first diaper change to the present weekly phone calls from my mother) have guided all that I have accomplished and will accomplish even after they are no longer able to update me in real time.

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Nomenclature

A^*	Nozzle throat area
A_c	Cross-sectional area
A_e	Cross-sectional area of the nozzle exit
c^*	Combustion chamber properties, characteristic velocity
c_p	Specific heat at constant pressure
C_T	Thrust coefficient
D	Diameter
ϵ	Permittivity of medium
$\mathbf{E}$	Vector representing the electric field
f_r	Frequency at which a cavity resonates
g_c	Acceleration due to gravity at Earth's surface
γ	Ratio of specific heat at constant pressure to specific heat at constant volume
	Volume per unit mass C_p/C_v
$\mathbf{H}$	Vector representing the magnetic field
I_{sp}	Specific Impulse, u_e/g_c
L	Cavity length based on flow considerations
λ	Wavelength of electromagnetic radiation
μ_p	Permeability of medium for electromagnetic calculations
μ_d	Coefficient of dynamic viscosity for fluid flow
ν	Kinematic viscosity of the fuel
P	Pressure
P_r	Perimeter of pipe for laminar flow calculations
P_s	Perimeter of the square resonant cavity
p_e	Pressure at the nozzle exit
p_a	Ambient pressure the nozzle outside
p_o	Chamber stagnation pressure
π	Ratio of the distance around a circle to its diameter
Q	Ratio of energy stored to energy lost per cycle in a resonant cavity
Q_{est}	Estimated energy lost per cycle due to cavity considerations
Q_R	Energy per unit mass added by the plasma to the fuel
$\mathbf{R}$	Vector representing the total radius of a pipe
R	Total pipe diameter
R / M	R , gas constant
Re_D	Reynolds number in a circular pipe
r_h	Hydraulic radius
ρ_o	Stagnation pressure
δ	Depth of penetration of electromagnetic radiation
T	Thrust of a rocket
T_o	Stagnation temperature
T_{01}	Initial temperature of the gas in the chamber
TE_{xyz}	Transverse electric mode xyz

TM_{xyz}	Transverse magnetic mode xyz
$\mathbf{U}$	Vector representing velocity
u_e	Exit velocity
U_m	Mean velocity
$\mathbf{V}$	Mean mass velocity
X_m	Zero of Bessel function

1.0 Background

For approximately 11 years starting with reference [1] the design and testing of a concept for a Microwave arcjet thruster utilizing a free-floating plasma discharge within a resonant cavity have been explored. Previous studies indicated that a cylindrical cavity in the TE_{011} mode would work best for thruster applications. Operation of several prototype designs has occurred. The basic operating principal is that a free-floating ac plasma discharge due to cavity design produces an axially located plasma which can be positioned upstream of a nozzle formed at one end of the cavity forming a constricted region for heating a propellant gas. Per reference [2] current designs have shown efficient operation over a wide range of power (250 W to 6000 W), propellant gas types, and propellant flow rates.

The basic design of the thruster is as shown in Figure 1 from reference [2]. The resonant cavity is physically divided into two chambers by a 1/4 inch thick boron-nitride pressure plate. The material of the pressure plate has minimal effect on the electrical field properties of the cavity when placed at mid-plane of the cavity. However, it allows the pressure at the nozzle end to be lowered with respect to the power inlet side. For operation of the thruster the shunt valve is closed and pumping down of the pressure on the nozzle side takes place. This results in a lower pressure in the nozzle side while maintaining an elevated pressure on the power inlet side of the chamber. This allows the formation of plasma at the desired throat location while preventing plasma

formation at the power inlet location. Once the plasma is formed the shunt valve is opened and the pressure equalizes on both sides of the plate. This allows for operation of the thruster at a higher pressure since the pressure on both sides of the plate is equal. The thruster can be operated with the adjustable probe placed in a fixed location prior that is set prior to the operation of the thruster. This probe can also be moved during thruster operation if the proper mechanisms and control system are in place. The probe acts as a mechanism to fine tune the plasma location. The adjustable shorts provide a mechanism to fine tune the cavity length to optimize resonance efficiency. Since both of these parameters have a major effect on fuel exit temperature both of these devices are critical for successful operation of the thruster.

A typical startup sequence for the engine is contained in reference [3] and is as follows:

The coupling probe is set so the tip is level with surface of moveable shorting plate. The cavity is then purged with test gas/fuel at pressure of 1 kPa. The stubs in the tuner are retracted to neutral position. The lowest power setting on generator is utilized to start with gradually increasing power levels until stable plasma forms at the discharge nozzle. After plasma formation both pressure and power are increased in unison at an approximate ratio of Energy to mass flow rate that the plasma formed at. As this process is continuing the simultaneous adjustment of stub tuner, shorting stub, and probe must occur to insure that maximum available amount power is coupled to the plasma. The coupling of incident power is typical 98% for properly tuned situations.

Figure 1: Schematic of the modified microwave arcjet prototype. The diameter of the cavity is 10.16 cm and the theoretical resonant length is 15.87 cm. While both the length of the cavity and the depth of the coupling probe can be adjusted, they must remain fixed during thruster operation. The entire cavity is divided into two pressure chambers which are connected by a shunt line and valve.

2.0 Objective of Thesis

The objective of this thesis is to:

- Derive a theoretical model / design of the thruster that will support shrinking the physical size of the thruster to a much smaller scale (Micro-Thruster, micrometers versus the present Macro-Thruster, centimeters).
- Model the effects of size reduction on the thruster performance.
- Utilizing this model, examine parameters of concern for near earth and interplanetary missions for the Micro, Macro, and other thrusters.

3.0 Resonant Cavity Model / Parameters

The following models and parameters are associated with the design of the resonate cavity.

3.1 Electromagnetic Model/Parameters

Per references [4] and [5] resonant cavities are spaces completely enclosed by conducting walls that can contain oscillating electromagnetic fields and possess resonant properties. The cavities resonant properties depend solely on it being conductive and properly sized. The cavity is sized based on the fact that an electromagnetic wave as it travels will oscillate between 100 % electric wave and 100 % magnetic wave during its travel along a waveguide at distances of $1/4$ wavelength ($\lambda/4$). In the microwave region resonant cavities have a very high ratio of stored energy to energy lost per cycle, defined as Q and can be built to handle relatively large amounts of power. Per reference [4] Q

values in excess of 30,000 are not uncommon. The high Q gives these devices a narrow bandpass and allows very accurate tuning. Simple, rugged construction is an additional advantage. The basic principles of operation are the same for all cavity resonators regardless of shape, frequency ranges, and applications. The following equations are for a square cavity but similar equations exist for round cavities that have to date been used for the Macro-Thruster geometry. Note, based on the small scale geometries involved it was felt by the author that the difference between a round chamber and square chamber may be less important to engine performance than the fabrication costs and difficulties. This assumption is discussed in detail later in this paper. See Figures 2 and 3 for representative cavity geometry. The parameters l, m, and o, represent the number of 1/4 wavelengths from the center of the cavity. Thus, for a square cavity there would be 1/4 wavelengths distance from the center along each axis and so each side is 1/2 wavelength in size for a cavity to have a TE₁₁₁ or a TM₁₁₁ mode wave resonance. Per reference [1] the TM₀₁₁ mode is perfect for this type of engine for a circular cavity.

Per reference [5] the basic equation for the sizing of the resonant cavity (rectangular) is:

$$\lambda = \frac{2}{\sqrt{\frac{l^2}{x^2} + \frac{m^2}{z^2}}} \quad (3.1.1)$$

Once the proper TM mode is chosen the length Z (circular), or X (rectangular) dimension can be determined by using flow field considerations as long as it does not exceed $\lambda/2$ by an appreciable factor per reference [5]. If these dimensions do increase significantly above $\lambda/2$ in length the risk of generating unwanted modes increases significantly. Per references [6] and [7] the size of the dimensions for circular and rectangular cavities are related to the resonant frequency for the Transverse Magnetic Mode by the following equations:

$$\text{Circular: } (f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{(X_{mn}/a)^2 + (p\pi/h)^2} \quad (3.2.1)$$

Where $m=0,1,2,3, \dots$ & $n=1,2,3$ & $p=0,1,2,3$, & X_{mn} is 2.4049 for the 011 mode used in the Macro-Thruster.

$$\text{Rectangular: } (f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{(m\pi/a)^2 + (n\pi/b)^2 + (p\pi/h)^2} \quad (3.2.2)$$

Where $m=1,2,3, \dots$ & $n=1,2,3$ & $p=0,1,2,3, \dots$

The choice of the proper mode for the resonant cavity starts with the cavity cross-sectional geometry and requires an examination of the magnetic and electric field lines for each resonant mode. For the circular geometry per reference [3] the TM_{011} mode was found to be optimum with a a/h ratio of 0.320. This then gave a diameter based on manufacturing considerations of 10.16 cm and a length of 15.87 cm. From references [3], [5], [7], and [8] the TM_{011} (circular) and TM_{110} (rectangular) mode field patterns are as shown in Figures 4 and 5.

—— E and - - - - H

Figure 4: TM_{011} mode field patterns

For the rectangular cavity the electric and magnetic patterns are much more complex. The closest pattern that appears to be usable is that for the TM_{110} mode shown in Figure 5. It comes closest to the pattern for the circular cavity TM_{011} mode with a concentration of electric field lines at each end of the resonant cavity and one at the center of the cavity provided the cavity is long enough. So depending on cavity length, if this mode is used plasma could form in the lower pressure section of the engine at an undesired location next to the dielectric pressure plate. Per references [6], [9]-[11] to prevent plasma formation next to the pressure wall (should a maximum occur at the cavity center) several nozzles injecting fuel at the pressure plate location at an angle (that cause rotation of the fuel flow) can be used. In addition, if the pressure plate is thickened and offset toward the far end of the chamber as shown in Figure 6 the pressure plate itself can be located in the maximum flux region. Since, there are two areas in the low-pressure region of the chamber where the plasma will form, and one of these regions is now contained within the dielectric plate, the plasma will only form at the desired nozzle end of the chamber. Thus, by selecting proper plate location the pressure plate acts as a blunt body from a fluid flow stand point assuring that any plasma that attempts to form at the cavity center will be pushed down stream (if the mass flow rate is sufficient) into the far end of the chamber where plasma formation is desired. In addition, by selecting the proper plate thickness, the plate itself occupies one of the two the physical locations that plasma will form at due to fuel pressure. Thus, stopping or reducing plasma formation at this unwanted location. Gas can then be circulated within the plate to cool it and to pre-heat the gas.

However, if the mass flow rate is not sufficient for stopping the plasma formation, and the cavity design is such that it does not place the dielectric pressure plate at one of the locations that the rectangular cavity allows plasma formation to occur at, plasma will form at two locations at the same time in the rectangular cavity. This raises an interesting possibility that the fuel may have a longer exposure to the plasma heating effects and thus reach higher temperatures than with the single plasma zone. The author proposes that this dual plasma formation zone concept warrants further investigation based on three observations contained in reference [10].

First, it was found by experimentation, that for this type of engine once the plasma has fully formed the only way to increase the power absorbed is by increasing the mass flow rate. This is due to the reflection of additional power by the plasma once it has been created. Thus, after a certain input power level is reached, rather than absorbing additional input power and raising the plasma temperature, the plasma reflects this power back to the source.

Secondly, as noted the plasma has a certain size that it will reach based on the power input that is independent of frequency. Thus, three hundred watts whether input at 3 GHz or 30 GHz results in the same size plasma in the fuel chamber. However, the laws of scaling require that the chamber that is designed for resonants at 30 GHz be 1/10th the size of the chamber designed for resonants at 3 GHz. Thus, with the two zones in the chamber forming plasma (due to chamber length) the chamber itself can be twice as big as a chamber design that allows for only one zone that forms plasma.

Finally, the third observation is that plasma moves toward the source of power as the input power increases. Thus, if the power and mass flow rate input into a square or rectangular resonant cavity is sufficient and the chamber is designed for dual plasma formation zones, the engine will handle twice the mass flow rate and power at a given frequency compared to that of the single plasma formation zone resonant cavity. This will allow in theory for design of an engine that can operate at twice the total output thrust level that would at first appear to be possible utilizing any microwave energy source operating at a given frequency based on the required design constraints for the resonant cavity dimensions.

The ability to literally double the total thrust available from a thruster over that available from another thruster of a similar design simply by using a square or rectangular cavity with dual plasma formation zones in the plasma chamber rather than a single plasma forming zone is a very exciting possibility. This is because it allows for much higher thrusts (possibly double) from an engine at the cost of only increasing the length of the plasma chamber, fuel mass flow rate, and adding some additional fuel injection nozzles. This in turn allows for the total number of thrusters to be reduced by half and yet allow the same total thrust level to be reached by an engine assembly. Figures 7a and 7b show a schematic comparison of the two approaches.

Figure 5: TM_{110} mode field patterns for rectangular cavity of square cross-section.

Figure 6: Thickened and offset pressure plate protected by swirl nozzles

3.2 Fluid Flow Model / Parameters

Per references [2] and [12] for the existing circular cavity Macro-Thruster, three nozzles that inject the fuel at a 15 degree angle parallel to the cavity wall create a circular rotating flow pattern of fuel that prevents plasma impact with the boron-nitride pressure plate and helps stabilize the plasma. For the miniaturized square cavities that are being proposed for use by this paper the number and location of the nozzles are significantly different. However, their function is the same; To prevent plasma impact with the cavity wall and to stabilize the plasma and fuel flow.

Next, to characterize the flow state with in the chamber it needs to be determined if it is laminar or turbulent. Per reference [13] a simple model for a circular cavity based on laminar flow inside a circular cross section pipe is proposed. It is assumed that a Newtonian fluid, under steady state conditions, and having constant properties exist until the plasma heating area is reached. The governing equation is then given by the following expression:

$$(\mu / r) (d / dr \{r \partial u / \partial r\}) = dP/dx \quad (3.2.1)$$

Subject to the following Boundary Condition's

Boundary conditions:

a) $\partial u / \partial r \}_{r=0} = 0$

b) $u(R) = 0$

The solution for the velocity distribution is:

$$U(R) = 2U_m [1 - \{r / R\}^2] \quad (3.2.2)$$

Where U_m = mean velocity and $Re_D = [U_m D] / \nu$.

These equations then allow a minimum length for the circular cavity to be predicted of $L = 0.0575 D [Re_D]$ [Langhaar's formula]. This length is a minimum for the flow to be laminar. Comparing it to the $\lambda/2$ desired maximum length for resonance cavity efficiency will give an idea as to whether the flow is laminar or not. From reference [14] a flow in a circular pipe is laminar if the Reynolds number is below 2300. From reference [3] the $D = \text{Diameter}$ is 10.16 cm. This requires a pipe length of $L = 0.0575 \times (10.16 \text{ cm}) \times 2300 = 1343.66 \text{ cm}$. Thus, the flow in the plasma chamber is always turbulent even though the chamber walls are smooth. This is consistent with the way that the chamber dimensions were chosen as detailed in references [3] and [14] and the results of reference [9] that detail swirl plasma stabilization.

Per reference [13] for noncircular cavity the governing equation is:

$$\mu \{ \partial^2 \mathbf{u} / \partial x^2 + \partial^2 \mathbf{u} / \partial y^2 + \partial^2 \mathbf{u} / \partial z^2 \} = dP / dx \quad (3.2.3)$$

$$Re = 4r_h \mathbf{V} / \mu_d \quad (3.2.4)$$

$$\mathbf{V} = m / Ac \text{ (mean mass velocity)} \quad (3.2.5)$$

$$\text{This gives } L \text{ for the cavity as: } L = \sqrt{(Re \mu P) / (4Ac \vec{V})} \quad (3.2.6)$$

As stated above, this length is a minimum for the flow to be well behaved or laminar. However, for the plasma chamber the flow is only required to have a swirl or high rotation rate to stabilize the plasma. So the electromagnetic field considerations such as the $\lambda/2$ desired maximum length for resonance cavity efficiency and the resonant frequency as a function of chamber dimensions from section 3.1 are what is used to set the cavity dimensions for the square cavity not the fluid flow considerations such as turbulent versus laminar flow fields.

3.3 Cavity Design

Per Section 3.1 the governing equation for the design of a square resonant cavity for TM modes is:

$$(f_r)_{mnp} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \sqrt{(m\pi/a)^2 + (n\pi/b)^2 + (p\pi/h)^2} \quad (3.3.1)$$

Where $m = 1, 2, 3, \dots$ & $n = 1, 2, 3$ & $p = 0, 1, 2, 3, \dots$

Since the 110 Mode was chosen for electro-magnetic field location and shape the cavity is sized using $m = 1, n = 1, p = 0$. For purposes of initial sizing of the chamber the $\mu\epsilon$ values used are those for a vacuum ($8.85\text{E-}9$ and $400\pi\text{E-}12$) instead of those of a fuel such as H_2 , N_2 , or He . The equation then becomes for a square cavity where the sides are

of equal length, so $a = b$: $(f_r)_{mnp} = \frac{\sqrt{2}}{2b\sqrt{\mu\epsilon}} \quad (3.3.2)$

Assuming an operating frequency of 3 THz (approximately 1000 times the Macro-Thruster operational frequency) the desired b dimension is $7.06785\text{E-}5$ meters. Per reference [4], for a square resonant cavity the governing equation is $\lambda = 1.41*b$ and the resonant frequency is given by the equation: $f_r = (3 \times 10^8)/\lambda$. Thus for a frequency of 3 THz the b dimension is $7.092199\text{E-}5$ meters. The average value of $7.08\text{E-}5$ meters was picked since the chamber surface is not a perfect conductor causing some attenuation of the energy in side it which is similar to the chamber being slightly too small. In addition, both formulas utilize approximate values for vacuum rather than the exact values for the fuel being used. If exact values were used for $\mu\epsilon$ the result would be a slightly smaller chamber dimension. Thus, an average between the two methods for determining

chamber dimensions was judged to be appropriate. Since the length of the chamber is not important for resonance purposes the half wavelength value of $5.0\text{E-}5$ meters governs. The Macro-Thruster ratio of width to length is 15.87 to 10.16 or 1.562. Just for comparison purposes it was decided to keep this ratio for the Nano-Thruster length to width ratio. So the final dimensions chosen for the square Nano-Thruster design are $11.06\text{E-}5$ meters for length and height and width of $7.08\text{E-}5$ meters.

Per reference [9], [10], and [15] the frequency chosen for operation of the Macro-Thruster was 2.45 GHz. This was based on availability of the microwave source (2.45 GHz is what microwave ovens utilize as a heating source), and an assumption made in reference [15] that because the cavity size scales directly with the frequency that an increase in frequency by only 10 times would result in a device too small to contain the plasma for the same input power. In addition, reference [10] notes that there are three frequencies; 2.45 GHz, 5.8 GHz, and 24.125 GHz that have been assigned by international regulating authorities for industrial, scientific, and medical purposes. Thus, frequencies much above the 2.45 GHz range have been ignored and 2.45 GHz has been the focus of attention. If a circular chamber is designed for a Nano-Thruster to allow Terra Hertz range operation then, by choosing 2.45 THz as the operating frequency the size of the chamber should scale directly from the Macro-Thruster. The fabrication and testing of this device would be an important step in confirming the viability of the Nano-Thruster concept since it would allow direct performance comparisons with the Macro-Thruster. Thus, for this thesis (which is exploring the feasibility of a Nano-Thruster) it was decided that the dimensions for the circular chamber Nano-Thruster were to be

chosen to be 1000 times smaller than the Macro-Thruster. The diameter of the chamber is $10.16\text{E-}5$ meters and the length of chamber is $15.87\text{E-}5$ meters. One other factor needs to be addressed concerning cavity design related to the fabrication process. For purposes of this paper as discussed later a fabrication process that creates parts by layers is proposed for use in fabrication of the Nano-Thrusters. This process as discussed in reference [14] creates layers that are as thin as $2\text{E-}6$ meters in height. Thus, a circular cavity formed by this process has a very jagged surface as shown in Figure 8. This surface effect is not important for flow field considerations since the flow is always turbulent and any slight pressure drop caused by surface irregularities can be easily compensated for. However the electro-magnetic effects may cause losses in the chamber. The jaggedness or offset is $\frac{2}{10}$ of the chamber base dimension. This is larger than would be desired to avoid electro-magnetic effects that are due to the surface roughness but, since the surface is a continuous conductor the undesired effects may be reduced considerably. Only a detailed field mapping and / or experiments carried out on both the Micro and Macro scale will be able to determine the effects on the electromagnetic field patterns within the cavity and the efficiency of energy reflection within the resonant cavity, if any, that are caused by the jagged stair-step edges that are created by the process that was chosen for the fabrication of the Nano-Thrusters for this evaluation of the Nano-Thruster concept. Other fabrication techniques will not necessarily have the layer formation height limitation. In addition as this fabrication technique matures the layer height may significantly be reduced.

4.0 Convergent Divergent Nozzle Design Model / Parameters

Per reference [16], the thrust of a rocket, T , can be modeled as equal to a function of the combustion chamber properties or characteristic velocity, c^* , times the thrust coefficient or nozzle performance, C_T . Thus, $T = m \times c^* \times C_T \times g_c$. So for the thrust coefficient, $C_T = T/[\rho_o A^*]$, ρ_o =stagnation pressure, A^* =nozzle throat area,

$$c^* = \text{Sqrt}\{1/\gamma ((\gamma + 1)/2)^{(\gamma+1)/(\gamma-1)} R T_o / M\} \quad (4.0.1)$$

To compare nozzles C_T is used:

$$C_T = \sqrt{(2\gamma^2/\gamma - 1)(2/(\gamma + 1))^{(\gamma+1)/(\gamma-1)} [1 - (p_e/p_o) (\gamma - 1)/\gamma] + [(p_e - p_a)/p_o] (A_e/A^*)} \quad (4.0.2)$$

See Figure 9 for a schematic of the various parameters that are important for nozzle design.

The above equations assume that the fuel/working fluid is a perfect gas of constant composition, the fuel under goes a constant-pressure heating process, and the expansion process is steady, one-dimensional, and isentropic. These assumptions should approximate the actual thruster conditions sufficiently to allow a good approximation of experimental / actual results for several different thruster design proposals. However, from reference [17] a NASA Glenn CET93 code can also be used to calculate engine performance. This code gives good agreement to experimental results for the case examined in this reference. It should be noted that this code is not a nozzle design code but a chemical equilibrium code. So nozzle design parameters must be inferred from the flow field/parameters obtained utilizing this code.

Normally, one of these two approaches would be used to model the exhaust nozzle. However, due to the scaling laws that apply, the nozzle utilized on the Macro-Thruster can simply be scaled down by a factor of 1000 to achieve a good starting design. Since, future nozzle designs should use both approaches and compare results to actual experimental data in order to obtain the best nozzle design they are included here for completeness.

Per reference [2] the nozzle has an area ratio of 153 and is constructed of a high-density graphite. The nozzle has a 30 degree converging half-angle and a 15 degree half-angle diverging with a throat diameter of 0.10 cm. So the area ratio of 153 is kept. The half-angles remain the same; 30 and 15 degrees, converging and diverging, respectively. But the throat area becomes $1.0\text{E-}6$ meters. This is on the order of the smallest scale dimension that can be placed in a layer by the chosen fabrication process. Thus, to get a smooth chamber wall design at this size it may require laser or ion etching after each layer is deposited to get the desired smoothness. If such processes are required the costs will increase however once such a process is incorporated into the fabrication it would allow for the smoothing of the circular plasma chamber cavity as well as the creation of a smooth CD nozzle wall.

The initial nozzle material proposed for the Nano-Thruster is graphite as used in the Macro-Thruster per reference [17]. It is planned in future studies to explore other materials for the nozzle once designs of the Nano-Thruster have been tested. These materials need to be conductors and should be located in the center of the end wall (stationary short) to enhance the field density pattern along the axis of the cavity. The

fact that graphite is a conductor causes the field pattern in the region of the nozzle to be very close to the desired ideal pattern. The material chosen for the nozzle also needs to be very heat resistant and tolerate of any inadvertent ablation due to the plasma impinging on its surface. The fabrication technology chosen is compatible with a number of metal alloys and forms of silicon per reference [18]. Thus, the nozzle material selection and its design are additional areas of future research that deserve closer attention utilizing trades studies that consider material and electromagnetic properties for nozzles and also consider the microfabrication considerations.

Figure 8: Jagged edge caused by fabrication process for a circular cavity utilizing the chosen fabrication technique.

5.0 Fuel Model / Parameters

The fuel used and the design of an engine that optimizes performance for a particular mission is directly coupled and strongly dependent. Per references [2], [12], and [17] this thruster can use and has been tested with He, N₂, NH₃, H₂, and H₂O as a fuel. The single molecule fuels such as H₂, He, and N₂ provide the highest exit velocity and Isp. More complex molecules such as water appear to allow energy to go into other modes than thermal excitement thus, reducing exit velocity. However, safety and cost concerns make water a desirable choice. For purposes of this study three fuels are to be considered Helium, Nitrogen, and ammonia. The theoretical model for fuel utilization is derived from an estimate of the coupling efficiency (how much of the microwave energy is absorbed and causes a temperature rise in the fuel) and the isentropic ideal rocket equation from reference [16],

$$u_e = \text{exit velocity} = \text{Sqrt}[\{2c_p (T_{01} + Q_R/c_p) [1-(p_e/p_{02})^{(\gamma-1)/\gamma}]\}] \quad (5.0.1)$$

The value for the energy per unit mass added by the plasma to the fuel or Q_R is obtained by using the following equation derived by the author:

$$Q_R = (E_q Q_{\text{source}}) - Q_{\text{est}} \quad (5.0.2)$$

Where: Q_{est} is approximately equal to 1/30,000 of energy provided by the source, Q_{source} .

For an even more accurate value per reference [7] the Q of an equivalent circular cavity is 8.26% higher than that of a square cavity. Per reference [5] for a rectangular cavity operating in the TE₁₁₀ mode the Q of the resonator is given by the equation $Q = (2/\delta) \times [\text{Volume of cavity}/\text{interior surface area of cavity}]$. Assuming copper is used for the cavity wall $\delta = [6.6E - 2]/[\sqrt{f}]$. So for the square resonator the Q is approximately

28,000 and for a circular resonator it is 30,300. Q_{source} = energy provided by the source = power rating of the microwave source times the conversion efficiency, E_q . E_q , the conversion efficiency, varies with frequency and the microwave source. For klystrons at 2.5 GHz it approaches 85% and at 7.5 GHz it approaches 65% for power levels of 100 W to 6kW. For a solid state device per reference [19] it is between 8.5% and 10% at 90 GHz for power levels of approximately 2 W.

This allows I_{sp} to be calculated from $I_{sp} = u_e / g_c$. Thrust values, T , can be calculated utilizing the formulas of Section 4, Convergent Divergent Nozzle Design Model / Parameters. With I_{sp} and thrust available the two major parameters for comparing fuel and engine design have been modeled.

Since no actual Nano-Thruster has been built the only data that can be used for evaluation of performance is that from the Macro-Thruster. This data was obtained from references [2] and [20]. It should be noted that chemical reaction rates increase as the scale is decreased per reference [21]. So, if a complex molecule such as ammonia is used in a Macro-Thruster the microwave energy can be coupled into modes of resonance that are undesirable in terms of thermal increase that is usable by the thruster. The energy does not become thermally usable until after the gas has been expelled. However, due to the much higher reaction rates in a Nano-Thruster this energy should be available prior to the fuel being expelled. For exploiting the ability to utilize various fuels using the same engine design this nano-scaling effect should give significant performance advantage to the Nano-Thruster. Based on this scaling effect it can be assumed that the results for

frozen flow are applicable to the Macro-Thruster but that for the Nano-Thruster all chemical reactions have occurred and the equilibrium state has been reached by the fuel.

Thus, per references [2] and [20] for the Macro-Thruster and 2200 W input power and utilizing the fact that 1 Watt = 1 J/second the values for engine performance listed in Table 1 were obtained. Micro-Thruster performance values were obtained by scaling by a factor of 1000^3 (see scaling section for explanation) and are listed in Table 2. These values should be considered a best case available at this time estimate of the expected Micro-Thruster engine performance based on the applicability of scaling laws and in the absence of actual test data. Based on scaling considerations and the active control features purposed for use in the Micro-Thruster it is expected that its performance should exceed that of the values listed in Table 2 once it is built.

Table 1: Macro-Thruster Engine Performance

	Thrust (N)	Isp	Specific Power (MJ/kg)	Mass Flow Rate (g/second)
Helium	747.07	625	18	0.12222
Nitrogen	722.33	235	7	0.31429
Ammonia	508.01	425	18	0.12222

Table 2: Estimated Micro-Thruster Engine Performance

	Thrust (nN)	Isp	Specific Power (MJ/kg)	Mass Flow Rate (ng/second)
Helium	747.07	625	18	1.2222
Nitrogen	722.33	235	7	3.1429
Ammonia	508.01	425	18	1.2222

Next the question of whether or not the Nano-Thruster can be feed sufficient fuel needs to be addressed. Based on the mass flow rates shown above the size of a single pipe to carry the fuel flow is estimated in the following manner. At room temperatures Helium, Nitrogen, and Ammonia have densities of 0.190 kg/m^3 , 1.140 kg/m^3 , and 0.793 kg/m^3 respectively. Per reference [21] a gas such as air in the scale that is of interest for the Micro-Thruster (50 μmeter diameter) capillary flows at a rate of $0.5\text{E-}3$ meters/second. Using a $2 \mu\text{m}^2$ flow area for a nozzle for the required Helium mass flow rate of 1.2222 ng/second 0.00645 nozzles are required. Thus, the required flow rate can be easily provided at this scale. For Ammonia the calculation yields approximately 0.0268 nozzles. Again, this demonstrates that the required flow mass flow can be provided to the engine.

6.0 Fabrication Models / Parameters

Three possible fabrication methodologies have been found that can be utilized for fabrication of the engine and microwave source. The first is the use of standard IC fabrication techniques to make the source and cavity. The second methodology involves the use of ink jet technology and the ability to fabricate nano-particles and is utilized by a company called NanoProducts Corporation. The third methodology is utilized by a company call Microfabrica Inc. It creates devices by depositing many precision layers 2 to 10 μ meters in thickness. Each of these three methodologies will be presented in brief detail with a discussion of the part that it can play in the creation of the engine.

6.1 Standard IC fabrication techniques

Per reference [22], the integrated circuit fabrication process creates devices on pieces of semiconductors. The key steps in this process are: Oxidation, Photolithography, Etching, Diffusion, Sputtering, Chemical Vapor Deposition, Ion Implantation, and Epitaxy. Figure 10 from reference [22] below shows the generic order, however, during manufacturing each step is usually repeated many times depending on the devices desired.

Oxidation is the process of converting silicon into silicon dioxide. Etching is the process of removal of layers of unwanted materials such as silicon and aluminum. It involves directing acid or hot plasma against a surface to remove some surface material. Photolithography is the transfer of a pattern from a mask to a wafer or surface utilizing light to effect the transfer of the pattern. Diffusion is the uniform distribution of

impurities (dopants) into a material in order to change its electrical, chemical, or mechanical properties. Sputtering and evaporation are non-chemical methods of depositing thin films of materials. Chemical Vapor Deposition is a gaseous process that deposits films or metals onto a surface at an elevated temperature. Ion Implantation is a methodology to add dopants to a material by using charged atoms accelerated by an electric field. Epitaxy is the controlled growth of a crystalline layer on a crystalline substrate.

Figure 10: IC fabrication process

For many years only integrated circuits were fabricated using these techniques. However, in recent years it was realized that devices such as resonant cavities, micro balance beam systems, valves, micro-fluidic pipes/channels and etc. could be fabricated utilizing these techniques. The array of nanoklystrons in reference [23] and the compact solid-state microwave source of reference [19] are examples of the use of this technology.

This technology is very mature and the device size utilized presently is small enough to support fabrication of the cavity and microwave source. However, this technology is extremely costly and only utilizable if the engines were to cost on the order of several million dollars each due to the costs to design and fabricate. Alternately, if the demand was such that at least 10 thousand engines a year were utilized the cost per engine would be acceptable.

6.2 Ink Jet Technology and Fabrication of Nanoparticles

Per reference [24], NanoProducts Corporation has been developing a technology for nano device fabrication based on ink jet technology and their patented Joule-Quench technology for fabricating nanoparticles, see Figure 11 from reference [24]. These particles are less than 100 nanometers in diameter. The particles are mixed with a resin and then applied to a substrate material. Devices can be built up utilizing ink jet techniques for very low costs and quickly redesigned.

The technology for nanoparticle fabrication is not very mature at this time. However, ink and ink jet technology is extremely mature. Thus, the major challenge to utilizing this fabrication technique at this time is lack of suitable nanoparticle stock. But, since the technique is just beginning to be developed there is a considerable flexibility in having access to persons who can fabricate custom particles and will support the fabrication effort of any new device type. The cost to fabricate engines is expected to be extremely small due to desire on the part of NanoProducts Corp. to develop devices that utilize this process. The device size required can easily utilize the 100 nanometer

Figure 11: NanoProducts corporation Joule-Quench technology for fabricating nanoparticles

particle size. The major ink jet unknown is how small an ink jet bubble (particle resin mixture) can be produced and how accurately it needs to be placed to support fabrication of the cavity and microwave source. However, this technology is extremely low cost and appears readily available. So, it should be utilizable if the engines are to cost on the order of several thousand to hundreds of dollars each due to design and fabricate. Alternately if the demand was such that hundreds to thousand of engines a year were required the cost to scale up and fabricate would be very small.

6.3 Deposition of Many Precision Layers

Per reference [25], Microfabrica Inc. (formerly MEMGen Corp.), has developed a technique for additive micromachining devices based on selective electrodeposition of multiple patterned layers of materials. This technology is fairly mature. Standard CAD tools can be used to create the devices and then software from Microfabrica Inc. converts it into fabrication instructions. Costs are expected to be in between that of the other two processes. Significantly lower than IC fabrication (very low setup costs) and more than Ink jet (due to the maturity of the process Microfabrica Inc. may not be as willing to fabricate for free). The scale of devices that can be fabricated and the ability to fabricate complex structures that are both electrical and mechanical in nature make this the most promising fabrication technology at this time. See Figures 12 (a) through (e) from reference [25] for details of the fabrication process. Figure 13 from reference [25] shows examples of the variety of microstructures that can be fabricated on a single substrate in the same fabrication run.

Figure 12 (a) – the first layer of material is patterned onto a substrate

Figure 12 (b) – the second material has been blanket deposited over the first material

Figure 12 (c) – the entire two-material layer has been planarized to achieve precise thickness and flatness

Figure 12 (d) – the process steps are repeated for all layers

Figure 12 (e) – the sacrificial material is etched to yield the desired device

EFAB technology can fabricate a wide variety of microdevices with complex 3-dimensional shapes, even on the same substrate, while silicon micromachining processes typically require different process flows to fabricate different devices. This Scanning Electron Micrograph of a 24-layer EFAB build is composed entirely of electroplated nickel. It includes an array of helical inductors, an accelerometer with capacitive sense plate, a fluid injector architecture, fluidic wells and channels, geometries for plastic molding and embossing, electrical resistance structures, and a range of other test structures and geometries.

Figure 13: Device variety available in single run

7.0 Scaling Laws/ Rules

Per reference [21] the scaling laws that are of interest and apply to the proposed Nano-Thruster engines are:

Time:	1^0
VanderWaals:	$1^{1/4}$
Diffusion:	$1^{1/2}$
Distance:	1
Velocity:	1
Surface tension:	1
Electrostatic Force:	1^2
Friction:	1^2
Thermal Losses:	1^2
Piezo-electricity:	1^2
Mass:	1^3
Magnetics:	1^3
Torgue:	1^3
Power:	1^3

So, for the Nano-Thruster the fact that Distance scales directly with size results in the direct scaling of chemical reactions. The governing equation is $x = \sqrt{2Dt}$ where t is time and D is the diffusion coefficient. Thus, the rate of movement of a molecule or 1 meter takes 1000 times longer than the movement across 1 millimeter. This leads to the conclusion that for chemical processes by scaling down by a factor of 1000 the reaction

rate effectively increases by 1000 times. This means that it is highly likely that chemical equilibrium will be reached should a complex molecule be used for fuel in the Nano-Thruster as opposed to when it is used in the Macro-Thruster.

This increase in likelihood that chemical/thermal equilibrium is reached is not increased directly by 1000 times. It is probably more on the order of 10 to 100 times. This is again due to scaling law considerations. The Velocity also scales directly with size so the fuel will travel through the Nano-Thruster nozzle in less time. However, the distance traveled through the nozzle is not the governing distance it is the distance between the plasma and the nozzle. This distance does not scale directly but scales as an electrostatic force or 1^2 . So for a plasma thruster size reduced by a factor of 1000 one would expect that the force keeping the plasma from contacting the nozzle to, decrease by $(1000^2) = 10E6$. Then taking into account that the inertia forces (based on mass) decrease by $(1000^3) = 10E9$ in magnitude the net result is that the plasma inertia that is balanced by the electromagnetic forces is relatively 1000 times less than the Macro-Thruster's. This should result in the plasma in the Nano-Thrusters cavity moving further from the nozzle. But, since the fuel mass flow rate drives the plasma toward the nozzle and it scaled directly with inertia the overall result should be a plasma that is at a relative distance that is further from the nozzle for the Nano-Thruster than the Macro-Thruster plasma is for its nozzle. However, this relative distance is not on the order of 1000 times since the forces generated by the electric and magnetic fields are governed by laws that state that the force applied decreases by the square of the distance. So the distance increases by about 31 times or the square root of 1000 based on the electromagnetic

forces however, mass flow forces will probably reduce this distance back to two to 5 times longer travel for the fuel in a working engine.

One interesting consequence of not fully understanding the utilization and magnitude of the scaling laws is that reference [32] assumed that a certain power was desired for various thruster purposes and that given this power a certain size plasma formed since plasma scales directly with power. Since the resonant cavity scales directly with frequency the highest practical frequency that would work for operating a thruster using a microwave source was between 3 and 30 GHz. This was based on the fact that at 30 GHz the plasma would be bigger than the cavity or waveguide that contained it. reference [3] then used this assumption to determine that approximately 3 GHz was the best frequency to use for thruster operation based on international law concerns and availability of highly efficient sources at a reasonable cost (microwave ovens operate at 2.45 GHz). But, an examination and understanding of how to utilize the scaling factors shown above results in quite the opposite conclusion. By reducing the size of a thruster by 10 to 1000 times the thrust output (a function of mass flow rate) scales directly as does the cavity size and input power that can be utilized by the thruster. Thus, to get the thrust levels desired from a thruster may require an input power of 3 kW. Assuming that this is barely achievable utilizing a single Macro-Thruster of with a 15.87 cm length cavity due to plasma size considerations smaller scale thrusters were ignored as not meeting the required thrust levels. However, the Nano-Thruster concept achieves the desired power level by utilizing assemblies of 10 to 1000 plus precision engineered thrusters. Thus, the overall thrust of the assemblies and power utilization matches the mission needs but each

individual thruster is 10 to 1000 times smaller than was previously thought as a usable size.

The major problem with Nano-Thruster fabrication is the fabrication setup costs are relatively high compared to the Macro-Thruster. However, Nano-Thrusters have a considerable advantage in production cost once fabrication starts. Utilizing scaling laws it is possible to build Macro models of the Nano-Thruster designs and test them. This should lead to a significant reduction in the cost to design working devices. For example, the fabrication of a circular chamber is difficult utilizing the Microfabrica process since it creates layers in 2E6 meter heights as discussed previously. The difficulty in fabrication of a circular chamber caused the consideration of the utilization a square or rectangular cavity for a resonant device. To determine the effect of a stair-step circular cavity a Macro model can be constructed and tested at say 2.45 GHz. The flow and electromagnetic field patterns can be quickly determined and possible design alterations made that would give assurance that the stair-step design would function. This would then justify the expenditure of funds to fabricate a Nano-Thruster version. Interestingly, once Nano-Thruster design concepts have been established, for the situation where Macro-Thruster designers are contemplating a number of hardware or software changes, the use of Nano-Thrusters fabricated in lots of 10 to 1000 at a time that can all be constructed differently allows the quick fabrication of a large number of design variations. These thrusters, because of their small size, can then be quickly and less expensively tested, resulting in a quick and low cost way to evaluate Macro-Thruster designs.

8.0 Nano-Thruster Compared to Macro-Thruster and Other Thrusters

Figure 14 shows a size comparison between the Macro-Thruster and the Nano-Thruster assemblies. Tables 1 and 2 contain a scaled comparison of their performances. Assuming that the proposed square cavity thruster is comparable in performance to the circular cavity thruster the performance of the Nano-Thruster should equal or exceed the Macro-Thruster performance for any planned use provided that there are sufficient numbers of the Nano-Thrusters employed in an assembly. The use of large numbers of engines has been avoided in the past due to reliability concerns. However, precision or microfabrication techniques make this a non-issue due to the high reliability of devices fabricated utilizing these techniques.

To understand the difference in size and performance characteristics between the Macro-Thruster and Micro-Thruster approach it is best to compare their performance directly. For a proposed mission if the Macro-thruster was chosen and a Δv of 40 m/s required for a 10000 kilogram satellite system with a thrust of 747 N. A time of burn of 535.47 seconds would be required. An estimated 3.25 Kg mass and volume of 3900 cm³ for the Macro-Thruster, waveguide, tuning stub, and its microwave power source based on mass volume estimates for the materials described in references [3], [14], and [17] was calculated. Also, assuming that the two thrusters used the same amount of fuel to accomplish the Δv (same Isp and efficiencies) allows a mass of Macro-Thruster engine assembly to Micro-Thruster engine assembly comparison to be made. The size and mass for the Nano-Thruster would be based on 10,000 Nano-Thrusters being required to equal the thrust level of the Macro-Thruster. The size of this assembly

assuming a spacing on center of 3 assembly diameters separation between each Micro-Thruster and 3.75 inches width available per layer based on reference [25] results in an engine assembly that is 312 Nano-Thrusters wide per assembly layer; Wafer width divided by assembly spacing (9.525 centimeters) / (10.16E-5 X 3) meters per assembly layer. This then rounds up to a height of 34 layers. Allowing for bottom and top structural and protection layers rounds the layer height to 40 assembly layers each of 30.48E-5 meters in height. Giving a total height of 1.2119 cm. This would give a total volume of 115.4 square centimeters times 9.525 centimeters or 1100 cm³. Taking an average density between silicon and copper for the average density of the assembly yields a mass of 6.56E-3 Kg/cm³. From (.2365 Lb / in³) / [(2.2 Lb/Kg) X (2.54 cm/inch)³]. Which gives a mass of 7.216 kg for the Nano-Thruster assembly block. This assembly block has a depth of 9.525 centimeters based on reference [25]. This allows for the assumption of each assembly depth to be 100 times the cavity depth to account for power source, fluid assemblies, and waveguide depth. So, 9.525 cm / 0.1587 cm = 60 assemblies. Using a yield of 20 actual assemblies per block gives 7.216 kg / 20 assemblies per block or a total mass per assembly of 0.3608 kg per Nano-Thruster assembly. Thus the estimated engine mass for the equivalent Nano-Thruster compared to the Macro-Thruster is 0.3608 kg versus 3.25 kg. Almost a factor of 10 less mass. This difference is based on estimates and actual working Nano-Thrusters will probably have even greater weight advantages. Why the great mass and volume advantage for the Nano-Thruster. The easiest way to explain it is that the Macro-Thruster utilizes only the space for the plasma and nozzle for thrust creation. The rest of the space is not necessary for

thrust production but only for support structure. The Nano-Thruster needs much less non-productive space because its volume is so much smaller. Thus, as with mass and length unproductive space also scales. Since unproductive space is related to the volume parameter that scales to the third power, in theory the wasted space is reduced by the scaling factor to the third power or in this case, since the frequency was increased by 1000, total wasted space should decrease by a factor of 10,000. Of course in the real world efficiencies of construction rarely reach the theoretical limits. Comparing volume estimates yields 1.832 cm^3 for the Nano-Thruster and 3900 cm^3 for the Macro-Thruster. This gives a volume reduction in theory of a factor of approximately 2000. Again based on practical considerations this will probably significantly be reduced. However, as with mass it appears that based on known and proven scaling considerations the Nano-Thruster assembly (consisting of 10 ths of thousands of engines) should have a significant advantage over the single Macro-Thruster.

Per references [20], [21], [26] - [29] the following comparisons between the Nano-Thruster and other proposed propulsion systems can be made. For spacecraft classified as small satellites as shown in Table 3 from reference [26] the Micro-Thruster has significant advantages over chemical thrusters that have a practical Isp of 220 seconds. This is not only because the Isp of the Nano-Thruster is almost double that of the chemical rocket but, also because it can be started and stopped much more efficiently than the chemical rocket which is sized for a certain thrust value that has to be high enough to address all needs. The Nano-Thruster because of its array of thousands of

separate engines can vary its thrust in increments of thrust as low as one thruster or 500 to 700 mN up to the 500 to 700 N range with 10,000 engines running. This allows for the same engine assembly to be used for orbit raising maneuvers for a satellite requiring thrust of hundreds of Newtons and still address attitude maneuvers that may require thrusts in the 1 to 2 mN range. No other proposed type of engine can efficiently operate over this wide a range. In addition the total mass of the engine assembly is small enough that it is suitable for all satellite classes as defined in Table 3.

Reference [27] examined a Space Station reboost utilizing electric propulsion systems operating in a continuous mode that required 0.5 N of constant thrust. Seven engine types were examined they were CO₂ RJ, MET, N₂H₄ arcjet, Hall, NSTAR Ion, and VASIMR. Their respective Isp's were 119, 460, 600, 800, 1770, 3160, and 5400. Respective efficiencies varied from as low as 32% to as high as 60%. Total power required for various engines and configurations varied from as low as 100 W to 30 kW. Thruster assembly mass varied from 18 kg to 1000 kg. For all these types of engines considered the overall performance of the Nano-Thruster makes it a much better choice across all categories. The MET (Microwave Electrothermal Thruster) engine is a version of the Macro-Thruster that was discussed in this paper. The mass estimate for that thruster is 10 kg and utilizing 1 kW. As discussed previously the Nano-Thruster assembly should significantly out perform the Macro-Thruster in terms of weight and size. In addition the fuel for the Macro-Thruster was chosen to be water. As discussed previously this type of fuel generates much lower Isp's than a fuel such as hydrogen that has no additional modes to absorb power that do not add to thrust. The conclusions of this

reference with respect to the Macro-Thruster was that it consumed more fuel (water) than the CO₂ resistojets, Hall thrusters, and ion thrusters and was not technologically as mature. However, even using water as a fuel this Macro-Thruster design saved an estimated 41 to 59.5 metric tons of fuel compared to the more mature technologies that saved on the average a predicted 45 metric tons of fuel over a chemical propulsion engine. It should be noted that this engine was assumed to have an overall efficiency of 44%. Per reference [2] with He efficiencies as high as 90% can be achieved.

Per reference [28] mission velocities for piloted deep space exploration fall into the range of between 10^4 and 10^5 meters per second. This corresponds to an optimum thruster Isp of 1,000 to 10,000 seconds. Isp's in this range are achievable with both the Macro and Micro Thruster concepts depending on the fuel used. In addition, these concepts have a distinct advantage for deep space missions over all the other concepts because of the wide variety of fuels that can be used by them. For example even the theta-pinch concept that is examined in detail in reference [28] is restricted to Neutral gases such as deuterium while the Micro and Macro thrusters can use water, ammonia, helium, deuterium, and etc. The fact that other concepts require specific fuels means that they require a fuel storage and support system that is extensive and not a function of what is readily available at the chosen destination. For example if Mars is the destination, CO₂ and CO are readily available in the atmosphere while deuterium may require extensive processing of atmosphere or soils to generate. If the Jupiter system is the destination methane, hydrogen, and nitrogen are readily available in atmospheres. The requirement of a specific fuel for an engine is a distinct disadvantage in deep space operations.

Table 3: Micro-Space Craft classification scheme

Designation	S/C mass, Kg	S/C power, W	S/C dimension, m
Micro-spacecraft	10-100	10-100	0.3-1.0
Class I (<10 Kg, nanosat)	5-20	5-20	0.2-0.4
Class II microspacecraft	1-5	1-5	0.1-0.2
Class III microspacecraft (picostat)	<1	<1	<0.1

Figure 15: Circular cavity nano-thruster

Figure 16: Nano-klystron concept.

Source: Reference [23]

9.0 Summary

This thesis has outlined the state of the art available for fabrication of a microwave arc jet thruster at a scale much smaller than had previously been accomplished, provide details for theoretical models that can be used for design and comparison purposes, and listed major parameters for use in evaluating Nano-scale microwave arc jet thrusters. Section 1.0, Background, described the microwave arc jet thruster design concept and detailed key components. Section 3, Resonant Cavity Model / Parameters, provided a brief summary of resonant cavity design and sizing. Both circular and square cavities were discussed. To date all models of the thruster have used round cavities. However, at the scales being discussed square cavities may work as efficiently. The cavity dimensions for a wave traveling in the X direction are based on the frequency of the microwave radiation being contained in the cavity for Y and Z dimensions and should not be significantly greater in the X direction. Based on non-laminar flow and electromagnetic field considerations a model for determining the minimum length for the cavity (both square and round) was obtained. Thus, models now exist to use for sizing the cavity height, width, and length for the Nano-Thruster. These are the same that can be used for the Macro-Thruster due to scaling laws.

Section 4.0, Convergent Divergent Nozzle Design Model / Parameters, listed models/equations to use for nozzle design utilizing parameters such as throat area, ratio of specific heats, nozzle exit area, gas stagnation pressure, etc. The two parameters of interest for comparing nozzle design were combustion chamber properties or

characteristic velocity, c^* , and the thrust coefficient or nozzle performance, C_T . It was also noted that the present design of the thruster uses a carbon nozzle and that other materials may be more suitable for utilization in the nano-scale design. However, the material must be electrically conductive and placed properly to support desired plasma shape, location, and formation.

Section 5.0 listed the three fuels desired to be used and modeled the exit velocity as a function of nozzle and plasma heating (resonant cavity design). Since I_{sp} = exit velocity/force of gravity, both I_{sp} and thrust are now modeled to allow comparison of fuel and engine design. Although not done for this thesis C_T can be obtained using u_e , thus tying the model of section 4.0 to that of 5.0 and providing for the ability to use an iteration process to optimize the thrust for a given fuel, nozzle, and cavity design (frequency).

Sections 6.0 through 6.3 briefly described the possible fabrication technologies and techniques available for engine and cavity manufacture. The Microfabrica Inc. process appears to be the most promising in terms of technology maturity, ease of design and technical risk. However, the ink jet based NanoProducts Corp. is a close contender. The deciding factors are the maturity of the technology at this point of NanoProducts Corp and what the costs are for utilizing the Microfabrica Inc. process.

Per reference [26] the Micro Space Craft classification scheme of Table 3 was selected for determining missions for thruster utilization and evaluation.

References [27], [28], [30], and [31] provide additional information sufficient to define thrust required, I_{sp} , and other parameters for comparison of the thruster design(s) with

possible missions and other thruster concepts. Based on what has been accomplished within this thesis it is now possible to model and optimize the microwave thruster design in a nano-scale and compare this design(s) to other thruster concepts using comparisons based on geometry, efficiency of energy storage/utilization, fabrication techniques/technologies available, missions that can be accomplished, thrust duration, thrust magnitude, and cost of fabrication. Also, it has been shown that rather than a concept that will not work as stated in references [10] and [15] the use of THz energy to power a Nano-Thruster is viable and has advantages over other types of Macro-Thrusters. Finally, the scaling laws indicate that if the frequency was scaled down by a factor of ten from 2.45 GHz to 0.245 GHz then mass flow rate and thrust should scale accordingly by 10^3 or 1000 times. This engine bears further study since it should have thrusts in the range of 747 kN for diameters approaching 10 meters and lengths approaching 15.8 meters. Based on its high Isp it would represent a good candidate for Mars and other interplanetary missions as do the Nano-Thruster arrays.

References

- [1] Hawley, M. C., et al, "Review of Research and Development on the Microwave Electrothermal Thruster", Journal of Propulsion and Power, Vol. 5, No.6, Nov-Dec 1989, pp 703-712.
- [2] Micci, M. M., Sullivan, D. J., "Performance Testing of a Fixed Configuration Microwave Arcjet Thruster", NASA Propulsion Engineering Research Center, Volume 2, Nov 1, 1994, pp 75-79.
- [3] Sullivan, D. J., Micci, M. M., "Development of a Microwave Resonant Cavity Electrothermal Thruster Prototype," IEPC-93-036, AIAA/AIDA/DGLR/JSASS 23rd International Electric Propulsion Conference, Seattle WA, September 1993.

[4] <http://www.infodotinc.com/neets/book11/44m.htm>, Cavity Resonators, Navy Electrical Engineering Training Series NEETS, CD-ROM, Module 11, Microwave Principles

[5] Kraus, J. D., Carver, K. R., Electromagnetics, Second Edition, McGraw-Hill, NY, NY, 1973, Pages 550 –600.

[6] Power J. L, and Sullivan D. J., NASA Lewis Research Center, Cleveland, OH, “Preliminary Investigation of High Power Microwave Plasmas for Electrothermal Thruster Use”, AIAA/SAE/ASME/ASEE 29th Joint Propulsion Conference & Exhibit, June 28-30, 1993, Monterey, CA, AIAA-93-2106.

[7] Balanis, C. A., Advanced Engineering Electromagnetics, John Wiley & Sons, Inc., New York, 1989.

[8] Lee, C. S., Lee, S. W., Chuang, S. L., “Plot of Modal Field Distribution in Rectangular and Circular Waveguides.,” IEEE Transactions on Microwave Theory and Techniques, Vol., MIT-33, No. 3, March 1985, Pages 271 to 274.

[9] Balaam, P., and Micci, M. M., “Investigation of Stabilized Resonant Cavity Microwave Plasmas for Propulsion,” Journal of Propulsion and Power Vol. 11, No. 5, September-October 1995, Pages 1021 to 1027.

[10] Mueller, J., Micci M. M., “Microwave Waveguide Helium Plasmas for Electrothermal Propulsion,” Journal of Propulsion and power, Vol. 8, No. 5, September-October 1992, Pages 1017 to 1022.

[11] Venkateswaran, S., Schwer, D. A., Merkle, C. L. “Numerical Modeling of Waveguide Heated Microwave Plasmas,” Journal of Fluids Engineering, Vol. 115, December 1993, Pages 732 to 741.

[12] Sullivan, D. J., and Micci, M. M., “Optimization of Energy Transfer in Microwave Electrothermal Thrusters”, Propulsion Engineering Research center, Department of Aerospace Engineering, The Pennsylvania State University, University Park, PA 16802, 1994.

[13] Fogiel, M., Chief Editor, The Handbook of Mechanical Engineering, Research & Education Association, Piscataway, N. J. 2004 pages E59 – E65.

[14] Fogiel, M., Chief Editor, The Handbook of Mechanical Engineering, Research & Education Association, Piscataway, N. J. 2004 page E61 Figure 6.6

- [15] Sullivan, D. J., Philippe, C., Micci, M. M., "Current Status of the Microwave Arcjet Thruster," AIAA-95-3065 31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 10-12, 1995, San Diego, CA.
- [16] Emmons, H.W., Penner, S. S., "Mechanics and Thermodynamics of Propulsion", Addison-Wesley Publishing Company, Inc., Reading Massachusetts, 1970, pages 573-565.
- [17] Micci, M.M., "Low-Power Solid-State Microwave Thruster Systems", Proc. 3rd International Conference on Spacecraft Propulsion, Cannes, 10-13 October 200, ESA SP-465, December 2000.
- [18] Brown, E., Microfabrica Inc., "RF Applications of EFAB Technology," White Paper, Microfabrica Inc., 1103 West Isabel Street Burbank, CA 91506-1405, 2004
- [19] Ingram, D.L., Chen, Y. C., Stones, I., Yamauchi, D., Brunner, B., Huang, P., Biedenbender, M., Elliott, J., Lai, R., Striet, D.C., Lau, K. F., and Yen, H. C., "Compact W-Band Solid State MMIC High Power Sources", 2000 IEEE MTT-S Digest, pages 955-958.
- [20] Souliez, F. J., Chianese, S. G., Dizac, G. H., Micci M. M., 'Low-Power Microwave Arcjet Testing: Plasma and Plume Diagnostics and Performance Evaluation," AIAA 99-2717. 35th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and exhibit, 20-24 June 1999 Los Angeles, CA.
- [21] Madou, M. J., Fundamentals of Microfabrication, CRC Presss LLC, 2000 Corporate Blvd., N. W., Boca Raton, Florida 33431, 1997.
- [22] McConechy, T., "IC Home Page", <http://www.csc.uvic.ca/~mserra/Fab1/> and <http://www.csc.uvic.ca/~mserra/Fab1/html/fabrication.html>
- [23] Siegel, P., "Array of Nanoklystrons for Frequency Agility or Redundancy", NASA Tech Brief, Vol. 25, No. 8, from JPL New Technology Report NPO-21033 available at <http://www.nasatech.com/TSP/PDFTSP/NP021033.pdf>
- [24] Johnson, R. C., "Nano research eyes ink jet printed sheets of circuits", EE times, November 20, 2003, <http://www.eetimes.com/story/OEG20031120S0017>.
- [25] MEMGen Corp., "Going Beyond Silicon MEMS with EFABTM Technology", White Paper, MEMGen Corp., 1103 W. Isabel Street, Burbank CA 91506-1405. <http://www.MEMGen.com>

[26] Micci, M. M., and Ketsdever, A. D., Editors, Micropropulsion for Small Spacecraft, Progress in Astronautics and Aeronautics Series, AIAA inc., 1801 Alexander bell drive, Reston, Virginia 20191-4344, pages 1 – 70.

[27] Oleson, S.R., and Benson, S. W., "Electric Propulsion for International Space Station Reboost: A Fresh Look", 37th Joint Propulsion Conference and Exhibit, Salt Lake City, Utah, July 8-11, 2001, NASA/TM-2002-211313 and AIAA-2001-3644

[28] La Pointe, M. R., "Primary Propulsion for Piloted Deep Space Exploration", NICA, NASA Institute for advanced Concepts, Phase 1 Final Report, December 1999. NICA Grant 07600-022 Propulsion Conference, Viareggio, Italy, Oct 1991.

[29] Sullivan D. J., Micci M. M., "The effect of Molecular Propellants on the Performance of a Resonant Cavity Electrothermal Thruster," IEPC-91-034, DGLR AIAA JSASS 22nd International Electric

[30] Takao, Y., Miyamoto, T., Yamawaki, K., Maeyama, T., Nakashima, H., "Development of ECR microwave discharge ion thruster", Pergamon Press, Vacuum Surface Engineering, Surface Instrumentation, and Vacuum Technology, volume 65 (2002) pages 361-366

[31] Birkan, M., and Micci, M., "Survey of Electric Propulsion Thruster Applicability to Near Earth Space Missions", NASA Technical Report, N89-27749, 1989

[32] Frasch, L.L., Fritz, R., Asmussen, J., "Electrothermal Propulsion of Spacecraft with Millimeter and Submillimeter Electromagnetic Energy," Journal of Propulsion and Power, Vol. 4, 1988, Pages 334 to 340.