Air-breathing Microwave Plasma Thruster (AMPT) for VLEO ABEP

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The Air-breathing Microwave Plasma Thruster (AMPT) is a microwave-powered air-breathing electrothermal thruster capable of generating newton-level thrust. The thruster uses a reduced-height waveguide design and initially operated at a microwave frequency of 2.45 GHz. Initial direct thrust measurements resulted in a maximum thrust of 0.89 N at 1 kW of input microwave power. The thruster concept is designed for drag mitigation between 70 and 90 km. Further development is underway, with the objectives of lowering the propellant flow rate, reducing the thruster size, and continuing plume diagnostics.

Nomenclature

A_e	= exit area, m^2
A^*	= throat area, m^2
c_p	= specific heat, J/kg·K
D_ram	= ram drag, N
M	= Mach number
$\dot{m}$	= mass flow rate, kg/s
$p_\mathrm{a,\ breakdown,\ e}$	= ambient, breakdown, and exit pressure, Pa
P_MW	= microwave power, W
R	= ideal gas constant
$T_\mathrm{a,\ e}$	= ambient and exit temperature, K
u_e	= exit velocity, m/s
$v_\mathrm{a,\ breakdown}$	= ambient and breakdown velocity, m/s
γ	= ratio of specific heats
η_MW	= microwave heating efficiency
τ	= thrust, N

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I. Introduction

AIR-BREATHING electric propulsion (ABEP) is an emerging technology motivated by the propulsion-related challenges of very low Earth orbit (VLEO). VLEO is defined loosely as orbits below 400 km, as drag becomes the dominant perturbing force on a spacecraft in this altitude regime. To counteract the drag, a constant propulsive force is needed, which could require many thousands of kilograms of propellant for a traditional electric propulsion (EP) system over the course of a mission [1]. ABEP depends on the continuous in-situ collection of atmospheric propellant rather than stored propellants, thus extending mission lifetime. Our research focuses on orbits below approximately 90 km, below VLEO where the drag force is significantly greater than at higher VLEO. A propulsion system that can deliver newton-level thrust is being developed to address these thrust requirements.

II. The Air-breathing Microwave Plasma Thruster

The Air-breathing Microwave Plasma Thruster (AMPT) is an ABEP concept that employs microwave heating of the atmospheric propellant, which is an electrothermal process. Figure 1 depicts the notional design of the AMPT, consisting of a compression stage, microwave applicator and ignition chamber, and expansion nozzle. The microwave source, which supplies microwave power to the thruster, is a 2.45-GHz GaN solid-state source.

Ambient rarefied air is ingested by a compressor, which compresses the atmospheric propellant to the pressures required for microwave breakdown (∼1 Torr). The ambient static pressures of the relevant environment at 70–90 km range from 2–30 mTorr. DC power is converted to microwave power using the solid-state source; however, the microwave source may be off-boarded from the spacecraft if beamed microwave power is employed.

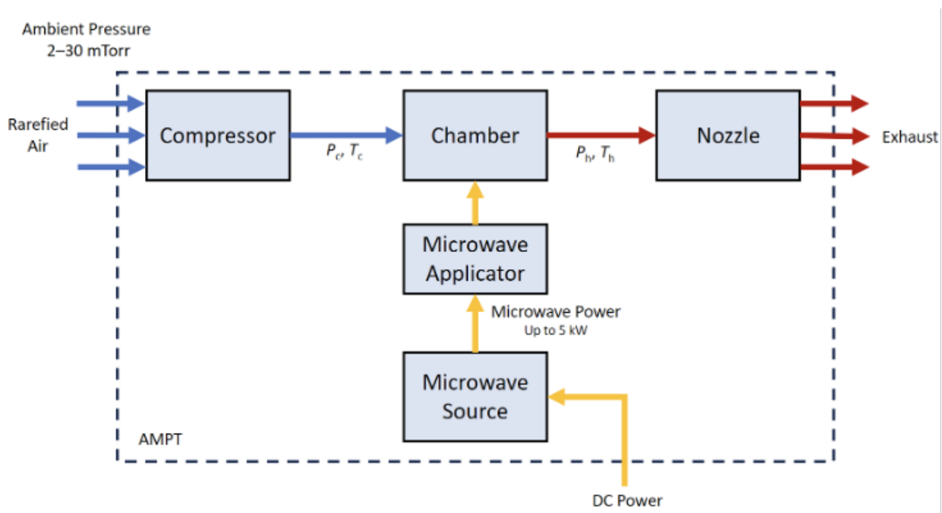


Figure 1: Notional systems diagram of the AMPT.

The thruster, depicted in Figure 2, consists of a microwave applicator and ignition chamber, which is a reduced-height waveguide (RHWG) microwave transmission line. A dielectric propellant tube passes through the reduced-height section of the waveguide, which allows the microwave-induced electric field to penetrate into the propellant while confining the propellant inside the tube. The AMPT operates using the principle of microwave heating of the atmospheric propellant. The electric field produced by the microwaves interacts with the propellant, causing the formation of a very weakly ionized plasma (approximately 1–2% ionization), which heats the propellant. The heated propellant undergoes isentropic expansion as it is expelled from a diverging nozzle, thus providing thrust. Whereas Hall-effect thrusters (HETs) and gridded-ion thrusters (GITs) accelerate individual charged particles, the propellant in the AMPT undergoes bulk heating and acceleration. The exhaust of the AMPT is neutral in charge, as is the nature of microwave plasmas.

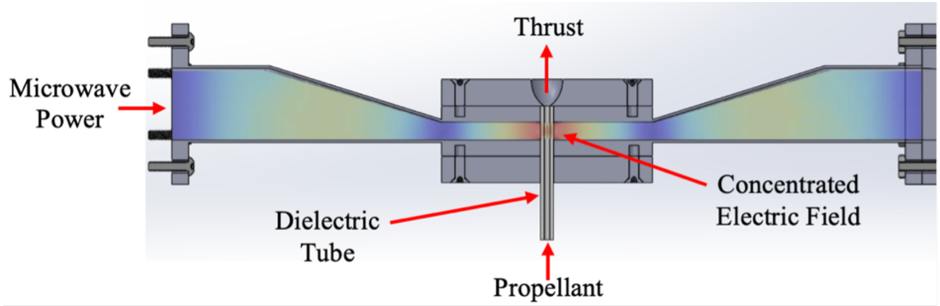
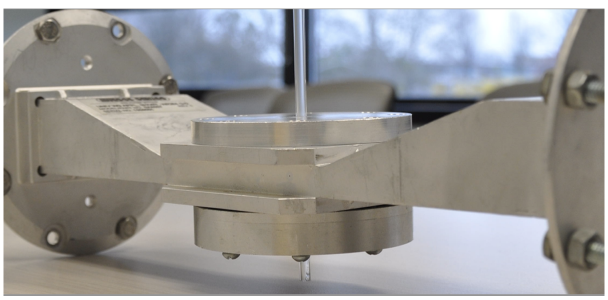


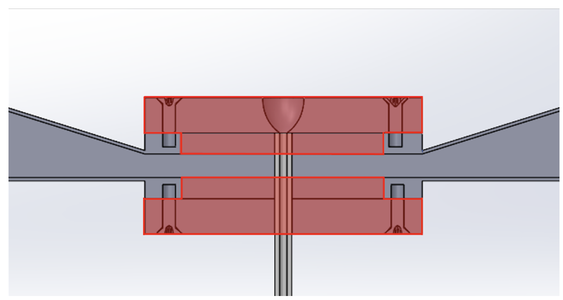
Figure 2: CAD rendering of the AMPT overlaid with the electric field.

A. Design of the 2.45-GHz AMPT

The initial thruster experiments, including first light, were performed at atmospheric pressure. Figure 3a depicts the 2.45-GHz AMPT with a quartz dielectric tube protruding through. Initially, the quartz tube was slid through an opening in the caps (depicted in Figure 3b), where the outer diameter of the dielectric tube is equal to the diameter of the hole bored through the center of the caps. This configuration was sufficient for thruster testing at atmospheric pressure; however, in order to test the thruster in a vacuum, the caps were modified to include compression seals around the dielectric tube and between the caps and the RHWG. In order to mitigate microwave breakdown in the non-reducing section of the waveguide, the waveguide is kept at atmospheric pressure during vacuum experiments.



(a) AMPT for testing at atmosphere.



(b) CAD rendering showing caps.

Figure 3: The initial AMPT configuration for testing at atmosphere with the caps highlighted that are modified for vacuum testing.

B. Predicted Performance of the AMPT

Isentropic relations can be used to determine the properties of the propellant in various states within the AMPT nozzle. The performance of the thruster can be predicted using the exhaust pressure and temperature of the flow. These performance metrics include thrust τ and exit velocity u_e. The thrust is given by

$$\tau = \dot{m} M \sqrt{\gamma R T_\mathrm{e}} + A_\mathrm{e}(p_\mathrm{e} - p_\mathrm{a}), \tag{1}$$

where p_a is the ambient pressure surrounding the thruster. The exit velocity is given by

$$u_\mathrm{e} = M \sqrt{\gamma R T_\mathrm{e}}. \tag{2}$$

These performance metrics are a function of the flow properties at the nozzle exit plane, which can be derived from the stagnation conditions. The stagnation conditions are functions of the input parameters of the AMPT, which are mass flow rate $\dot{m}$ and microwave power P_MW, and nozzle dimensions A_e and A^*. The microwave heating efficiency η_MW was taken to be 0.75. Maximizing η_MW improves the performance of the thruster by ensuring that microwave energy is transferred into the propellant as heat. Figures 4 and 5 assume

$\eta_{\mathrm{MW}} = 0.75$. Whereas other microwave-powered electrothermal thrusters like the microwave electrothermal thruster (MET) [2] suffer from cold-flow slippage [3] due to the use of a large microwave-resonant cavity, the AMPT produces a plasma that is confined to a small propellant tube, thus forcing all of the propellant to pass through the plasma and achieving a higher η_{MW}.

Figure 4 depicts the thrust and exit velocity as a function of mass flow rate at various power levels ranging from 500 to 5000 W. The thrust increases with increasing flow rate and increasing power. The exit velocity increases with increasing power and decreases with increasing flow rate. It is evident from the figure that the AMPT performance is greatest when the microwave power is maximized. In order to be a viable thruster for a spacecraft in orbit, the exit velocity must be greater than the orbital velocity of ~ 7.8 km/s. This requirement is only fulfilled at lower mass flow rates. At 5000 W, the maximum mass flow rate that yields an orbital exit velocity is 4.34 slm. However, at this flow rate, the thrust is only 750 mN. One newton is achievable at 5000 W, but the exhaust velocity is only 5.9 km/s. It is noted that the background pressure is set to 0.1 Torr, corresponding to the ground-based vacuum testing conditions for the AMPT rather than the hypothetical in-flight conditions. However, this difference is negligible ($\sim 0.2\%$ change in thrust).

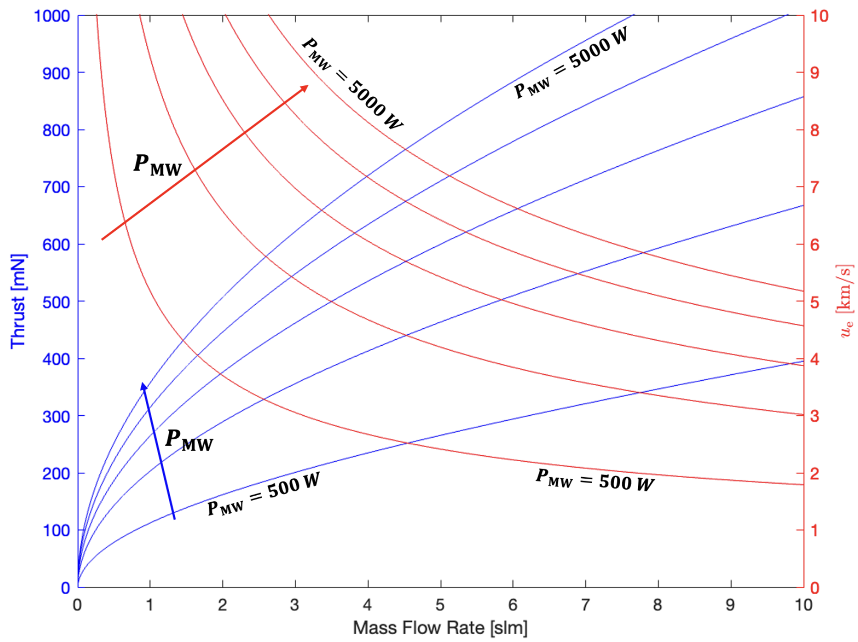


Figure 4: AMPT thrust and exit velocity as a function of mass flow rate at various microwave input powers. $A_e/A^* = 43.34$.

Figure 5 depicts the thrust and exit velocity as a function of the mass flow rate at nozzle area ratios A_e/A^* varying from 5 to 50. Thrust increases with increasing A_e/A^* and exit velocity increases with increasing A_e/A^*. However, each incremental increase in A_e/A^* results in a diminishing increase in exit velocity and thrust.

The mass flow rate, microwave power, and area ratio can be optimized to achieve the desired performance parameters of $u_e > 8$ km/s and maximum thrust. Figure 6 shows the dependence of thrust on the aforementioned thruster inputs. These predicted performance metrics assume η_{MW} is 0.75, c_p is 1300 J·kg^{-1}·K^{-1}, γ is 1.3, the ambient temperature is 300 K, R is 287 J·kg^{-1}·K^{-1}, and the ceramic tube inner diameter is 2.4 mm.

For the analysis in Figure 6, the computed value for thrust would only be accepted if the corresponding exhaust velocity is greater than the orbital velocity at 100 km of 7.85 km/s, thus all combinations of the AMPT inputs and resulting thrust depicted in the figure correspond to an exhaust velocity of 7.85 km/s. For each data point in the figure, any additional increase in area ratio or power or decrease in flow rate will result in an exhaust velocity higher than 7.85 km/s. The orbital exhaust velocity assumption is a consequence of the compressor, which is required in order to produce a sufficient propellant pressure in the dielectric tube for microwave ignition to occur. Passive inlet devices do not achieve the compression ratios required for microwave ignition. In theory, a compressor stagnates the ambient rarefied atmosphere, which is traveling

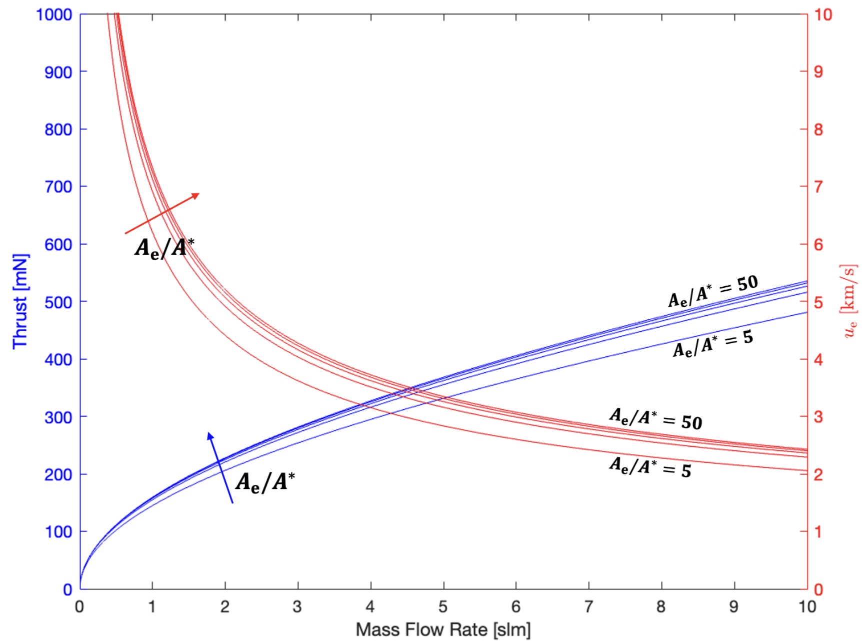


Figure 5: AMPT thrust and exit velocity as a function of mass flow rate at various area ratios. $P_{\mathrm{MW}} = 1000$ W.

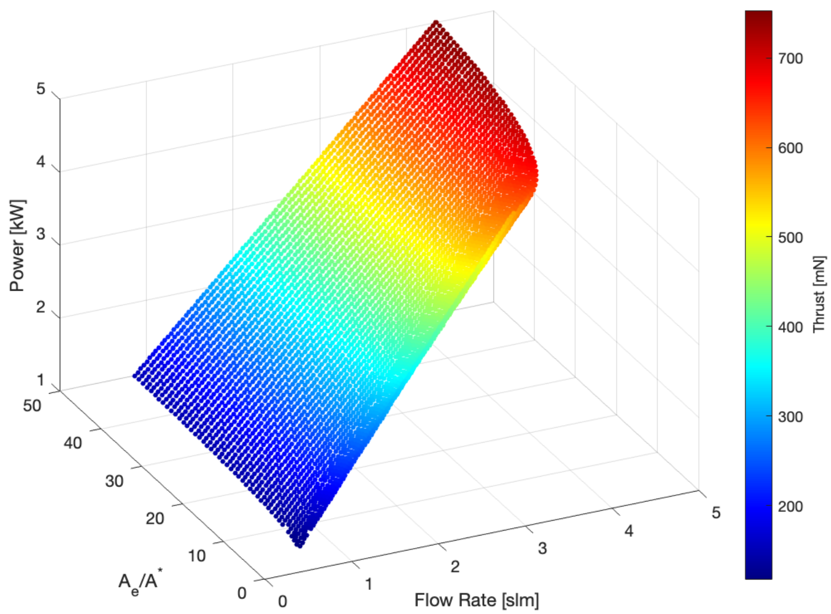


Figure 6: AMPT thrust as a function of area ratio, microwave power, and mass flow rate.

at 7.85 km/s with respect to the spacecraft, thus inducing more ram drag than satellites with passive inlets that have compression ratios of 100 times less than compressors. The area-normalized ram drag D_{ram} can be given by

$$D_{\mathrm{ram}} = p_{\mathrm{breakdown}} - p_{\mathrm{a}} = \frac{1}{2}\rho\left(v_{\mathrm{a}}^2 - v_{\mathrm{breakdown}}^2\right), \tag{3}$$

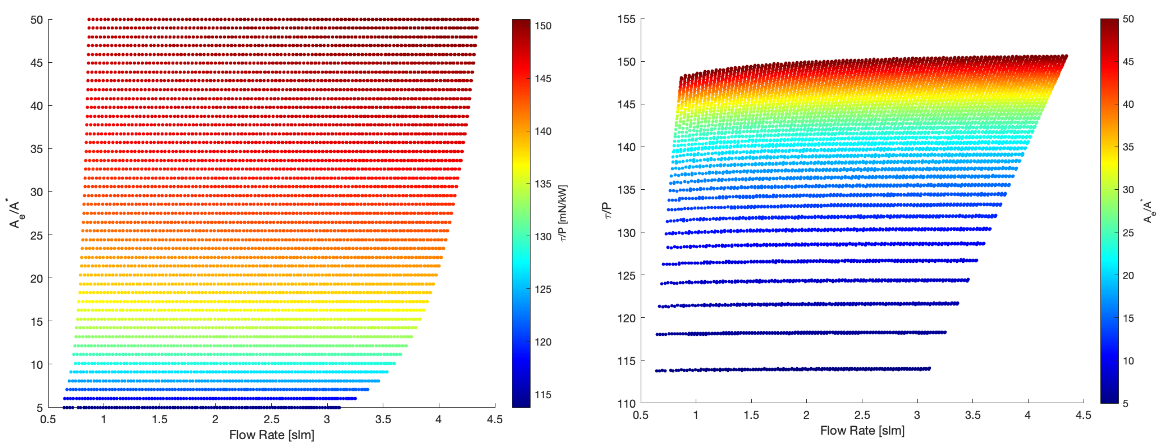
where D_{ram} is in units of $\mathrm{N/m^2}$, p_{a} and v_{a} are the pressure and velocity of the incoming flow, and $p_{\mathrm{breakdown}}$

and $v_{\mathrm{breakdown}}$ are the pressure and velocity within the dielectric tube. It can be demonstrated using the densities in the sub-Kármán-line regime that, above 88 km, the atmospheric propellant within the dielectric tube will be completely stagnated at a breakdown pressure of 2 Torr, while the propellant will maintain some fraction of its initial velocity once the breakdown pressure has been reached. In fact, at 70 km, the propellant will maintain over 93% of its initial velocity after it has been compressed to 2 Torr. However, once ignited, the incoming propellant will encounter a plasma at a much greater pressure (> 100 Torr), which may further stagnate the incoming flow.

For the purposes of this investigation, it was assumed that the flow within the propellant tube is stagnated, which is indeed the case during ground-based vacuum testing of the thruster. Thus, in order for the thruster to produce any net thrust (i.e., generate more thrust than induced D_{ram}), the exhaust velocity must be greater than the velocity of the incoming atmosphere.

Approximately 1.5 N of thrust is needed to overcome the drag imparted on a spacecraft at 100 km with an assumed frontal area of 0.04 m^2 and C_{D} of 2.24. It may be reasonably assumed that the frontal (pressure) drag is the dominant contributor to the total drag and that the flow will stagnate with or without a compressor, with the difference being the location of the stagnation point. For a spacecraft with no inlet (i.e., a flat plate on the ram side), the flow will stagnate upstream of the spacecraft. For a spacecraft with a compressor, the flow will stagnate downstream of the inlet (i.e., within the spacecraft). Given the presence of a stagnated flow in either circumstance, the presence of a compressor should not cause a significant deviation from the aforementioned thrust requirement. Therefore, it may be reasonable to assume that the performance of the AMPT is sufficient if the thrust is equal to D_{ram} and the exhaust velocity is equal to the incoming velocity.

The performance of the AMPT can also be presented in terms of the thrust-to-power ratio. Figure 7 shows the behavior of the area ratio and mass flow rate with respect to the thrust-to-power ratio. Each data point achieves an exhaust velocity of 7.85 km/s. Higher thrust-to-power ratios are achievable at higher mass flow rates; however, the corresponding exhaust velocities will be sub-orbital.



(a) Area ratio vs flow rate.

(b) Thrust-to-power vs flow rate.

Figure 7: The relationship between area ratio, mass flow rate, and the thrust-to-power ratio.

The thrust-to-power ratio increases with increasing area ratio. Additionally, Figure 7a is bounded by an exponential-like curve that corresponds to the maximum propellant flow rate at a given area ratio that still results in orbital exhaust velocities. Any additional increase in mass flow rate will result in a sub-orbital exhaust velocity, which does not meet the thruster performance requirements. This curve can be expressed analytically by

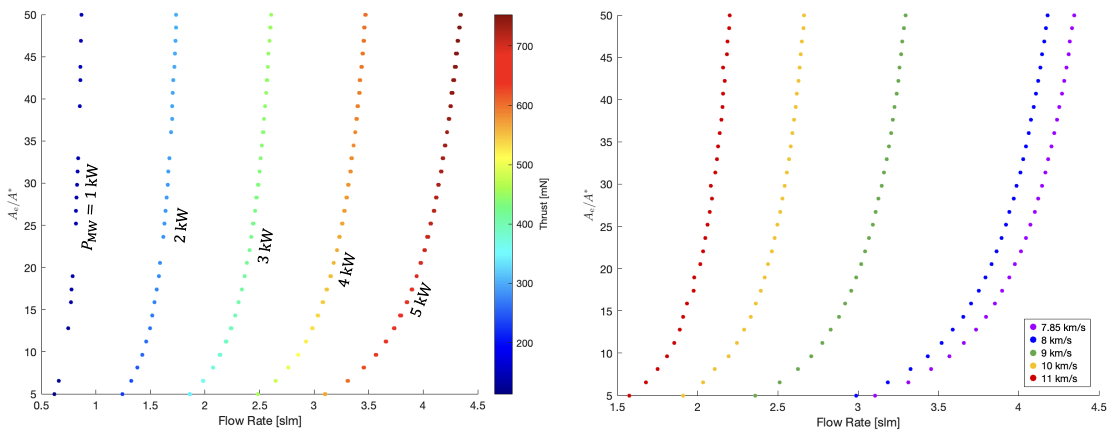
$$u_{\mathrm{e}} = M\sqrt{\gamma R \frac{T_{\mathrm{a}} + \frac{\eta_{\mathrm{MW}} P_{\mathrm{MW}}}{\dot{m} c_{\mathrm{p}}}}{1 + \frac{\gamma - 1}{2} M^2}}. \tag{4}$$

A numerical solver can be used to determine M given a nozzle area ratio from

$$\frac{A_\mathrm{e}}{A^*} = \frac{1}{M}\left(\frac{2}{\gamma+1}\left(1+\frac{\gamma-1}{2}M^2\right)\right)^{\frac{\gamma+1}{2(\gamma-1)}} . \tag{5}$$

Given the area ratio, exhaust velocity, microwave power, and microwave heating efficiency, the maximum mass flow rate for that particular exhaust velocity can be determined. Inputting a range of area ratios produces the aforementioned bounding curve in Figure 7a.

The behavior of this bounding curve can be explored for various powers and exhaust velocities. Figure 8 provides the relationships between the maximum flow rate for a given exhaust velocity as a function of the microwave power and the exhaust velocity itself.



(a) Variation with power.

(b) Variation with exhaust velocity ($P_\mathrm{MW} = 5000$ W).

Figure 8: The bounding mass flow rate curves as a function of the nozzle area ratio, power, and exhaust velocity.

Figure 8a shows that the maximum allowable mass flow rate increases with increasing power. That is, the thruster can maintain orbital exhaust velocity with higher flow rates if the microwave power is increased. The increase in power and increase in mass flow rate both result in increases in thrust, so the effect on thrust is amplified for a given exhaust velocity should the available power to the thruster be increased.

There are two methods of attaining more thrust, should the required thrust be greater than anticipated by the previous calculations. One method is by increasing the mass flow rate, which must be compensated for by also increasing the power to maintain an orbital exhaust velocity. The other method involves designing for either (1) an exhaust velocity greater than 7.85 km/s or (2) a maximum power level for the thruster. This method requires multiple nozzles to be used, as the allowable flow rate is further constrained, as dictated by the subsequent curves in Figure 8b, thus limiting the thrust of one nozzle. This method may be preferred as the amount of power that can be transmitted through a waveguide transmission line is limited by the dimensions of the waveguide. Additionally, the relationship between the power and plasma temperature dictates that an increase in power will result in an increase in plasma temperature, and the propellant tube may not be able to withstand such temperatures. Thus, multiple thruster heads, each with a certain mass flow rate and power, may be necessary to maintain the required exhaust velocity and also meet the required thrust metric. A rendering of a notional four-thruster head configuration is depicted in Figure 9. This configuration can fit within a $2 \times 2 \times 1$ U volume for a 5.8-GHz AMPT. It is noted that each thruster is truncated on one side of the reduced-height section of the waveguide. This truncation can be applied since there is an anti-node in the electric field at this location.

For example, the following configuration can produce the requisite 1.5 N of thrust for orbit at 100 km. Assuming a nozzle area ratio of 50 (Figure 7 makes it clear that a large area ratio produces the highest thrust-to-power ratio and increases the allowable flow rate for orbital exhaust velocities), one thruster can produce 391 mN of thrust with 1.98 slm of propellant and 3 kW of microwave power with an exhaust velocity of 9 km/s. Four of these thrusters will produce 1.56 N of thrust with 7.92 slm of propellant and 12 kW of

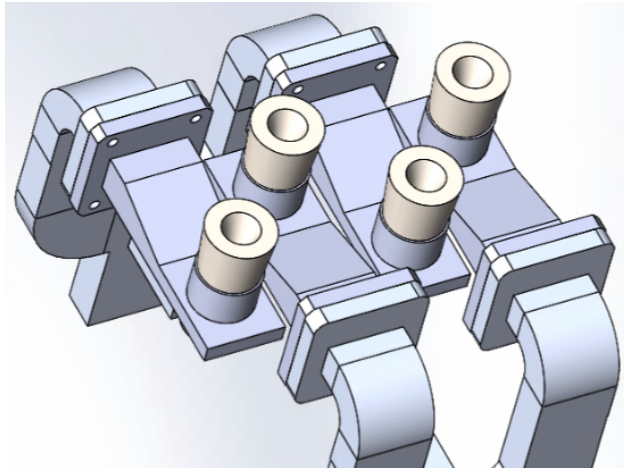


Figure 9: A CAD rendering of a notional concept for a four-thruster head configuration of the AMPT.

power. Using the configuration provided in Figure 9, four of these thrusters may reasonably fit within a 4-U cross section.

III. Initial Thrust Stand Testing

Figure 10 depicts all of the thrust measurements that were achieved during the first year of AMPT testing. The plot includes the four cold flow data points, shown in purple. The highest thrust measurement was 890 mN at 30 slm and 1 kW of microwave power.

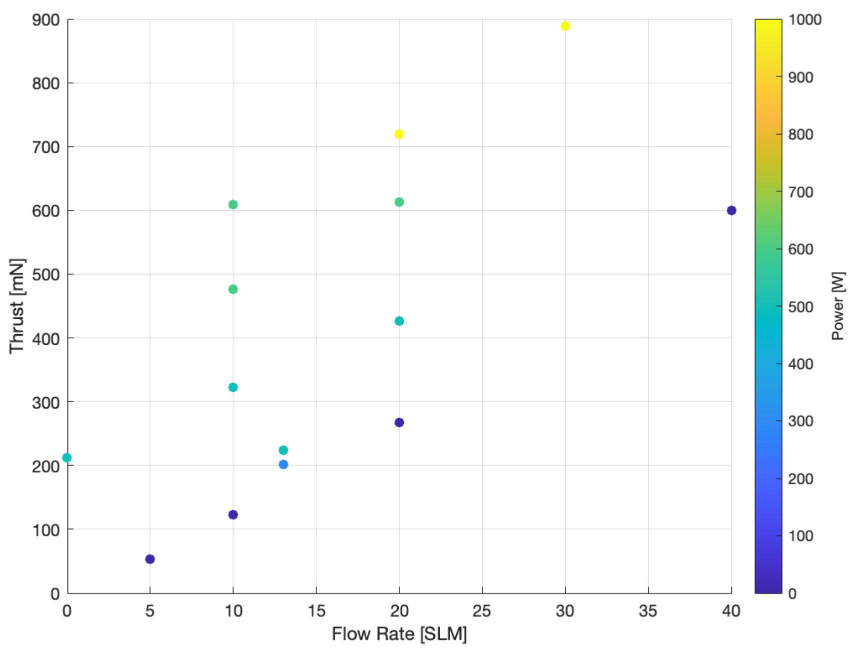


Figure 10: Experimental data from the AMPT depicting the relationship between flow rate and measured thrust.

Figure 11 shows the relationship between the measured thrust of the AMPT as a function of both microwave power and propellant flow rate. Both of these generalized relationships follow intuition: as flow rate and/or power increase, the measured thrust also increases. Thrust is theoretically directly proportional to mass flow rate. However, if mass flow rate is increased but power is not, then specific power absorbed by the flow decreases; thus, an increase in flow rate returns a diminishing increase in thrust. However, if power alone is increased, the increase in absorbed microwave power into the propellant is increased, thus resulting in a higher temperature, which also results in increased thrust. Therefore, it follows that in order to have a proportional increase in thrust with flow rate, power must also be increased.

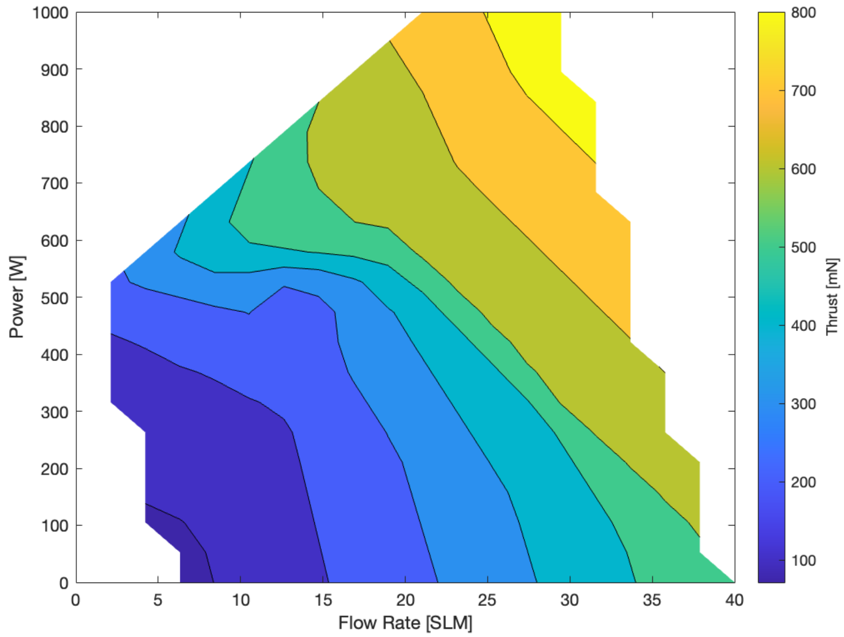


Figure 11: A contour plot showing how thrust is a function of both flow rate and microwave power.

Due to the nature of VLEO, particularly the regime of interest between 70–90 km (which technically falls below VLEO), power generation is a considerable challenge. Solar arrays that are large enough to supply 10s of kW of power would impart more drag than a propulsion system could feasibly counteract. Thus, thrust-to-power is of particular importance for VLEO propulsion. Figure 12 shows the measured thrust-to-power values achieved for this testing campaign, achieving a maximum value of 1022 mN/kW at 10 slm and 600 W of microwave power.

It is noted that the goal of the reported testing campaign was to achieve a thrust > 1 N, thus 10s of slm were needed with available microwave power. Further efforts are underway with the goal of achieving a thrust-to-drag ratio > 1. As previously mentioned, there is a limiting flow rate that results in an exhaust velocity greater than the orbital velocity. Thus, recent testing has focused on lower flow rates (< 2 slm per thruster head) and higher powers. In order to achieve more thrust with a specific-impulse-limited mass flow rate, multiple thruster heads are required. Thrust-to-power ratios > 100 mN/kW are still attainable at these flow rates and powers.

IV. Optical Emission Spectroscopy

Optical emission spectroscopy was used to determine which species are present within the thruster plume. The results show that the plume consists of atomic nitrogen (N I), atomic oxygen (O I), hydrogen (H I), sodium (Na I), and molecular nitrogen (N_2 I), with all of the species being neutral. These peaks are depicted in Figure 13a. The presence of sodium is likely the result of ablation of the alumina ceramic nozzle, as sodium is a common contaminant in alumina ceramic. The hydrogen is likely a result of the presence of water vapor in the propellant. The oxygen comes from two sources. The first source is a component of the propellant (dry compressed building air). The second is likely the result of nozzle ablation (the chemical formula for alumina ceramic is Al_2O_3). This was confirmed during testing of pure N_2 propellant, in which the atomic oxygen spectral lines were still present.

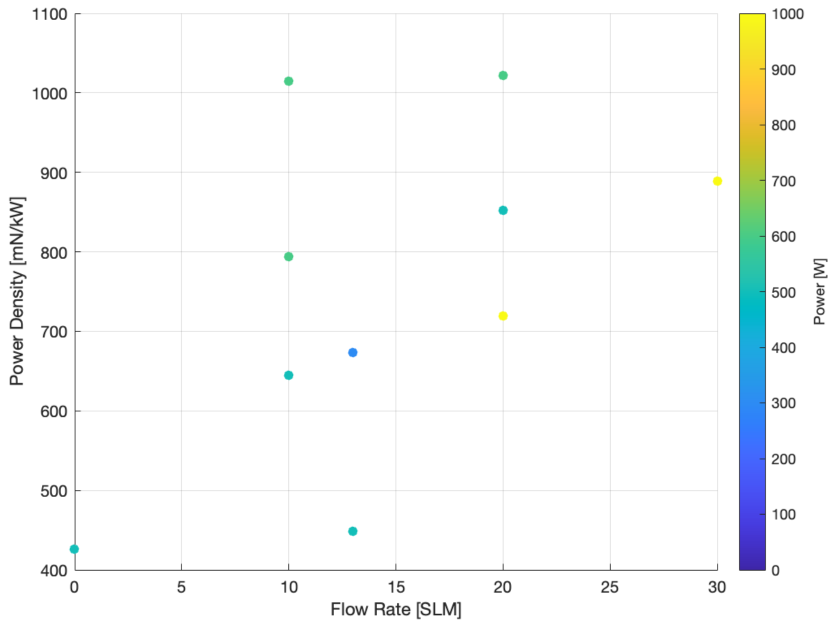
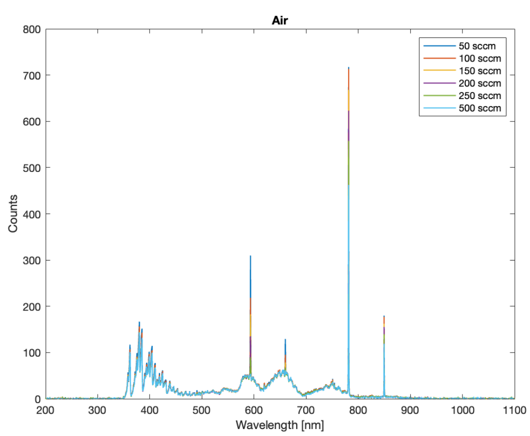
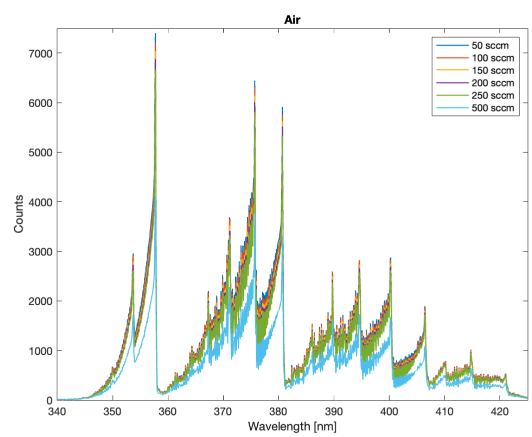


Figure 12: Experimental thrust-to-power values as a function of the flow rate and microwave power.

Two spectrometers were used. The first was a broad-spectrum spectrometer with a spectral range of 200–1100 nm and a resolution of 0.45 nm. The second spectrometer had a spectral range of 200–400 nm with a higher resolution of 0.073 nm. Using a spectrometer with a higher resolution in the ultraviolet range allows the second positive system of the molecular nitrogen spectrum to be observed. This system can be used to fit a rovibrational temperature to the data, thus allowing for a neutral gas temperature to be inferred. The second positive system of neutral molecular nitrogen as a function of flow rate is depicted in Figure 13b. Preliminary results show a neutral gas temperature of ∼2000–3000 K, depending on the propellant flow rate and the bands that were chosen for fitting. Instrument broadening and other instrument and facility effects need to be characterized. There is a clear correlation between spectral intensity and flow rate, with intensity being inversely proportional to the flow rate. As the flow rate increases and the power remains constant, the specific thermal heating decreases, thus the bulk neutral gas temperature decreases.



(a) Broad range (200-1100 nm)



(b) UV range (340-425 nm)

Figure 13: The relationship between area ratio, mass flow rate, and the thrust-to-power ratio.

V. Conclusion

The AMPT is a microwave-powered electrothermal thruster capable of newton-level thrust at high thrust-to-power ratios, which is a requirement for the altitudes of interest. The initial AMPT was designed for operation at a microwave frequency of 2.45 GHz. Direct thrust measurements were performed, showing 0.89 N at 30 slm of air and 1 kW of input power. This operational scheme can be characterized as high flow rate and low power. Performance analysis showed that a high power and low flow rate operational scheme is required to achieve a thrust-to-drag ratio greater than 1. Subsequent design and testing is underway for this scheme. To reduce the volume of the AMPT propulsion system, a 5.8-GHz AMPT was designed, which offers a volumetric reduction of $> 80\%$ in the thruster head.

Several thruster diagnostics are underway for the 2.45- and 5.8-GHz AMPTs. These efforts include further OES testing, direct thrust measurements, and impact pressure probe, Langmuir probe, and microwave interferometry plume diagnostics.

Appendix: AMPT Experiments

Figure 14 depicts microwave interferometry tests on the plume of the 5.8-GHz AMPT, which allows the plasma density to be mapped in three spatial dimensions.

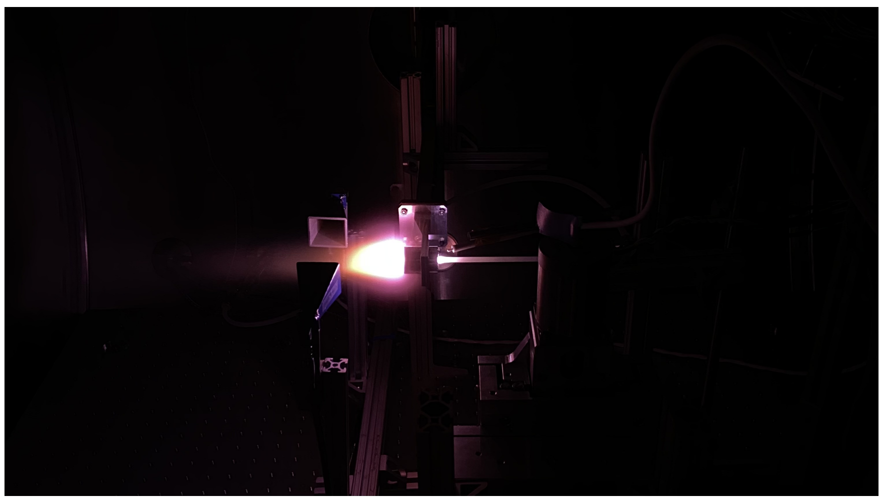


Figure 14: AMPT testing with microwave interferometry on 5.8-GHz AMPT.

Figure 15 depicts Langmuir probe measurements in the plume of the 2.45-GHz AMPT. Because the AMPT was tested at high pressures ($\sim$ 100 mTorr) to simulate a relevant sub-VLEO environment, the I–V traces produced with the Langmuir probe were not well-behaved.

Figure 16 depicts the bow shock that forms over a Langmuir probe immersed in the 2.45 GHz AMPT plume. The shape of the shock can be approximated with a hyperbola. The hyperbolic angle can be used to approximate the Mach number of the exhaust, which was 3.6. Isentropic flow relations predict a Mach number of 3.98 with the nozzle geometry. The estimated and hypothetical Mach numbers agree to within 10%.

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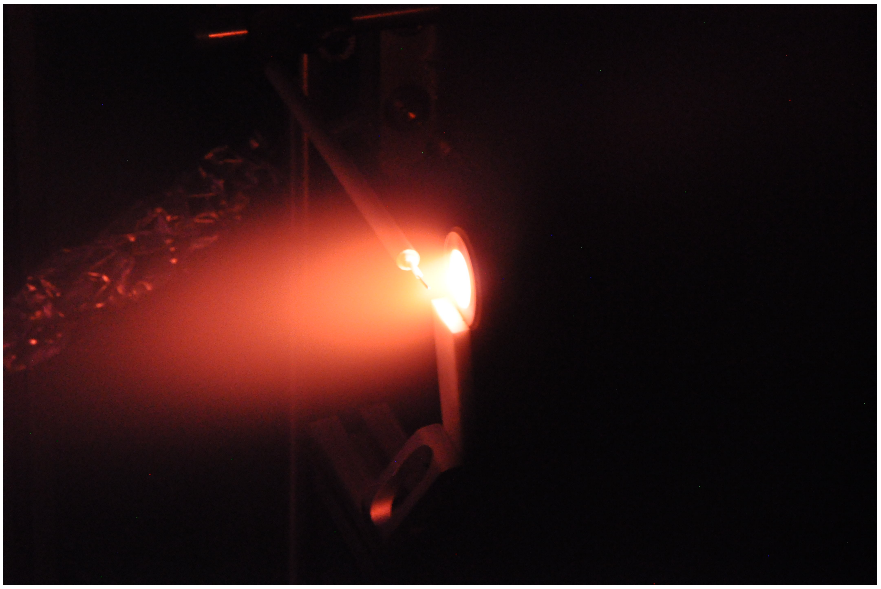

Figure 15: Langmuir probe testing of 2.45-GHz AMPT.

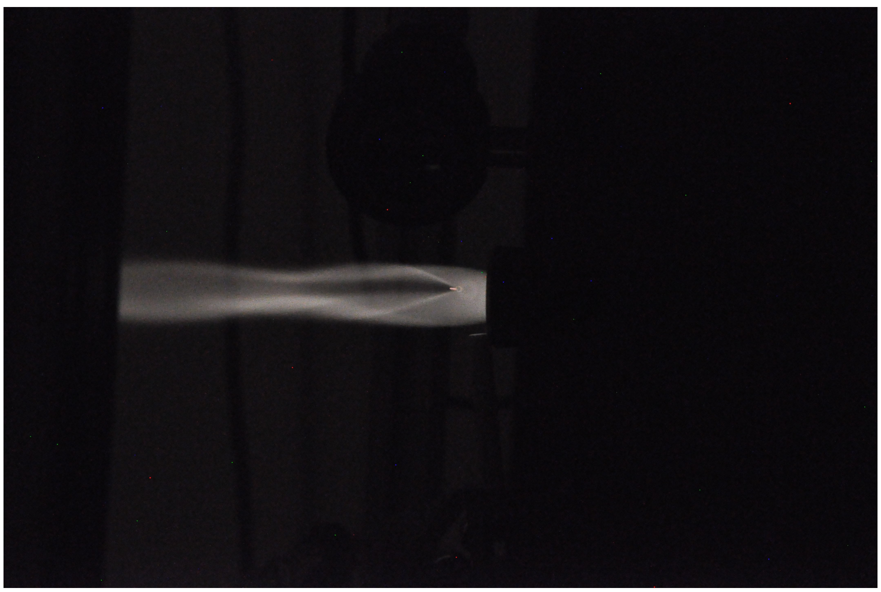

Figure 16: Bow shock over Langmuir probe.

References

[1] McCreary, L., "A Satellite Mission Concept for High Drag Environments," *Aerospace Science and Technology*, Vol. 92, https://doi.org/10.1016/j.ast.2019.06.033 (2019), pp. 972–989 .

[2] Micci, M. M., S. G. Bilén, and D. E. Clemens, "History and Current Status of the Microwave Electrothermal Thruster," *Progress in Propulsion Physics*, Vol. 1 (2009), pp. 425–438 .

[3] Biswas, S., "An Investigation of Plasma Dynamics within Microwave Electrothermal Thruster Cavities," Dissertation (2023), https://etda.libraries.psu.edu/files/final_submissions/1358.