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VASIMR® Spaceflight Engine System Mass Study and Scaling with Power

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Mission planners require mass values of electric propulsion systems with scaling formulas as a function of input power in order to develop full spacecraft mass models and mission architectures. We develop a simplified model for a complete VASIMR® single-core spaceflight engine system called a TC-1. This model is valid in the power domain of 50 to 250 kW and maintains variable specific impulse control over the range of 3000 to 5000 s using argon propellant at a selected constant total power. The model is based on commercial and laboratory hardware, detailed designs, and parametric modeling. The resultant model for the specific mass, $\alpha = A + B/P_e$, is a simple inverse linear relationship with a constant component, $A = 1.2 \pm 0.1$ kg/kW, and a fixed mass component, $B = 444 \pm 44$ kg, divided by the input electrical power, P_e [kW]. The system α ranges from 10 ± 1 down to 3 ± 0.3 kg/kW with 50 to 250 kW, respectively. If a fixed I_{sp} is selected at 5000 s, α is as low as 2.7 ± 0.3 kg/kW at 250 kW.

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Nomenclature

A_{sys}	=	mass scaling, TC-1 system [kg/kW]	m_R	=	radiator areal mass [kg/m^2]
A_{RF}	=	mass scaling, RF PPUs [kg/kW]	N_s	=	number of radiator sides [1 or 2]
A_{TM}	=	mass scaling, Thermal Mng. [kg/kW]	P_e	=	Input electrical power [kW]
B_F	=	fixed mass, TC-1 system [kg]	PM	=	Propellant Management
B_{RC}	=	fixed mass, RC [kg]	PMEM	=	PM electronics module
B_{RF}	=	fixed mass, RF [kg]	PPU	=	Power Processing Unit
B_M	=	fixed mass, HTS Magnet [kg]	Q	=	thermal power [kWt]
B_{TM}	=	fixed mass, TM [kg]	R	=	ICH to HEL power ratio
B_{PM}	=	fixed mass, PM [kg]	RC	=	Rocket Core
$B_{C\&DH}$	=	fixed mass, C&DH [kg]	RF	=	Radio Frequency
CAD	=	Computer Aided Design	TC-1	=	Single VASIMR® Thruster Core engine system
C&DH	=	Command and Data Handling	TM	=	Thermal Management
COTS	=	Commercial Off the Shelf	T_R	=	radiator temperature [K]
EP	=	Electric Propulsion	TRL	=	Technology Readiness Level
HEL	=	Helicon plasma stage	VF	=	VASIMR® Flight model
HTS	=	High-Temperature Superconducting	VFCM	=	VASIMR® flow control module
ICE	=	Integrate Cooling and Electrical	VX-200	=	VASIMR® Experiment 200 kW
ICH	=	Ion Cyclotron Heating plasma stage	XFCM	=	Xenon flow control module
I_{sp}	=	specific impulse [s]	α	=	specific mass [kg/kW]
M	=	mass [kg]	α_{VF}	=	specific mass for the TC-1 VASIMR® flight system [kg/kW]
MLI	=	Multilayer Insulation			

I. Introduction

THE VASIMR® VX-200 laboratory engine has produced a large body of performance data, completing more than 10,000 high power pulses at up to 200 kW.[1-3] Recently, the work has led to a measurement of thruster performance over a broad range of specific impulse (*Isp*).[3] The solid-state radio frequency (RF) generators' (built by Nautel Ltd) total efficiency exceeds 95% for DC to RF power conversion. The thruster efficiency (RF power to jet power) is over 60% at or above an *Isp* of 3,000 s using argon propellant.[3] Even when including laboratory conventional superconducting magnet cryocoolers and other auxiliary laboratory power systems, totaling approximately 10% of the power, the system efficiency is competitive. A model for system efficiency using krypton propellant predicts similar efficiency shifted to a lower *Isp* range, ~2,000 s.[3]

Detailed mapping of the plasma plume has been accomplished at a power level of 100 kW in a volume extending more than 2 m downstream of the exhaust exit, without significant neutral background interaction. This has led to a compelling demonstration of how the plasma effectively flows away from the magnetic nozzle of a VASIMR® type device.[4,5]

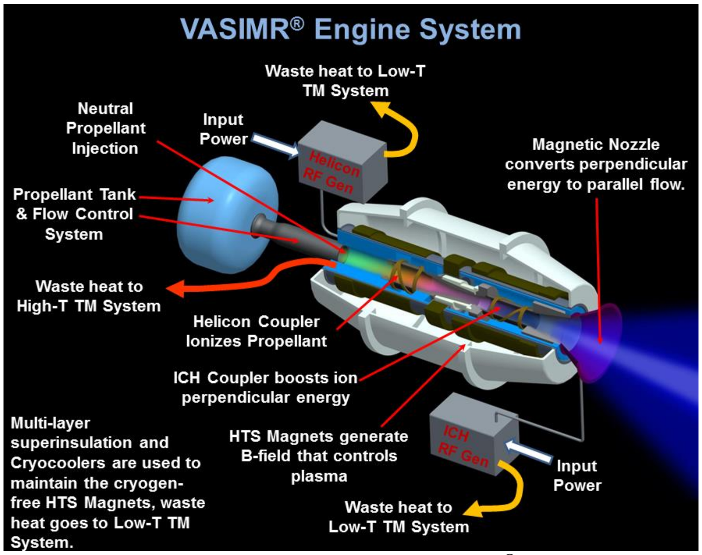

Figure 1. Schematic diagram of a VASIMR® system

An important factor for the practical implementation of a VASIMR® engine for spaceflight is the effective system specific mass (α, kg/kW) and the scaling of α with power. Application of modern technologies (superconductivity, solid-state power components, advanced materials and modern heat rejection) enables such a system to achieve competitive system alphas in a power range near 100 kW, as compared to existing flight EP systems.[7-11] Analysis points to significant improvement at higher power levels.[12]

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There are many studies detailing the masses and estimates for highly developed electric propulsion systems.[7-10] More recent work has performed a parametric study with a focus on the individual thruster elements at power levels less than 50 kW,[13] while in the past there are studies at much higher powers.[14] Following such work, this paper endeavors to perform a mass estimate for a VASIMR® thruster element, called TC-1 that is now in the preliminary design phase, in the power domain of 50 to 250 kW. We use a combination of techniques including: bottom-up accounting from detailed designs, similarity, and parametric modeling.

II. VASIMR System Description

A VASIMR® engine is a two-stage RF driven magnetized plasma rocket. The first stage is a helicon-type plasma source and is referred to as HEL in this paper. The second stage uses ion cyclotron resonance to efficiently couple RF power into ion kinetic energy and is referred to as ICH in this paper. Detailed descriptions of a VASIMR® engine function have been included in many previous papers;[15,16] therefore, we will not go into further detail here. Two major elements of a VASIMR® engine are the RF power processing systems and the high magnetic field enabled by state-of-the-art superconducting magnet technology. The unique element of the VASIMR® technology resides down the bore of the magnet and we refer to this as the Rocket Core (RC). This is where the electromagnetics and structure of the system are carefully designed to couple with the dense magnetized plasma to achieve the desired function of the rocket.

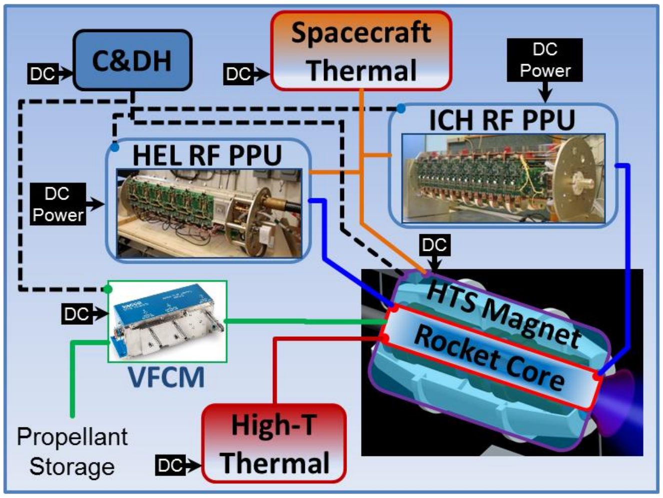

Figure 2. Block diagram of a TC-1 system, showing major systems used in the mass estimate.

A complete single rocket core thruster system is referred to as a TC-1. A VF-200™ engine[2] is a specific embodiment of two TC-1 cores with opposing magnetic polarity clustered such that they form a magnetic quadrupole. This nulls any torque in earth's magnetic field and greatly reduces any stray magnetic field strength around the spacecraft. Since this clustering is a mission specific integration of two TC-1 thrusters, this paper focuses on the mass estimate and scaling for only a complete single rocket core TC-1 thruster system.

A VASIMR® TC-1 thruster comprises six basic systems: 1. Rocket Core (RC); 2. RF Power Processing, including both helicon (HEL) and ICH RF generators with impedance matching; 3. High Temperature Superconducting (HTS) Magnet; 4. Thermal Management (TM), including spacecraft heat rejection (~ 35 °C) and high temperature heat rejection (~ 250 °C); 5. Propellant Management (PM); and 6. Command & Data Handling (C&DH). Figure 2 contains a simplified block diagram of a VASIMR® TC-1 system. For comparison to traditional EP systems: the magnet, rocket core, and high temperature management systems together are analogous to the thruster — while the RF power processing systems are analogous to the Power Processing Units (PPU).

III. Mass Model

We develop a linear mass scaling model where large portions of the TC-1 system mass are fixed assets that enable the efficient function of the VASIMR® engine system. We restrict the domain of the total input electrical power (P_e) from 50 to 250 kW, where the VX-200 performance data and plasma physics models are accurately extrapolated. In this power domain, there is little gain in scaling the size of the rocket core or HTS magnet, though would raise risk. Therefore, these two systems are the primary components of the fixed assets. On the other hand, the RF and thermal managements systems can readily scale with input power, with some fixed overhead, so are primary component in a mass that scales with input power. The PM and C&DH systems are small fixed mass elements that enable function, which would not grow significantly in a clustering scenario.

With this linear mass model, the mass of a TC-1 VASIMR® flight system (M_{VF}) scales as the following,

$$M_{VF} = A_{sys}P_e + B_F \tag{1}$$

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where A_{sys} represents system components that scale with input power and B_F represent the fixed asset components. To assess a system alpha (α_{VF}), we simply divide this Eqn. 1 by P_e and arrive at the following,

$$\alpha_{VF} = A_{sys} + \frac{B_F}{P_e} \tag{2}$$

Again, this scaling is only applicable for a single-core VASIMR® TC-1 engine system. Clustering effects that are mission specific are not considered in this model. The reader may note that the parameter *A* and *B* are similar in definition as in previous work.[13]

The following subsections describe the basis of estimate for the parameters *A* and *B* by TC-1 subsystem. The resultant total system values are just summations of all the subsystems.

A. Rocket Core

The TC-1 rocket core is a fixed mass system that combines the RF power with propellant to produce the plasma and then accelerate it. Plasma facing components are ceramic materials that are magnetically insulated from the plasma. The rocket core is cooled by integrated cooling and electrical (ICE) jackets. The rocket core has no moving parts other than the cooling fluid flowing inside the ICE jackets. Heat load estimates are based on infrared camera and infrared sensor data obtained during operation of the VX-100 and VX-200 devices between 2007 and 2011. Thermal requirements are met by increasing the cooling fluid flow with increasing system power for efficient operating modes of the rocket between 3000 s and 5000 s of specific impulse using argon propellant. Within this efficient band of operation, Dittus-Boelter[17] heat transfer analysis indicates that system power levels of up to 250 kW or more can be handled per TC-1 core with an average heat rejection temperature of up to 280° C. Pressure drop analysis has been performed using an effective length to diameter ratio as measured from an engineering prototype and von Karman analysis.[18] Manufacturing tests of a prototype rocket core are underway in support of the critical design for the rocket core system. Detailed CAD modeling and engineering prototypes determine that the fixed dry mass of the TC-1 rocket core system is 70.5 kg. Cooling fluid in the channels of the design is estimate as 6 kg. MLI is required to protect the bore of the superconducting magnet from the hot core and this weight is estimated as 5 kg. The total fixed mass is $\boldsymbol{B_{RC}}$ **= 82 ± 4 kg**.

B. RF Power Processing (PPU)

Modern solid-state RF broadcast technology has reliably operated in the custom developed experimental RF generator units (Nautel Ltd. models VX-200-1 and VX-200-2) for over 5 years. They have accomplished tens of thousands of varying pulsed conditions, which is harsh for power electronics. We refer to the two units that drive the rocket as RF generators for the HEL and ICH stages of the device. We maintain a name distinction from the generic PPU term to distinguish these units because they are simpler than traditional PPUs that perform DC-to-DC voltage conversion. The RF generators use single-stage converter modules that switch incoming DC power to RF and then combine RF power using a robust inductive technique that provides inherent redundancy, and naturally isolates solid-state switching components from the high-voltage load. The laboratory RF generators' are lightweight ($\alpha \approx$ 0.6 kg/kW) and actively cooled with fluid.[1] The generators alone do not comprise the entire RF Power Processing system. We must also account for impedance matching circuitry, excess power capacity to achieve variable specific impulse, enclosures, transmission lines, and sensors. We account for these extra details in this mass estimate.

Since the development of the VX-200 RF generators in 2007, there have been significant advancements in RF component technology. For example, Cree, Inc. now produces RF products using GaN on silicon-carbide substrates that provide higher efficiency and power density. In addition, silicon-carbide enables higher temperature operation, though implementing a 3rd pumped loop to support ~100° C cooling for the RF generators does not seem to pay off in terms of mass, unless a TC-1 is running close to 300 kW of system power. In terms of volume, there may be volume savings associated with implementing a 3rd pump, if volume in the fairing is an issue, and the mass penalty is not too big. For this study, we assume the RF generators do not run at elevated temperature, so the generators are cooled on the same thermal system as the spacecraft electronics. However, we do assume a modest efficiency gain (from 91 to 94%) for the HEL RF generator, since it operates at a much higher frequency than the ICH system and will benefit the most from the silicon-carbide innovation of the past 5 years.

The RF generators combine multiple power modules to provide the total required power. The HEL RF generator processes approximately 2 kW per module and the ICH RF generator processes 10 kW per module. The power capability of the RF generator units simply scale by changing the number of modules, and thus the mass is

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optimized to the application. To parameterize the mass scaling with power, we use the actual weight of the operating units and scale the weight by the number of modules and include a fixed overhead mass. To account for the RF technology innovation as describe above and further optimization from the first generation models, we reduce the mass scaling of both RF generators by 10% from that based on the existing units.

RF power processing is not complete without impedance matching. Impedance matching techniques using fixed capacitor technology can efficiently (~ 99%) couple the RF power into the RC load. RF losses in the core before coupling to the plasma result in heat on the high temperature system and are accounted for in the RC subsytem. Vacuum capacitor technology as produced by Jennings Technology or COMET Technologies, along with careful circuit design leads to very little loss for the HEL impedance matching system. At the lower frequency of the ICH system, mica capacitor technology has a high efficiency and packaging factor. We estimate the mass of impedance matching by performing bottom-up accounting with COTS capacitor components rated for this application and hardware to assemble the circuits. Sensors are estimated by weighing laboratory models.

To complete the RF systems, we account for the mass of the power transmission from the RF generators to the load. This is analogous to the high voltage cabling in the traditional EP systems.[13] We base the mass of this element by using oversized COTS coaxial components, such as those produced by Myat, Inc. For mass consideration, we assume that the coaxial transmission line will be made from aluminum. This element of the system is highly efficient and the lower frequency of the ICH system gives rise to higher power handling capability of the same line as used in the HEL system.

Lastly, to achieve variable specific impulse the TC-1 must carry excess power processing capability in each RF system. We account for this factor by sizing the HEL system for operation at the lowest desired I_{sp} and the ICH system at the highest I_{sp}. Variable I_{sp} in this case is achieved by changing the ratio of the ICH to the HEL power, $R = P_{ICH}/P_{HEL}$, while also optimizing the propellant flow.[3] The summary RF power mass scaling parameter, A, is a power weighted average of the two power processing systems. For the case of argon propellant and the I_{sp} range of 3000 to 5000 s, the power ratio spans R_{min}= 2 to R_{max} = 6, respectively, as measured from VX-200 data.[3] This gives rise to the power weighted average formula of

$$A_{RF} = \frac{1}{(1+R_{min})} A_{HEL} + \frac{R_{max}}{(1+R_{\max})} A_{ICH} \tag{3}$$

and the fixed mass components, independent of the power level, simply sum.

Table 1 summarizes the scaling factors for the RF power processing system based on detailed spreadsheets incorporating all the factors described in this section. The result for the RF system is $\boldsymbol{A_{RF}}$ **= 0.8±0.1 kg/kW** and $\boldsymbol{B_{RF}}$ **= 63 ± 6 kg.**

C. High-Temperature Superconducting (HTS) Magnet

High temperature superconductor technology has made tremendous gains in the past decade and is now rapidly advancing second generation (YBCO) tape, e.g. SuperPower® Inc. The current carrying performance of the tape already exceeds that needed to build a practical magnet with a field strength as high as the conventional low temperature magnet of VX-200 (~ 2 T). This innovation enables the use of low power, lightweight cryocoolers, such as Sunpower® Inc CryoTel® models. The conduction cooled, cryogen-free, VX-200 magnet has operated reliably for more than 11,000 hours showing that such a system is robust. The following is a description of the analysis to estimate the mass of a single HTS magnet system.

The HTS winding geometry is based on the TC-1 magnetic field profile specification and wire current-carrying capability. Based on the dimensions of each coil and using a mass density based on the SCS12050 superconducting tape with 40 μm of total copper thickness, a mass of 64 kg for the windings is assessed from the CAD and parametric model calculations. This mass represents a conservative estimate, since the detailed construction will include additional materials like Kapton® insulating tape, aluminum thermal buses and epoxies, which have lower mass densities than the superconducting tape. Also, HTS tape performance has been rapidly improving with time.

The coils' mandrel and supporting accessories' mass is calculated by using aluminum 6061-T6 and titanium Ti-5Al-2.5Sn alloys with a density of 2710 kg/m3 and 4484 kg/m3 respectively, and assigned to the appropriate parts of a CAD model. The selection of the 6061-T6 aluminum alloy is based on its previous usage in a wide range of applications, including cryogenic applications requiring strength. The Ti-5Al-2.5Sn titanium alloy is well suited to cryogenic applications.[19] This material selection is also important for heat transfer purposes.

A structural finite element analysis was performed in order to explore the inertial stresses caused by axial accelerations present during launch on a Falcon 9 rocket.[20] These axial accelerations could reach 6g levels during that flight phase. None of the coil support components showed stresses leading to failure. This result serves the

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purpose of validating the previous mass estimations, and parametric studies determine an acceptable safety factor, including lateral 3.5g accelerations as a potential worst case. Further mass reduction efforts, while maintaining the thermal conduction performance of the elements, are being scheduled as future work

The cryostat mass estimations were performed by using the mass density of 6061-T6 aluminum alloy and the geometry data from the CAD model. The cryostat structural evaluations included the simultaneous 6g axial launch inertial forces and external pressure forces (due to cryostat vacuum) at an external pressure level of 1 atm. None of the components showed stress levels exceeding the yield strength of the aluminum alloy, with a failure index of 0.55 on the most critical parts and using the Distortion Energy (Von Mises) criterion.

The cryocoolers' weight were estimated by using vendor information, and weighed laboratory models. Cryogenic thermal analysis has identified the need for 6 cryocoolers on one TC-1 system. This includes redundant cryocooler units for reliability.

Table 1 summarizes the scaling factors for the HTS Magnet system based on analysis described in this section. The total fixed mass for the HTS Magnet system is $\boldsymbol{B_M}$ **= 199±20 kg**.

D. Thermal Management

An engineering trade study has been performed concerning the total mass and volume of all of the heat rejection systems, and considering risk for manufacturing and reliability. The thermal management analysis presented here is based on two pumped loop systems. The spacecraft loop that cools the cryocoolers, RF PPUs and auxiliary systems, runs with an average radiator temperature of approximately 35° C, limited by the thermodynamic efficiency of the Sunpower® cryocoolers. The design for the rocket core allows it to be cooled with average radiator temperatures as high as 280° C, although trade-offs in temperature can impact material choices with impact on manufacturing risk. The analysis shows diminishing returns from running the rocket core significantly above 200° C. Choosing the average temperature of the rocket core pumped loop system at 250° C significantly broadens the material choices for the rocket core subsystem and high temperature radiator.

The present baseline TC-1 design for this study uses one pumped loop to first cool the cryocoolers/spacecraft and then cool the RF Power Processing (PPU) system with an average heat rejection temperature at the radiator of **35° C**. As a lower risk approach, the baseline rocket core heat rejection temperature is **250° C** for this study.

The following describes the process in this analysis. The relationship for the mass scaling of each pumped loop heat rejection system is assumed to be linear as follows:

$$M_{plj} = M_{fj} + \left[\alpha_{pl} + \frac{m_R}{N_s \eta_{Rj} \sigma T_{Rj}^4}\right] Q_{Rj} \tag{4}$$

where M_{plj} is the mass (kg) of the jth cooling loop support system, M_{fj} is a fixed mass (kg) associated with the pumping and radiator infrastructure needed to support the jth loop, α_{pl} is the specific mass (kg/kWt) associated with the work that must be done to pump the cooling fluid, m_R is the areal mass of the radiator (kg/m^2), N_s is the number of sides for the radiator (1 or 2), η_{Rj} is the efficiency of the radiator including emissivity and effective view effects, σ is the Stefan-Boltzmann constant, T_{Rj} is the radiator temperature (K), and Q_{Rj} is the thermal power (kWt) that must be transferred to the radiator for rejection to space. If the fluid loop temperatures are compatible with the parts to be cooled, then multiple loops can share pumping infrastructure.

The heat to be rejected and temperature requirements depend on the parts that are being cooled. Cryocoolers must be cooled below approximately 35° C to maintain high efficiency. The heat load from electronics is relatively small and compatible with 35° C cooling, so it makes sense to combine the electronics and cryocoolers into a single pumped loop at 35° C. The existing RF generators (TRL-5) can be very effectively cooled at ~35° C, and they can tolerate somewhat higher temperatures. Modern silicon-carbide power modules are commercially rated to operate with cooling temperatures as high as 125° C, although perhaps with some loss of efficiency. The RC loop has the most waste heat, and is designed to operate at temperatures as high as 280° C to allow that heat to be removed efficiently. However, the mass and volume advantages offered by operating the RC loop above 250° C should be traded against the increased risk associated with manufacturing because of the restrictions that higher temperature operation places on the materials and fluids that can be used in the RC loop.

The results presented here assume that the infrastructure fixed mass, M_{pfj}, is 25 kg if a dedicated pumping system is required for the loop, or zero if the loop can be added to an already existing pumping system. Additional assumptions are: α_{pl} = 0.26 kg/kW$_t$, m_R = 4 kg/m^2 based on modern radiator designs[14], N_s = 2 , and η_{Rj} = 0.75. Q_{rRF} is 4% of the TC-1 system input power based on RF system efficiency, and the RC heat load, Q_{rRC}, is 21% of the TC-

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1 system input power based on VX-200 data, and the spacecraft (SC) heat load, Q_{rSC}, is fixed at 2 kW independent of the system power level.

Table 1 summarizes the scaling factors for the thermal management system based on analysis described in this section. The result for the thermal management system is $\boldsymbol{A_{TM}}$ **= 0.4 ± 0.04 kg/kW** and $\boldsymbol{B_{TM}}$ **= 61 ± 6 kg**.

E. Propellant Management

Propellant storage and delivery are two important system level functions on any spacecraft. For spacecraft involving electric propulsion, propellant storage is a mission specific system that includes storage vessels, valves, transducers, and regulators. Mission specific components are out of the scope of this mass scaling study. The mission independent components of the propellant management system are designed to accept a feed gas from the propellant supply (up to a pressure of 3000 psig) and deliver a precise flow rate to the rocket core. These include redundant, internally and series, flow control modules, control electronics, and generalized flow system hardware (i.e. tubing, standoffs, cable/connectors, etc.). The design of the flow control modules involves concepts from earlier electric propulsion propellant flow studies done by NASA GRC and the use of the xenon flow control module (XFCM) fabricated by VACCO Inc. The VASIMR® flow control module (VFCM) is a pressure manifold where gas, up to 3000 psig, is filtered and split into parallel paths. A micro-latch valve (MiLV) serves to isolate flow ahead of a piezoelectric control valve (PCV) which regulates the gas pressure immediately downstream. This regulated pressure, upstream of a passive flow control device (e.g. orifice), governs the amount of propellant delivered to the rocket core. The propellant management electronics module (PMEM) communicates with each VFCM by providing control voltages while receiving analog signals in return and digitally communicates the system status back to the main command and data handling system.

A mass estimate was performed on the mission independent components. The mass does not directly scale with input rocket power, but will grow with the addition of more rocket cores as more VFCMs will be needed to provide redundant flow. The mass of a single VFCM is 1.2 kg based on similarity to the actual mass of the XFCM. A single unit is used on a TC-1 system up to 250 kW. The PMEM has the highest uncertainty for this system having a mass of 7±3 kg. The mass of a flight-like AiTech E900 onboard computer was used to provide a conservative baseline estimate for the PMEM. Tubing (0.25” SS316), fittings, standoffs, and mount hardware combine for 6.5 kg. Connectors, cabling, and kapton heaters make up the rest of the mass of the system (5.0 kg). The connectors are multipin circular MIL-DTL-38999 Class III space rated connectors whose masses were provided by the manufacturer (Amphenol and ITT-Cannon). Cable bundles are composed of individual stranded conductors of nickel plated copper (MIL-C-22759/12) adhering to MIL-C-27500 standards. A mass per unit length formula, from MIL-C-27500, was used to estimate the weight of each cable bundle and is based on a number of parameters (e.g. number of conductors, amount of shielding, jacket material, etc.). The total propellant system mass is then $\mathbf{B_{PM}}$ **= 20 ± 3 kg**. Changes in hardware layout or electronics are expected to have a negligible effect on the mass of this system. Doubling the number of rocket cores and allowing for sufficient redundancy and mass reserve raises the system mass to only 25.3 kg.

F. Command and Data Handling

For completeness, we include controlling computer and electronics with cabling. This component is a small fraction of the total mass, though we account for it since the TC-1 system will require control management to monitor the multiple systems and accomplish optimal performance over the desired I_{sp} range. Again, mission specific clustering, or relying on a spacecraft computer, will likely effect this mass component, so the level of detail for this estimate is minimal. We rely on similarity to a commercially available control system by AiTech, models E900 and S950, used in VX-200. We estimate the cabling by considering the number of systems. The total mass for the C&DH system is estimated as $\mathbf{B_{C\&DH}}$ **= 20 kg**.

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Subsystem	Basis of Estimate	*A* [kg/kW]	*B* [kg]	*P* proc [kW]	*M* [kg]
Rocket Core	Mass independent of power		**81.5**	**95**	**81.5**
Dry structure	Detailed CAD design, VX-200SS		70.5		
Cooling fluid	Calculated from channel volumes		6.0		
MLI	Block heat to the magnet bore		5.0		
RF Power (PPUs)	Power weighted average enabling the Isp throttle range.	**0.8**	**62.7**	**98**	**144**
Helicon (HEL)		**1.1**	**25.4**	**33**	**60.1**
RF Generator	Scaled from Nautel model VX-200-1 upgraded to modern power components	0.8	11.9		
Impedance Matching	Design with COTS capacitors	0.2	11.1		
Transmission Line	Aluminum 50 Ω hard line	0.1	1.1		
Sensors and control	Weighed lab models		1.3		
ICH		**0.5**	**37.3**	**84**	**82.5**
RF Generator	Scaled from Nautel model VX-200-2 upgraded to modern power components	0.4	16.6		
Impedance Matching	Design with COTS capacitors	0.1	18.3		
Transmission Line	Aluminum 50 Ω hard line		1.1		
Sensors and control	Weighed lab models		1.3		
HTS Magnet	Mass independent of power		**199**		**199**
Windings	Calculated using SuperPower® windings		64.1		
Mandrel	Mechanical model		28.2		
Cryostat	Simplified mechanical model		58.4		
Structure&MLI	Struts, and insulation		3.1		
Cryocoolers	Sunpower® GT models, qty 6, with controllers		25.4		
Power Supply	Weighed lab model with spare		20.0		
Thermal Management	Scales with power	**0.4**	**61.2**	**26.4**	**101**
Spacecraft Temperature ~35 °C	Modern spacecraft radiator	**0.24**	**36.2**	**5.3**	**59.9**
Cryocoolers, electronics, etc.	Overhead mass to support magnet, electronics, etc. Includes pump.		36.2	2.0	36.2
RF PPU	Power depedant addition to spacecraft	0.24		3.3	23.8
High Temperature ~250 °C	Scaled with T^4. Includes pump.	**0.17**	**25.0**	**21.2**	**41.5**
Propellant Management	Fixed mass		**19.7**		**19.7**
VFCM	Based on Vacco XFCM		1.2		
Valves, fittings & tubing	Bottom-up list of components		3.8		
Electonics and cabling	Similarity and MIL spec components		11.6		
Mounting Hardware	Bottom-up list of components		3.1		
C & DH	Traditional spacecraft control		**20.0**		**20**
Interface computer	Base on AITech E900 and S950		10.0		
Distributed electonics and cables	Esimate from the number of systems		10.0		
	Total	**1.22**	**444**	**100**	**566**

Table 1. Mass breakdown by system with scaling factors valid in the P_e domain of 50 to 250 kW and an I_{sp} range of 3000 to 5000s with argon. Reference point values for an input power level of 100 kW are included in the two right columns.

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IV. Results and Discussion

All of the system parameters described in the previous section are combined into resultant system values for Eqn. 2. Table 1 summarizes all values for the subsystems and combines them. This table is generated from a variety of spreadsheets that account and calculate the individual values for subsystem components. We show extra significant digits, beyond the uncertainty, in the table to check for consistency and we only reported rounded values in the previous section, with estimated uncertainty. The combined system alpha for a TC-1 capable of 50 to 250 kW and an I_{sp} range of 3000 to 5000 s is as follow,

$$\boldsymbol{\alpha_{VF} = 1.2 \pm 0.1}\ \text{kg/kW} + \boldsymbol{444 \pm 44}\ \text{kg}/\boldsymbol{P_e} \tag{5}$$

In Table 1, we also include two columns on the right for the specific case of 100 kW. This is convenient because then the power values are the same as percentage values. Processed power for each system is reported. This value is the power that that particular system processes. The following description steps through the power processing for 100 kW. First, the base overhead systems of electronics and HTS magnet cooling consume 2 kW and the thermal management system must process that power to reject it. This leaves 98 kW of electrical power for the RF generators to process and then of that power, 94 kW is processed by the RC system to make and propel plasma. In the RC system, 21 kW of power is generated as waste heat and must be processed and rejected by the high-T thermal management system. For the 100 kW case, the system alpha is 5.7 kg/kW.

The system alpha rapidly reduces as the power increases, since the fixed mass term, *B*, dominates Eqn. 5. Only at the upper power level of **250 kW** do the two terms become almost equal. At this level, the system alpha becomes **3.0 ± 0.3 kg/kW**. Figure 3 shows system alpha scaling using Eqn. 5.

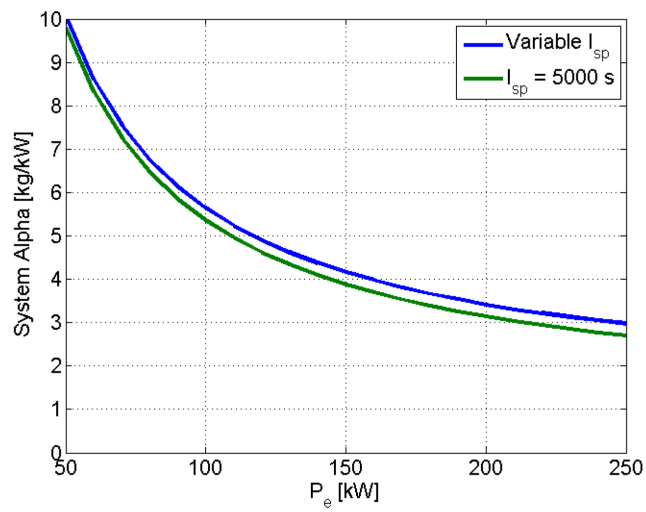

Figure 3. Plot of α_{VF} for variable and a fixed I_{sp} at 5000 s.

This scaling maintains the capability of variable specific impulse for a broad range. If the system were optimized for a fixed mission specific I_{sp}, the system alpha will be reduced. For the fixed case at I_{sp} = 5000 and 100 kW, the system alpha is 5.4 kg/kW. The primary effect is that the TC-1 does not have to carry as much HEL RF power processing capability, and the ICH stage is much more efficient, so there is less waste heat for the high-T system to reject. Since these systems are relatively mass efficient, the mass difference to achieve variable specific impulse turns out as a small factor, only about a 5% effect. At 250 kW, it is a more pronounced effect, though still only a 10% mass change to achieve the variable specific impulse. The additional power processing capacity installed for variable specific impulse operation naturally offers redundancy and mission flexibility, with a minimal mass penalty.

V. Conclusion

We have completed a study to estimate the mass and alpha of a complete VASIMR® single-core spaceflight engine system, called a TC-1. The power domain is 50 to 250 kW and variable specific impulse, I_{sp}, capability at constant total power is enabled over the range of 3000 to 5000 s using argon propellant. The estimates are based on detailed designs, parametric modeling and performance measured with VX-200 hardware. This same system would likely run krypton propellant and efficiently extend operation down to I_{sp} = 2000 s. The system alpha ranges from 10 down to 3 kg/kW for 3000 s to 5000 s, respectively. For fixed I_{sp}= 5000 s, the alpha is as low at 2.7 kg/kW at 250 kW, also showing that the added mass needed to enable variable specific impulse is less than a 10% impact.

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