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Development Toward a Spaceflight Capable VASIMR® Engine and SEP Applications

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Extensive testing using the VASIMR® VX-200™ experiment at power levels up to 200 kW has established system DC-to-jet power performance while the injected-gas and plasma operated in steady-state conditions. The thruster efficiency, using argon propellant, ranges from 60% to 72% in the I_{sp} domain of 3000 to 5000 s. These tests were performed using highly efficient (~ 95%) and light-weight (< 1 kg/kW) solid-state RF power processing units built by Nautel, Ltd and a cryogen-free superconducting magnet. Detailed mapping of the plasma plume over a large scale length (> 2 m) and low background pressure (< 2×10^{-4} Torr) has revealed plasma detachment from the system. A recent study has evaluated that a system alpha in the range of 3 kg/kW at high power (~ 250 kW) is achievable with existing technology. A benchmarked physics-based model predicts further improvement in efficiency with argon and efficient (~ 70% system) krypton propellant operation extending down to an I_{sp} of 2000 s. Efficient operation and mass performance is competitive with Hall effect thruster technology at power levels of 50 kW and improves with increasing power. With the physics of the electrical and plasma power flow demonstrated and understood, a progressing effort is to demonstrate the operation in thermal steady-state and long duration testing (> 100 hours). With thermal measurements from VX-200™ and fluid flow analysis, an active high-temperature (> 200° C) thermal control system meets the power density needs to readily operate a single core VASIMR® system at up to 250 kW. This paper reviews the state-of-the-art of VASIMR® technology and describes activities toward testing a spaceflight relevant system in steady-state, a program named VX-200SS. With a thermal solution in hand, the elements of a VASIMR® system are ready for a straight forward progression to spaceflight. Such a system has many exciting applications using a VASIMR® Solar Electric Propulsion (VASIMR®-SEP) spacecraft, such as cislunar cargo, orbital servicing and debris removal, orbital reboost, asteroid redirection, deep space missions and others.

Nomenclature

A_{TC1m}	=	variable mass scaling for a TC-1m
B_{TC1m}	=	fixed mass for a TC-1m
HEL	=	Helicon plasma stage
ICH	=	Ion Cyclotron Heating plasma stage

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I_{sp} = specific impulse
jet-α = specific mass divided by system efficiency
PPU = Power Processing Unit
RF = Radio Frequency
TC-1 = Single VASIMR® Thruster Core engine system
TC-1m = Single VASIMR® Thruster Core engine system, "mini"
VX-200 = VASIMR® Experiment 200 kW
VX=200SS = VASIMR® thermal steady-state experiment
α = specific mass
η_{Vsys} = VASIMR® system efficiency
η_{Hsys} = Hall effect thruster system efficiency

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, 2, 3] Recently, the work has led to a measurement of thruster performance over a broad range of specific impulse (I_{sp}).[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 I_{sp} of 3,000 s and over 70% at or above an I_{sp} of 5,000 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 with other EP technologies. For applications requiring higher thrust, our model for system efficiency, using krypton propellant, predicts similarly efficient operation in the ~2,000 s I_{sp} range.[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]

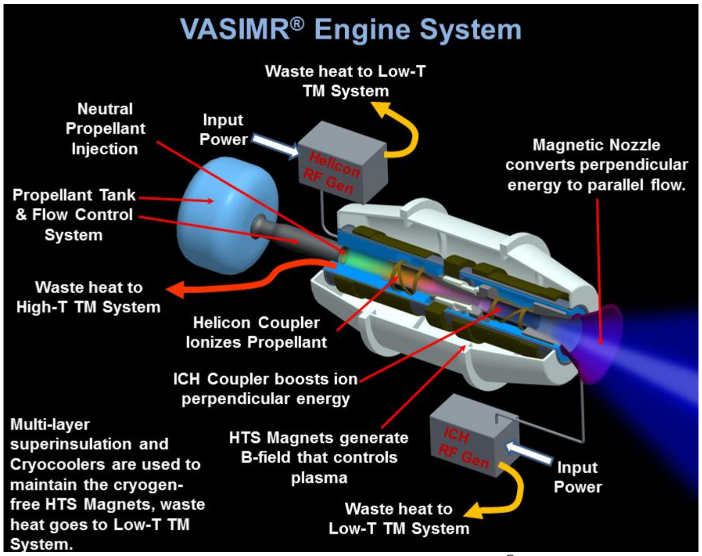

Figure 1. Schematic diagram of a VASIMR® system

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 a competitive system α in a power range above 50 kW, as compared to existing flight EP systems [5,6,7,8,9]. Analysis shows significant improvement at higher power levels where α is below 3 kg/kW for a complete thruster string system [10].

In this paper, we review the elements and power scaling of a VASIMR® system and then describe how a detailed physics-based model, benchmarked against experimental data, predicts improved performance for the next design iteration that could be readied for spaceflight testing. By comparing VASIMR® propulsion system scaling to the state-of-the-art Hall effect thruster systems, we find that at a power level of about 50 kWe the transition to VASIMR®-SEP type systems is more advantageous. This advantage becomes increasingly compelling at the higher power levels (~100 kWe and higher) relevant to Mars exploration.[11] We describe testing plans to demonstrate long duration operation of a VASIMR® system. Finally, we briefly point out a few near term applications using solar electric power.

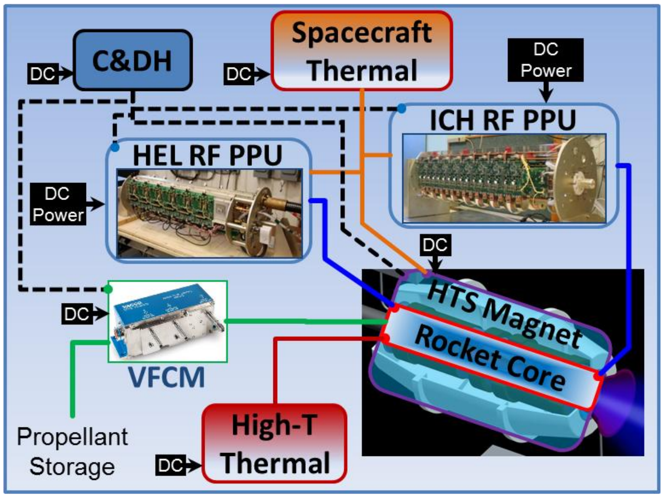

Figure 2. Block diagram of a TC-1 system, showing major systems.

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 several previous papers[12, 13]. Four major elements of a VASIMR® engine are: the RF power processing units (PPU), the high magnetic field enabled by state-of-the-art superconducting magnet technology, the thermal management, and the rocket core. The Rocket Core (RC) element resides down the bore of the magnet and is designed to utilize the RF power in conjunction with the high magnetic field to create and accelerate a high power-density plasma stream and manage any waste heat from the process. The RF PPU is based on a robust and highly efficient single-stage power amplifier design. These have heritage in the radio broadcast industry, and have been proven to full power operation in the VX-200 system. High temperature superconducting magnet technology is progressing rapidly and is ready for this application.

A complete single rocket core thruster system, such as the VX-200 laboratory prototype, is referred to as a TC-1. A VF-200™ (flight-class) engine[2] is a specific clustering of two TC-1 cores with opposing magnetic polarity, forming a magnetic quadrupole. This clustering nulls any torque induced by the Earth's magnetic field and greatly reduces the residual magnetic field surrounding the engine. This clustering also provides redundancy, as we discuss later.

A VASIMR® TC-1 thruster comprises six basic subsystems: 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 (at ~ 35 °C) and high temperature heat rejection (at ~ 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 thermal management subsystems together are analogous to a thruster unit — while the RF power processing subsystem is analogous to a Power Processing Unit (PPU).

A description of the state-of-the-art of each subsystem has been included in a previous paper[10], particularly as to

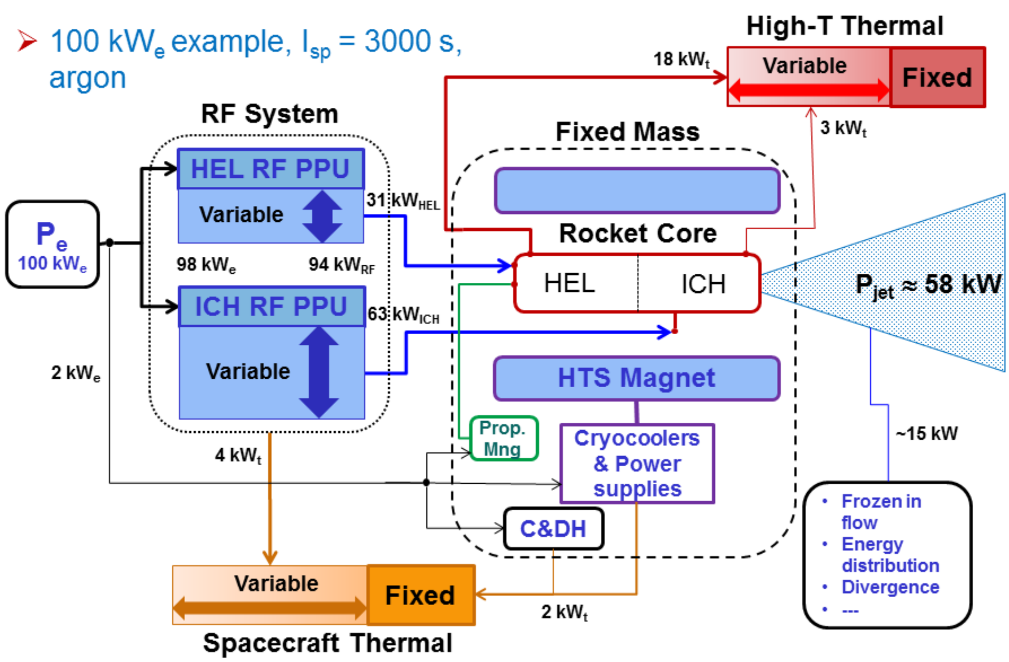

Figure 3. Schematic diagram of a TC-1 system, showing power flow and components that scale.

how this sets the mass scaling. To further illustrate the system elements and the mass scaling, Fig 3 contains a diagram and an example of the power flow at 100 kWe power input for argon propellant operation at the relatively low I_{sp} of 3000 s where the heat load is the greatest in the design domain for this system. Components that vary in size with power are indicated. This power flow and heat is based on experimental data. As will be discussed in the next section, detailed models predict improvement in the next technology design iteration. Also, the same modeling predicts similar performance using krypton with an I_{sp} of 2000 s. Next we discuss the application of this predictive model.

III. Benchmarked Physics based Performance Model

During the early development of the VASIMR® propulsion technology, we also began the development and testing of a self-consistent physics-based model for the predictive design of the rocket, including fundamental understanding of the underlying physics, particularly the challenging plasma environment. This model stands on the tremendous body of knowledge grown over decades in the pursuit of fusion energy and other applications of high power RF driven plasma technology. The AdAstraRF model includes: RF Maxwell solver with magnetized plasma, coulomb and neutral collisions, sheath solver, neutrals model, diffusive model with different coefficients parallel and perpendicular to the magnetic field, and enhanced ambipolar ion extraction with ICH. AdAstraRF iterates to produce a bulk 2D magnetized plasma transport solver with RF and plasma power balance. Additionally, practical thermal engineering is applied to set power density limits. We successfully used this model to design the VX-200™ device and lessons learned have been applied to an updated AdAstraRF model. The code calculations have been benchmarked with VX-200™ test data to give us a highly valuable and accurate predictive tool for designing the next versions of VASIMR® devices.

Most recently a computationally intense effort has been undertaken to analyze two VASIMR® versions. The first is the TC-1™, a close derivative of the VX-200™ describe above. The second is the TC-1m, a reduced ("mini") size version intended for missions that may desire lower power operation.

A. TC-1

The TC-1 takes an incremental step from VX-200™ and has high performance confidence because the plasma and RF scale size are very similar. The VX-200™ experimental system was purposely oversized in our early technology development program to assure plasma function and give room for uncertainties that we had at the

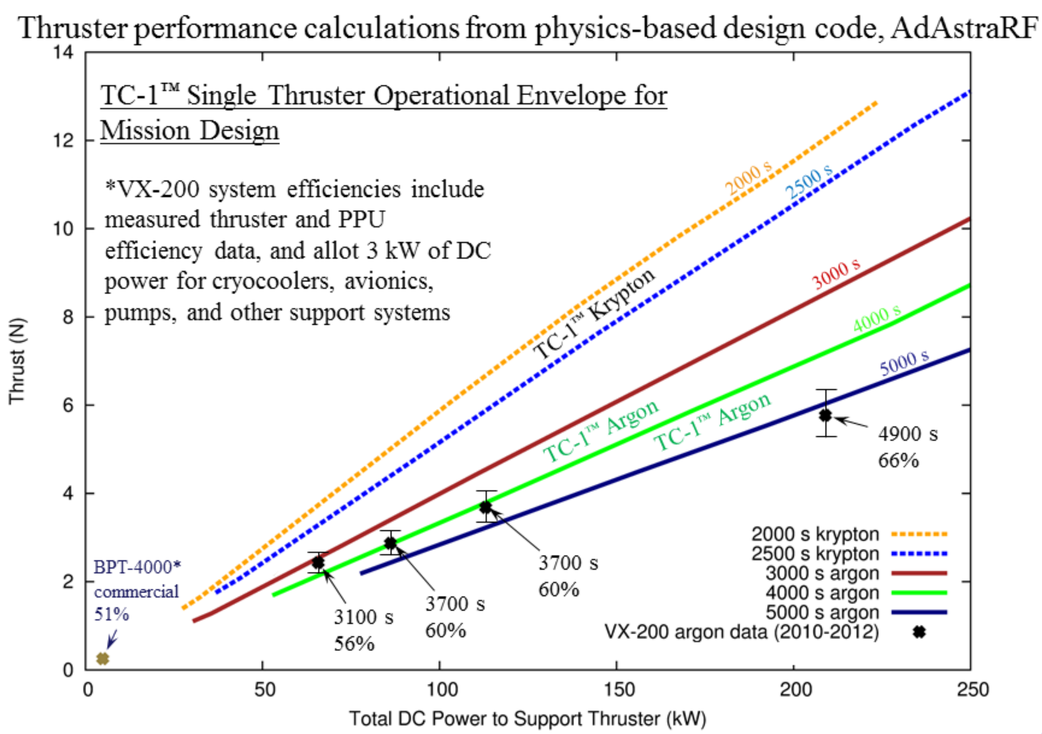

Figure 4. TC-1™ system performance curves for argon and krypton, Thrust verses DC input power, I_{sp} from 2000 to 5000 s.

beginning of the program. With the plasma function now demonstrated with high confidence and the model benchmarked, we have optimized the RF and plasma configuration together with state-of-the-art HTS magnet technology. A great number of computational iterations were performed to produce a self-consistently converged performance space to characterize the TC-1 operation with argon and krypton propellants. The results are summarized in Fig 4 that plots thrust versus input DC system power for both propellants and different I_{sp}.

The power level spans from 30 to 250 kWe and includes complete system power, as described in Fig 3. For argon, the curves are for fixed I_{sp} of 3000, 4000 and 5000 s and any value between can be interpolated. The thermal system is designed for the efficiency of the low I_{sp} value, as described in section II. The highest I_{sp} is limited by practically achievable RF voltages, and we do not show predictions for levels that we have not demonstrated in the laboratory. Krypton propellant provides higher thrust, up to 12 N at 200 kW, and the lower I_{sp} of 2000 and 2500 s. From the curves and I_{sp}, one can calculate system efficiency and see that it spans from 60 to 70% for both propellants.

B. TC-1m

Near term missions plans such as the asteroid redirect mission, SEP-ARM[14], are targeting EP system power levels of about 40 kW. The successful development and demonstration of such SEP in space will give rise to a variety of applications, starting at this power level and increasing with time, as history shows. With this in mind, we applied the VASIMR® modeling tool to reducing the fixed mass component of a single core system, particularly the magnet and rocket core. We named this version TC-1m, for "mini." The modeling successfully reduced the fixed mass to approximately half while maintaining efficiency equal to that of the TC-1. The reduced size also limited the maximum power handling level to about half, or approximately 150 kW. The fixed mass components associated with the RF, thermal and other systems are kept the same, a conservative estimate, since those subsystems would likely be reoptimzed to lower power levels. Nevertheless, the scaling coefficients show this system to be more competitive than the TC-1 in the regime at or below 50 kW, while having high and variable I_{sp} advantages. The specific mass scaling coefficients for fixed I_{sp} are: A_{TC1m} = 0.95 kg/kW and B_{TC1m} = 328 kg, where $\alpha_{\mathrm{TC1m}} = A_{TC1m} + B_{TC1m}/P_e$. This system is in the earlier stages of development, therefore with less fidelity in the design. Nevertheless, the success of the AdAstraRF model gives us high confidence in the plasma and power performance prediction.

IV. Comparative System Mass Scaling

With both the VASIMR® system mass scaling and efficiency established, we can perform a comparison to Hall effect thruster based systems[15] and find a power level above which it is advantageous to transition to VASIMR® type technologies for application in future higher power missions. For a complete picture we must also consider the entire system, including efficiency and solar power, though to begin exploring the comparison we can simply look at the mass scaling of a single thruster string, as described in earlier papers.[10, 15] When factoring in solar power mass, the transition power level shifts to a value lower than shown here, owing to the VASIMR® higher efficiency. We also consider simple clustering and point out that strategies are strikingly different for the two technologies because of the respective scaling of single strings.

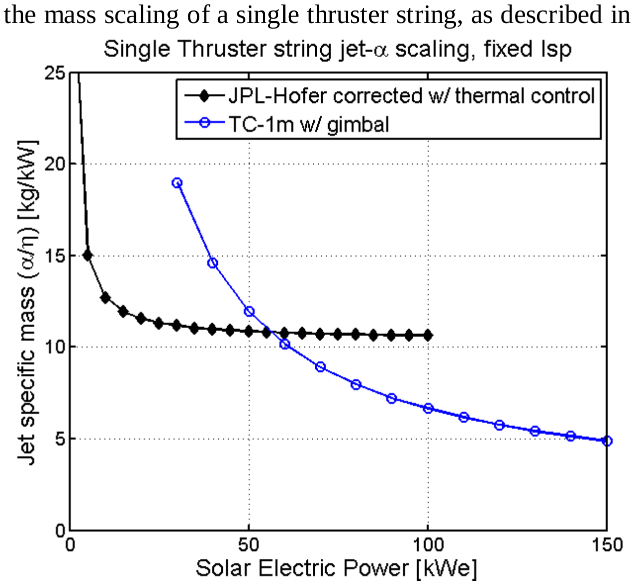

Figure 5. Jet-α curves for single thruster string systems, TC-1m and Hall effect thrusters.

Only considering the thruster string α does not factor in efficiency, so we consider a simple factor that is α divided by system efficiency, which is effectively the mass divided by jet power, or jet-α. This better compares technologies that may have different thruster efficiencies. For VASIMR®, we use a TC-1m and the efficiency results as discussed in section III for krypton at a fixed I_{sp} of 2500 s that presents a system efficiency of $\eta_{Vsys} = 0.7$. We add gimbaling mass, not considered in Squire,[10] to the TC-1m system, as done in Hofer[15], though with $f_{gim} = 0.5$, since VASIMR® would not use traditional gimbal techniques and would benefit by an economy of scale. For Hall thruster technology, we use the thruster efficiency for the NASA 457M-v2[16] results

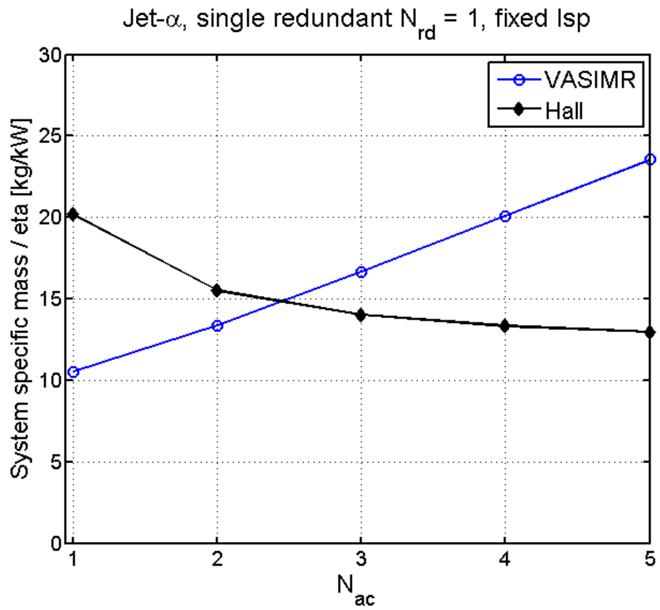

Figure 6. Jet specific mass scaling verses the number of active thruster strings in a cluster with single string redundancy for a 150 kWe system.

for the highest power level and I_{sp}, where η_{thr} = 0.61, and we assume 95% PPU efficiency and a 2% parasitic loss, so η_{Hsys} = 0.57. This compares the two systems at about the same I_{sp}. We only adjust the Hall thruster mass scaling formula to account for PPU thermal control, assumed as 0.5 kg/kW, which is not in the referenced paper[15], though is accounted for in the VASIMR® TC-1m system.

Figure 5 shows the comparative jet-α scaling for a single thruster string. We see that mass becomes favorable for a VASIMR® system at power levels above 60 kW, beginning about where the Hall thruster jet-α becomes asymptotic and showing that VASIMR® is really a complementary technology. At the maximum TC-1m input power level, the VASIMR® jet-α is about half that of the asymptotic Hall thruster value. Furthermore, if we consider the mass of the solar power source of about 7 kg/kW, we note that the jet-α cross-over could be lower than 50 kW.

Now we take a simple look at clustering with single string redundancy. As we saw above, the mass scaling is significantly different for the two technologies, so clustering strategies are different. For example, if we follow the single redundant (able to sustain one string failure and remain fully operational) thruster string analysis as in Hofer, there is never an advantage to clustering high numbers of VASIMR® TC-1m strings. A unique feature for redundancy in a VASIMR® system is the addition of a magnetic dipole canceling coil. A cluster of two TC-1m thruster strings is single-fault tolerant, though not for magnetic dipole cancelation. An additional simple canceling coil will be lighter than one of the TC-1m thruster coils, so we add 60% mass of a thruster coil to the system. If we scale the number of active thruster strings for a 150 kW system, we find a strikingly different behavior for the two technologies. It is not favorable to have more than two TC-1m strings in a single-redundant system, since one string can process all of the power and adding redundant VASIMR® PPU power to a single string has a small mass penalty. On the other hand, the Hall effect thruster technology favors higher numbers of active thrusters.

The VASIMR® system performance and mass becomes more advantageous as we move to the increasing power needed for deep space exploration to destinations such as Mars. At power levels of 300 kWe, the VASIMR® system offers disrupting applicability in support of human Mars exploration by delivering cargo.[17] With the development of higher power solar or nuclear electric technology, operational power levels higher than 1 MW become valuable for crew transport[18] and tremendous cargo capability. The VASIMR® technology's flexible and higher specific impulse, together with attractive performance, offers near-term robotic SEP commercial capability and unmatched increasing value to later human exploration.

V. VX-200SS Upgrade

The VX-200™ – shown in Figure 7 – program has produced a wealth of high-quality data. It was designed for steady-state plasma operation (neutrals and plasma equilibrium) for economical performance and thermal studies. Presently, the VX-200™ system has been removed and disassembled for inspection and significant upgrades to the components in the rocket core and RF subsystems to establish the new VX-200SS program. Active cooling is being added to the

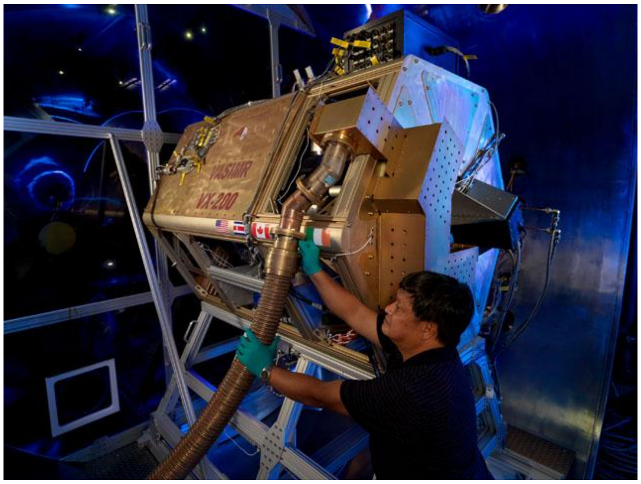

Figure 7. VX-200TM installed in Ad Astra's vacuum chamber.

rocket core components and conductively cooled high-power RF low-loss circuits are being implemented. Additionally, the vacuum chamber requires upgrades to withstand the high mass flows and power levels of the high energy plasma jet, about 80 kW for a 100 kW thruster operation. Modifications to the Ad Astra vacuum facility will include an actively cooled plasma beam dump and pump shielding. A major chamber feature already in progress is an internal wall to enable differential pumping to keep the rocket components at high vacuum, even when the plume is at high pressure, > 10^{-4} Torr. This enables the economical testing of the rocket in thermal steady state without a large investment in pumping capability. The VASIMR® engine's electrodeless technology is well suited for this mode of testing, as the power couples to the plasma through RF windows. This feature of the engine's architecture permits the straightforward isolation of the plasma pressure plenum from that of the high-vacuum where the rocket components operate. The plasma pressure at the exhaust exit is very high (~ 1 Torr) due to the high power density, so a downstream neutral background pressure, as high as 10^{-3} Torr, does not significantly affect the function of the plasma processes in the core. With these upgrades we can economically test a 100 kW system for continuous firings of hundreds of hours.

VI. VASIMR®-SEP Applications

A 50 to 300 kW class VASIMR® Solar Electric Propulsion (VASIMR®-SEP) spacecraft opens many possibilities. In earth orbit, the high power and specific impulse enable propulsively intensive plane changes to capture and deorbit large orbital debris objects. Figure 8 shows an artistic rendition of such a vehicle approaching a spent Zenit upper stage and carrying a set of solid rocket motors for de-orbiting up to 19 such objects in a single mission. The fuel efficient operation also reduces the cost of maintaining large structures with atmospheric drag in low earth orbit and can perform reboost. Beyond earth orbit, the same type of spacecraft can efficiently redirect the significant masses of asteroids, enabled by the high-power combined with high specific impulse. An accompanying paper discusses the deep space application that enables exciting missions to the Jupiter system to explore the recent discovery of activity at Europa.[19] Such VASIMR®-SEP space tugs can also provide great benefits to human exploration of Mars[20] and many more applications.

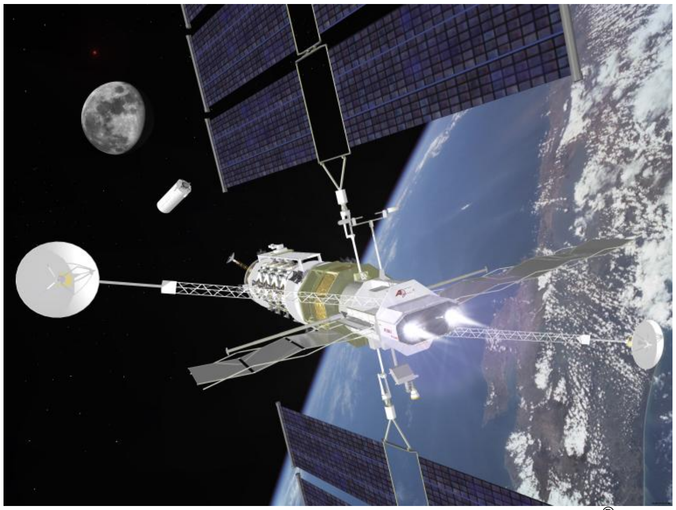

Figure 8. Artistic diagram of a 200 kW VASIMR®-SEP spacecraft performing debris rendezvous.

VII. Conclusion

The VASIMR® system technology has made tremendous progress toward a spaceflight ready application. The VX-200™ program has verified plasma and power performance, DC to plasma jet power. Plasma plume measurements in a low background pressure environment have measured plasma detachment. Design and analysis of existing technologies have produced a mass scaling model that show VASIMR® thruster string specific mass is achievable below 3 kg/kW. A sophisticated physics-based design tool has been developed and applied to next generation spaceflight relevant devices, capable of running on krypton and argon propellants. System efficiencies are as much as 70% for high specific impulse modes of operation, 2500 s for krypton and 4000 s for argon, and performance curves for both propellants are presented spanning 30 to 250 kWe. This same tool was used to design a TC-1m, "mini", version of a VASIMR® thruster core that is optimized for about half of the power of a VX-200™ derived version, while maintaining the same efficient operation. The TC-1m is performance competitive with Hall effect technology in the regime at about 50 kWe. A comparison of mass scalings shows a VASIMR® mass advantage transition at about 60 kWe. Simple analysis at 150 kWe shows that there is no need to cluster more than two TC-1m cores to achieve single-string redundancy, owing to the high power density of the single-string VASMIR® system and lightweight PPUs. In contrast, Hall effect technology benefits from clustering more than four strings.

We are presently planning and implementing designs to demonstrate thermal steady-state operation. This involves significant upgrades to the rocket core, RF subsystems, and vacuum chamber. The upgrades will enable duration testing for more than 100 hours.

VASIMR® technology presents a large portfolio of applications in the near-term use of solar electric power in the range of 50 to 300 kWe, complementary to Hall effect thruster technology. The VASIMR® technology then easily scales to still higher power levels for the future of human exploration.

Acknowledgments

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