Design of a Water-Propellant 17.8-GHz Microwave Electrothermal Thruster

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We report on recent efforts to advance water-propellant-based microsatellite electric propulsion using the Microwave Electrothermal Thruster (MET). This thruster uses microwave power at 17.8 GHz for plasma production within a resonant cavity. Water is utilized as the propellant, unlike previous MET models that have used helium, ammonia, and hydrazine decomposition products. Prior miniaturization efforts have resulted in a CuMET version that can be integrated into a 3U CubeSat bus. An overview of a proposed implementation is presented. Redesign of the CuMET allows for implementation of the thruster block into the "tuna can" volume available in the CubeSat standard, increasing either propellant or secondary payload space onboard. The theoretical underpinnings of water as a propellant in an MET are also detailed, including challenges faced in testing and discovered through analysis of the MET flow and heating system. Continuing work involves the development of viable spacecraft microwave signal sources and an adequate heater configuration for water vapor production aboard a spacecraft.

Nomenclature

A	=	Surface area, m^2
c_p	=	Heat capacity, J/K
d	=	Separation distance/cavity diameter, m
e	=	Electron charge, 1.602×10^{-19} C
E	=	Electric field strength, V/m
I_{sp}	=	Specific impulse, s
m_e	=	Mass of an electron, 9.109×10^{-31} kg
n	=	Plasma density, m^{-3}
STP	=	Standard temperature and pressure, 273.15 K and 101.325 kPa
T	=	Temperature, K
U	=	CubeSat "unit": 10 × 10 × 10 cm cube
v_e	=	Electron velocity with respect to reference, m/s
v_c	=	Electron collision frequency, s^{-1}
ε	=	Emissivity
σ	=	Stefan–Boltzmann's constant, 5.67×10^{-8} $W \cdot m^{-2} K^{-4}$
σ_{H_2O}	=	Cross-sectional collision area of a water molecule

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I.Introduction

Electric propulsion for spacecraft has historically required optimized utilization of propellants that are synthesized for their specific desirable molecular qualities.[1] For example, many small form-factor satellites employ resistojets using propellants such as hydrazine; large-scale missions have moved towards Hall and ion thrusters using xenon for their high specific impulse, and optimization occurs within those spaces.[2] Water represents perhaps a new paradigm, with a number of water-based thrusters being described in the literature recently. Penn State's Space Propulsion Laboratory is exploring the use of water, a fuel source facing many challenges in its application, as a propellant choice for the CubeSat Microwave Electrothermal Thruster (CuMET), a nanosatellite propulsion system using microwaves to produce thrust.

The microwave electrothermal thruster (MET) works on the principle of microwave power being injected into a resonant cavity to produce plasma that is exhausted from a nozzle. A TM^{z}_{011} resonant mode is established within the cylindrical cavity, as shown in Fig. 1. Propellant inlets are placed near the top, where the nozzle is located, and a vortical flow is induced around the primary plasma formation region. An antenna for injecting the microwave power is at the bottom of the cavity, which region is separated from the propellant vortex by a dielectric separation plate. Electric fields are maximized at the bottom and top of the cavity, and breakdown occurs producing a plasma at the nozzle since the bottom is separated and held at a higher pressure.

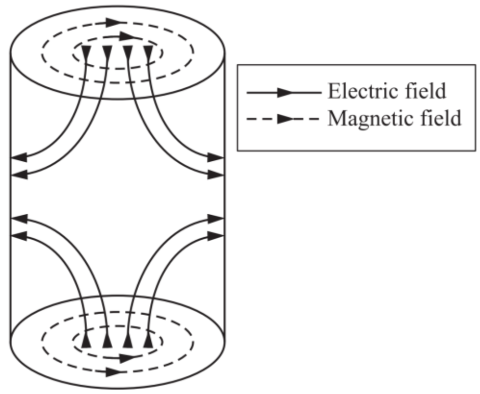


Figure 1. Electric and magnetic field lines representing the TM^{z}_{011} resonant mode in a circular cavity [3].

Prior to the development of a 17.8-GHz thruster begun in 2012,[3] earlier MET instantiations were designed to work in the range of frequencies from 2.45–14.5 GHz. These METs primarily utilized helium, ammonia, and hydrazine decomposition products as propellants,[4] although other propellants have also been demonstrated, which include water at 2.45 GHz.[3] Due to its increased frequency and correspondingly smaller cavity, the 17.8-GHz design point enables operation with only 10–100 W of input power, which places the device within the feasible power range for 6U and 12U CubeSats, as well as 3U CubeSats conducting higher-power mission profiles.[4]

Because METs can produce plasmas with a wide variety of gases and due to the interest in using water for myriad purposes in human spaceflight systems, we are seeking to develop a water-propellant MET. The potential integration of water propulsion systems on LEO CubeSats supported by the ISS or future efforts to bring water to Earth orbit provides the space industry with the prospect of agile, long-lifetime spacecraft with the ability to be refueled on demand and employing a benign, safe propellant. Of notable interest is how space resource acquisition can be self-sustaining, as water content is a significant fraction in the mass of some asteroid bodies.[5]

The concept of utilizing water as a propellant was explored in the 1980s at NASA's Glenn Research Center (then Lewis) for resistojet applications,[6] and many lessons learned from their work can be applied in modern applications as many of the fundamental challenges of using water as a propellant remain. However, lessons learned in miniaturization efforts of water systems,[7] general design work minimizing volumetric requirements of the system on a CubeSat bus, and the power delivery capabilities of the miniaturized 17.8-GHz MET have made implementation of a water-fed CuMET possible.

Penn State's Student Space Programs Laboratory (SSPL) delivered the OSIRIS-3U satellite in mid-2017, a CubeSat designed and assembled by students to conduct ionospheric plasma characterization in response to solar flares and simulated ionospheric excitations.[8] Follow-up work aims to leverage SSPL's flight heritage with nanosatellite systems to demonstrate the operation of the CuMET as well as a suite of diagnostic payloads, which, through the development

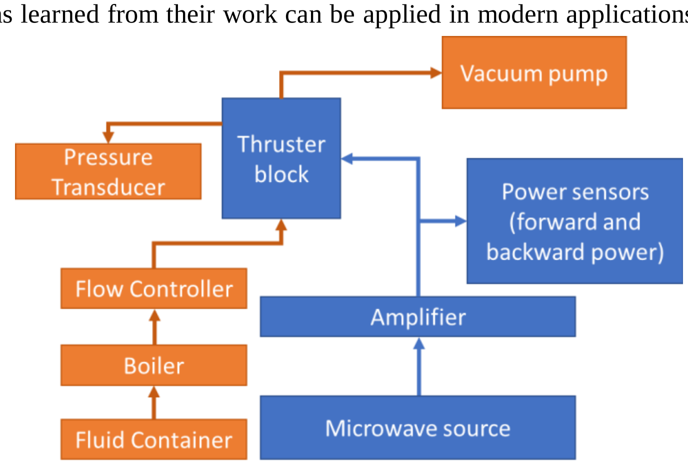


Figure 2. Block diagram of benchtop MET flow system: orange denotes pressure/propellant line, and blue denotes microwave signal and power.

lifecycle of its integrated system, will greatly increase the understanding of water flow systems' integration into small spacecraft.

II.MET Operations

A. Benchtop Testing

The overarching challenges in miniaturizing the MET system have been extensively presented in recent years.[3,4] Decreased power requirements have been achieved by the corresponding smaller cavities used for plasma production, in which higher electric fields are achieved at lower input power. Laboratory operation of the 17.8-GHz MET is conducted with the system shown schematically in Fig. 2. Unlike previous propellants tested in the MET system, which are in the gaseous state at ~290 K, i.e., standard operating conditions for benchtop testing,[4] water exists in a liquid state at that temperature. This necessitates the introduction of a boiler into the system, with the aim of producing a homogenous vapor at the inlet of the thruster block. Various boiling methodologies are available for use in producing a steam, but the current setup utilizes a pot-style boiler that feeds a flow controller and finally into the MET cavity. This is shown in Fig. 3.

The microwave source and amplifier produce a up to 40 W of microwave power that is introduced into the microwave cavity for plasma production. Electrical breakdown is typically understood to be a function of pressure, cathode–anode separation, and voltage differential, as per Paschen's Law,[9] but Brubaker[10] discusses the determination of a critical frequency above which the assumptions of Paschen's Law break down, and where the Paschen curve is not a good indicator of breakdown conditions due to electron entrapment within an area within a separation distance d. This critical frequency is

$$f_{\mathrm{cr}} = (eE)/(\sqrt{2}\pi m_{\mathrm{e}} \nu_{\mathrm{c}} d), \tag{1}$$

where e is fundamental charge, m_{e} is electron mass, E is the electric field strength, and ν_c refers to electron collision frequency, determined by Raizer[11] to be:

$$\nu_{\mathrm{c}} = n\sigma_{\mathrm{H_2O}}\nu_{\mathrm{e}}, \tag{2}$$

where n refers to the neutral gas density, $\sigma_{\mathrm{H_2O}}$ refers to the total cross-sectional collision area of gas molecules, and ν_{e} is the relative electron velocity with respect to the gas particle. The minimum mass flow rate numbers wherein plasma ignition was achieved with ammonia were 0.08 mg/s at 6 kPa.[12] We need to experimentally, rather than analytically, determine breakdown, which is the subject of ongoing experimentation.

B. Water as a Propellant

As mentioned, at frequencies beyond the critical frequency, neither models nor analytical methods of determining the breakdown voltage for a microwave system broadly exist yet. However, the attainable electric field strength 2.5×10^5 V/m has produced plasma in water vapor testing, albeit a qualitatively poor and inconsistent one.

As determined in work done at NASA Glenn from 1961–1988,[6,13] typical boiler and supply systems can produce oscillatory behavior once liquid film coating the walls of pipes containing two-phase flows begins to evaporate. Therefore, with a pot boiler system, it is desirable to maintain a high degree of liquid phase water mixed into the propellant stream for thermodynamic purposes; however, the resonant frequency of the microwave cavity is highly-dependent on its configuration and contents, and issues with consistent plasma production could be attributed to, among

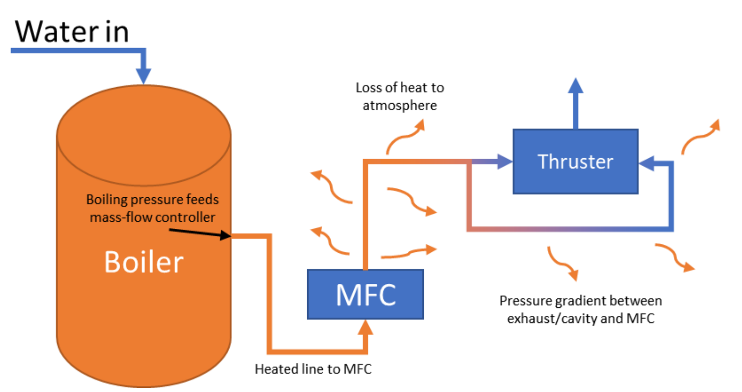


Figure 3 Water flow loss diagram, noting pressure concerns with pot boiler and thermal losses from the original boiler. "MFC" refers to the mass-flow controller proposed for use on the bench, but not implemented.

other factors, contamination of the vapor phase by suspended liquid particles.

Water's high thermal conductivity and insulating properties can cause issues when in a plasma, as the enthalpy required for water to enter the thermal phase is 40.65 kJ/mol, which is roughly five times what is required to heat liquid water from 0 to 100 °C at atmospheric conditions.[14] The electrothermal production of additional plasma is complicated with a "wet" vapor being input.

Water plasma production has been done under current bench conditions, but with not enough consistency that it is functional beyond as a proof of concept. It is believed that these issues stem from the boiler system in place for producing the water vapor, and current operating temperatures of the system being at room temperature. Further, the pot-style boiler system does not produce enough of a consistent flow. Follow-up bench-testing of the MET water system will necessitate significant insulation of both the thruster block, flow system, and development of a robust boiler system. Losses and complications in the system are summarized in Fig. 3.

C. Water and Ammonia Comparisons

Previous work on the 17.8-GHz thruster has predominantly used helium and ammonia as working gasses. Table 1 notes similarities and differences between ammonia and water in their liquid and gaseous states. Unless otherwise stated, values are at STP.

Table 1. Comparison of various characteristics of water and ammonia as propellants.[14]

Propellant	Water (H_2O)	Ammonia (NH_3)
Enthalpy of vaporization [kJ/mol]	40.65	23.35
Liquid heat capacity (c_p) [J/(mol·K)]	75.327	80.80 (not achievable at STP)
Vapor heat capacity (c_p) [J/(mol·K)]	37.47	35.06
Mass contained in 1U volume [kg]	1 (liquid), 0.00059 (gas, 1 bar)	0.73 (liquid), 0.00086 (gas, 1 bar)

At 1 bar, water vapor and ammonia vapor are very similar mechanically: water vapor has a density of 0.59 kg/m^3 compared to that of ammonia gas, which is 0.86 kg/m^3. The enthalpy of vaporization of water, which is significantly higher than ammonia's, is a key aspect of the challenges with a water MET system. With adequate compression of the propellant, however, ammonia remains eminently viable as a propulsion system given its operational history in testing and >250 s I_{sp} displayed performance.[4]

III. Satellite System Concept and Development

Integration of the propulsion system into a satellite bus also entails the development of a robust, miniaturized system that enables operations remotely and within a limited volume, mass, and power budget. The fundamental requirements of a functional propulsion system are microwave production, microwave amplification, fluid transport, and fluid heating. Relatedly, two significant challenges faced at the benchtop scale are adequate and consistent fluid transport and heating, as well as frequency tuning for maximum performance. The maturation of the CubeSat architecture and spacecraft-based propulsion system will thus be conducted in tandem with increased fidelity of the benchtop testing configuration.

There are five overarching challenges for implementing the system into a CubeSat: mission feasibility, heat management, integration into a CubeSat bus, and satisfying viable power requirements for a CubeSat.

A. Mission

Propulsion on a CubeSat enables new mission profiles that require delta-V to maintain or modify orbits. In implementing the CuMET in one of the first water propulsion-powered CubeSats, we are interested in characterizing how the propulsion system integrates into and interacts with the overall system as well as the surrounding environment. The MET's electrothermal plasma production produces a water vapor plume, and this plume's mixing into the surrounding ionosphere is a matter of scientific interest.

The Penn State Space Propulsion Lab contains facilities for characterizing the space environment such as its own Low Earth Orbit (LEO) simulation chamber.[15] Langmuir probe systems and spacecraft component coatings for the OSIRIS-3U spacecraft were tested using this vacuum chamber. By producing plasma flow conditions similar to those in LEO, the chamber can be used to characterize the effects of the MET's plume in a relevant space environment. Further, introducing a Langmuir probe to a floating spacecraft within the chamber could provide insight on potential recoupling and recombination mechanisms for water vapor and its decomposition products. Conducting plume observation, interaction, and mixing analyses would aid in the understanding of fundamental metastable plasmas and the rarefied ionosphere. Further, floating potential analysis implemented into the mission could provide secondary insight on mixing patterns and rates, if the system remains electrically connected after plume emission.

Other proposed mission tasks entail providing insight on thruster operations: backflow analysis, if possible; thrust and specific impulse determination using inertial measurement units; and analyzing differences between Earth- and space-based readings for potential using state-of-the-art retarding potential analyzers. The implementation of various scientific payloads into the CuMET technology demonstrator would not only provide potential mission synergies with prospective collaborators, but also provide unique insight on how a nanosatellite can fulfill varied and complex missions.

B. Thermal System

Heat management has two significant factors to consider: maintaining propellant storage at a viable temperature and producing a consistent vapor for plasma production. Water is most easily stored in its liquid state, but the enthalpy of vaporization is a significant factor in power requirements to run the propulsion system. The trade-offs between minimizing thruster operation costs and lowering passive liquid-state maintenance cannot be done without a more mature system, but assuming the densest storage of water in a rectangular tank, Stefan–Boltzmann's Law—which states that the total power emitted by a blackbody P is a function of its surface area A, Stefan–Boltzmann's constant σ, and T^4, the temperature in Kelvin to the fourth power—assuming an emissivity of ε = 1, is

$$P = Aj = A\sigma T^4 \tag{3}$$

and can be used[16] to define a baseline number for passive energy requirements. As such, a 1U volume of water with a surface area of 0.06 m^2 at 276 K, where its density is highest, with σ = 5.67×10^{-8} W·m^{-2}K^{-4}, radiates a steady-state 1.96 W of heat. This can be used as the baseline power requirement to keep the propellant from freezing in containment, although insulation can reduce this number.

The second significant factor in thermal system design is that the flow from the reservoir to the thruster itself must be heated to produce a water vapor that is then excited into plasma. Current benchtop experiments rely on a pot boiler producing sufficient head based on the temperature of the container, which is fed directly into the thruster. Heating of lines from the boiler has been attempted to maintain the vapor phase, but controlled pressure and temperature have yet to be achieved.

The development of a new water flow system will be conducted both for bench and spacecraft systems, based on lessons learned at NASA Glenn[6,13] and, reflecting development of the MET system in the past years, new flow regimes are being explored. Just as vortical flow was induced within the MET system to separate the plasma production region from significantly cooler input gas, vortical flow channels can be used to induce turbulence and improved thermodynamic diffusion.

The flow system developed by boiling within a pot is inherently chaotic at a given time; this produces a poor-quality factor χ, which is defined by the percentage of total fluid mass that is vapor within a flow. Inducing swirl within the flow in a small-radius channel with heated walls is a proven method of improving quality at the outlet. One significant issue with this method, however, is that it also causes an increased pressure drop across the channel. Advancements in microfluidics in the past decades have produced several miniature aerospace solenoid valves with respectable pressure stand-off ability. Further, their scaling down could enable the introduction of multiple such valves into the proposed system. Such a "push-pull" system separated by a coiled heating system, inducing turbulent flow throughout, is proposed as shown in Fig. 4.

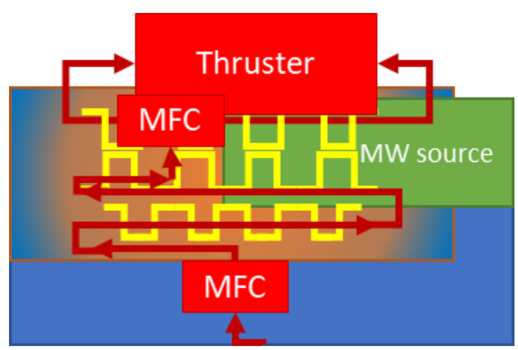


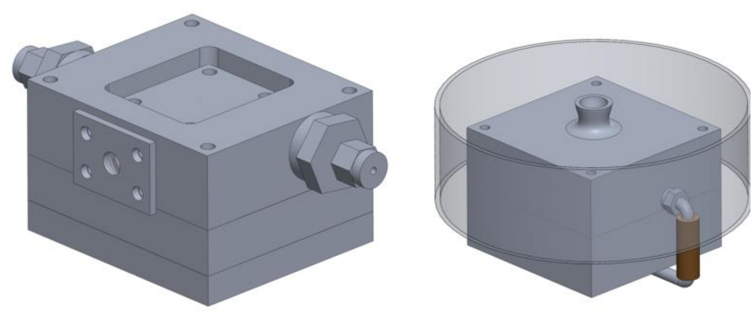
Figure 4. A block diagram representing the propellant flow system: blue denoting "cold" propellant, orange heated area, yellow heating coils, and red propellant flow lines. A microwave source and thruster head are shown for reference of system scale within a 1U volume.

Figure 4 represents a miniaturized and simplified system proposed at NASA Glenn for a water resistojet,[6] albeit with a secondary valve as opposed to an outlet. The NASA Glenn propulsion system is an 8-cm-long mechanism for vortical water heating, but its purpose of providing thrust makes it inherently more power-hungry; CuMET's feed system only needs to output high-quality steam. Based on the water resistojet's middle-point electrical efficiency of 4.25 MJ/kg, a ballpark for the power requirements of a water vapor feed system can be approximated. Maximum mass flow producing a plasma was measured to be 0.25 mg/s. Therefore, scaling the NASA Glenn system to CuMET flow rates gives a maximum power requirement of 1.05 W of heating applied to 0.25 mg/s of mass flow to the thruster head. While this number is relatively small, it is derived from empirical results for a wholly different system that did not include active control mechanisms and is not necessarily scalable down to our scale. However, single-digit watts as the heating requirement for the system is expected, since the ideal gas law points towards even lower energy requirements for achieving vaporization enthalpy for 0.25 mg of water.

A third component of thermal system development that is important is satellite thermal contamination from the CuMET system. While water vapor can be formed below 100 °C due to low flow system pressure, heating coils and the MET thruster head will not be limited to these temperatures. Many CubeSat payloads and components are not built for operation near 100 °C, and so shielding must be developed. One proposed method of shielding other delicate components from the hot thruster subsystem is the usage of the propellant tank as a heatsink for the system. Further development of this concept must be conducted, but benefits from being able to utilize regenerative heating to decreasing aggregate system heat loss between duty cycles, make it feasible as a preliminary concept.

C. System Integration to CubeSat Specifications

Bench models of the 17.8-GHz thruster have been designed for laboratory use and easy modification; the outside dimensions of the thruster head are 45 × 55 mm in width and length, and 35 mm in height. Although will fit within a 1U CubeSat volume, in does not optimize for volume. As the cavity is actually much smaller, significant reduction in volume is possible in a flight version; the key components—nozzle, propellant inlets, and resonant cavity—all easily fit within a <60 mm diameter. Thus, a concept of a miniaturized CuMET model is shown, compared to current bench models, in Fig. 5.



(a) (b)

Figure 5. Comparison of (a) benchtop 17.8-GHz thruster and (b) scaled-down design compared to the "tuna can" volume for a 3U CubeSat, including a sample nozzle.

The "CubeSat Cpec", which drives CubeSat modular system design, represents the boundaries within which a CubeSat must fit. Of note during the concept development of a CuMET-integrated system is the "tuna can" volume specified as usable depending on the deployer used and the CubeSat's location in it for 3U+ CubeSats. It is a 64-mm diameter, up-to-36-mm deep cylinder specified as available space for payloads such as deployables, sensors, and propulsion systems. Fig. 6 shows a mock-up of the miniaturized 17.8-GHz CuMET model placed within a 20-mm deep "tuna can" for reference, partially protruding into the 3U CubeSat bus below.

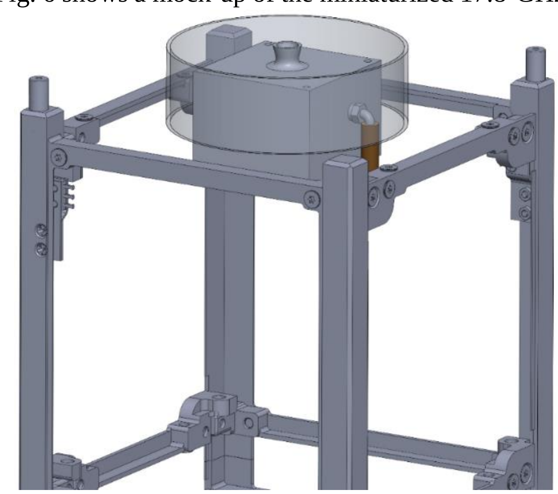


Figure 6. Sample of thruster placement within a CubeSat bus, occupying less than 1/10th of 1U of space. Structure courtesy of ISIS – Innovative Solutions in Space.

D. Power System Integration

As discussed in Section III.B, the power requirements for simply heating the propellant to a vapor and maintaining a storable liquid are non-negligible within a CubeSat mission. 3U CubeSats often have under 20 W of peak power unless deployable solar panels are used. The OSIRIS-3U mission should utilize roughly 1.5 W at idle conditions. The doubling of this number for passive heating of the propellant tank implies large changes in the power architecture requirements for implementing water propellant into a CubeSat.

Signal generation for the microwave system is a significant power draw component, and its miniaturization will be a driver for the viability of the mission. Contemporary nanosatellite projects using high-power microwave systems include the NASA JPL MarCO mission, which uses an X-band antenna for communication purposes.[17] However, the MarCO communication system uses minimal power to sustain its 8-

kbps link: CuMET requires up to tens of watts of microwave power for plasma formation, which could require as much as three times the input power to produce at the K-band. Experimentation is being done with a 30-W Ku-band miniature solid-state power amplifier (SSPA) by Sophia Wireless, which can produce similar power outputs to those desired for the mission with only ~50 W of input power. Internal volume of its components could fit within one third of a 1U volume.

The components within the SSPA only require ~70% of the total volume of the COTS system, and so there is a clear path towards decreasing the microwave system footprint in designing an in-house signal generation and amplification solution. Further, recent development of CubeSat-scale Ka-band traveling-wave tube amplifiers (TWTAs) might validate the development of a K-band TWTA for the 17.8-GHz thruster mission. These will be explored in the future, and the preliminary power budget assumes an SSPA at $\leq$50% efficiency.

Maximum microwave power delivery to the resonant cavity has been measured at 33 W.[13] However, typical start-up power requirements are between 2 W to 8 W, and sustained microwave power requirements are below 5 W. This produces a total microwave system power requirement of ~20 W. Combined with a ~10-W load from thermal management systems, 5 W to 10 W for supporting payload systems, and 10 W of total rest-of-the-bus power for subsystems such as guidance, navigation, & control (GNC) reaction wheels, the total system power requirement under maximum load adds up to 40+ W.

Assuming 30% efficiency solar panels, 40 W can be supplied constantly by 9.4U of solar panel coverage, which can be achieved with two longitudinally-deployed 3U solar panel arrays. However, this number could double to work around eclipse phase operations and desires to increase system tolerances. Table 2 summarizes the overall system power requirements.

Table 2. Power load ranges based on predictions of load requirements from preliminary mission systems as well as on components used in previous work.

Subsystem – Component	Power Draw (W)		
	Idle	Nominal	Maximum
Propulsion – Microwave source	Negligible	5–10	20
Propulsion – Tank heater	Negligible	2	5
Propulsion – Boiler	2	2	~5
GNC – Reaction wheels	<0.25	1	5
GNC – Magnetic torquers	Negligible	1–2.5	2.5
Science – Misc. payloads	Negligible	0–10	10
Critical bus systems (on-board computer, sensors, boiler system valves, TT&C components)	2	2–10	10

While the CuMET technology demonstrator approaches a 50-W-class CubeSat, this is not unprecedented in a 3U bus.[18] Further exploration of novel solar panel solutions must be conducted to approach desired power delivery, and a mission concept of operations must manage system energy carefully when developing a propulsion demonstrator.

The preliminary concept involves placing the SSPA and signal source within the envelope of the propellant tank: this could significantly decrease heater requirements during thruster operations due to thermal energy production of the microwave chain, but thermal output of these systems must be characterized before budgeting accounting these factors can occur.

IV.Summary and Future Work

An early concept of the CuMET's integration and implementation as part of a working CubeSat platform has been outlined. Design points for the development of an improved vaporization and vapor delivery system have also been determined, such that laboratory testing of a water CuMET may be done to adequately characterize water's behavior in the resonant cavity. A forced flow-through pump system and addition of increased insulation in the flow system should greatly increase efficiency in the system, as well as vapor quality and delivery. Moving forward, trades must be conducted on the balance of thermal and fluid-flow parameters in the vaporization system. Optimal fluid residence time for the production of a high-quality vapor will drive the specifications of stop-gap and filling valves populating the vaporization chamber.

Estimates for the total required system volume and power have been provided. The water CuMET's operational parameters fit within the accommodations of a 3U CubeSat bus. Mission profile as well as system architecture development will be integrated into an upcoming Penn State CubeSat mission.

The development of microwave power delivery systems at K-band that fit within the CubeSat form-factor, and space environment testing to validate proposed mission profiles that could support the technology demonstrator, will be key hardware development goals in the upcoming years. Integration of the system into a CubeSat bus will be done with the assistance of SSPL students, the aegis under which CubeSat development at Penn State is currently being conducted.

Acknowledgments

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