Advances in Duration Testing of the VASIMR® VX-200SS System

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The VX-200SS program will complete design verification, testing and lifetime estimates of a VASIMR® prototype engine, operating under thermal steady-state at power levels greater than 100 kW for at least 100 continuous hours. The work will bring the integrated VX-200SS VASIMR® prototype to Technology Readiness Level of 5 (TRL-5), including RF Power Processing Units (PPUs), superconducting magnet, propellant management system, internal thermal management subsystems and the rocket core. The rocket core 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 accumulation of significant operating time will allow a measurement of the wear of plasma-facing components with sufficient accuracy to evaluate their projected lifetime. The VX-200SS program builds on the successful VX-200™ program and involves manufacturing of a new rocket core and significant upgrades to the RF subsystems, vacuum chamber, computer control, and performance measurement diagnostics. This paper describes the three-year multi-phase VX-200SS program that has been underway for one year.

Nomenclature

α	=	specific mass [kg/kW]
C&DH	=	Command and Data Handling
EP	=	Electric Propulsion
HEL	=	Helicon plasma first stage
ICE	=	Integrated Cooling and Electrical
ICH	=	Ion Cyclotron Heating plasma second stage
I_{sp}	=	specific impulse [s]
PM	=	Propellant Management
PMFS	=	Plasma Momentum Flux Sensor
PPU	=	Power Processing Unit

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RC = Rocket Core
RF = Radio Frequency
RTD = Resistance Temperature Detector
TC = Thermocouple
TRL = Technology Readiness Level
VX-200™ = VASIMR® Experiment 200 kW
VX-200SS = VASIMR® thermal steady-state experiment

I. Introduction

THERE is a growing consensus that solar electric propulsion (SEP) tugs at high power levels, greater than 50 kW, will play a vital role in service to human exploration of the solar system near Earth and Mars.[1-6] Great advancements in solar electric power technology and clever deployment mechanisms are enabling the consideration of space solar power levels of hundreds of kilowatts and approaching 1 MW. Application in the near future is possible with practical specific mass values and form factors that fit in available launch fairings.[7, 8] Economically delivering large cargos to Mars orbit is a prime example of an exciting application of SEP technology.[4, 6] These SEP tugs can also support more significant science payloads and enhance sample return possibilities. The very same technology enables enhanced exploration of asteroids and other deep space exploration. Closer to home, the SEP tug technology can double the payload capacity to lunar orbit.[9] Commercial telecommunication satellites are already taking advantage of SEP technology to enhance the delivery and operation of GEO satellites.[10]

Transportation vehicles have shown a progression of increasing power levels throughout human history. Logistics advanced from horses through sailing ships, steam engines, internal combustion engines, turbines, chemical rockets and nuclear reactors. All of these successful technologies are still in use today and have unique advantages in their specific areas of use. Advances in space propulsion will be the same. Developing variants and refinements to flown heritage units remains a valuable endeavor. But, consistent with mankind's technical evolution, the VASIMR® team is motivated to develop and test new electric rocket technologies that enable exciting and revolutionary capabilities. In the near-term, SEP applications using efficient VASIMR® engines with power levels greater than 50 kW and specific impulse up to 5000 s are ready to begin on a flight development path. The scalability of this technology to much higher power levels (MWs) is also of great interest for the future of human exploration.

Extensive testing using the VASIMR® VX-200™ experiment for pulse lengths up to 30 s and at power levels up to 200 kW has established the system's DC-to-jet power performance while the injected-gas and plasma were operating in steady-state conditions[11]. Figure 1 shows the installed VX-200™ device. The thruster efficiency ranges from 60% to 72% in the specific impulse (I_{sp}) domain of 3000 to 5000 s using argon propellant.[11] These measurements were performed using highly efficient (~ 95%) and light-weight (< 1 kg/kW) solid-state RF power processing units built by Nautel, Ltd and a superconducting magnet that is free of liquid cryogens.[11] Detailed mapping of the plasma plume over a large scale length (> 2 m) and low background pressure ($< 2\times10^{-4}$ Torr) has shown that the plasma is detached from the VX-200™ device's magnetic field at a distance of approximately 2 m from the exhaust exit.[12] A recent study has evaluated the overall propulsion system specific mass, finding it to be in the range of 3 kg/kW at high power levels (~ 250 kW) using existing technology.[13] A physics-based model that is benchmarked with VX-200™ data predicts that design refinements can further improvement the efficiency with argon and krypton propellant operation extending down to an I_{sp} of 2000 s.[14] Flexibility in the propellant choice makes it possible to further expand the operational envelope and to use condensable propellants.

Figure 1 The VX-200™ installed in Ad Astra's vacuum chamber.

With the physics of the electrical and plasma power flow already demonstrated and understood for the VASIMR® engine, engineering tests are now underway. This effort will demonstrate thermal management during continuous operation at 100 kW for 100 hours. The active thermal control system was designed using thermal measurements from the VX-200™ device and fluid flow analysis. Operating at high-temperature (> 200° C), the thermal management system is expected to meet the power density requirements for a single-core VASIMR® system at up to 250 kW. With a thermal solution in hand and long duration testing, the elements of a VASIMR® system will be ready for a straightforward progression to spaceflight.

This paper describes ongoing activities to perform testing of a spaceflight relevant system in thermal steady-state using the VX-200SS test unit under a NASA contract entitled, "Thermal Steady State Testing of a VASIMR® Rocket Core with Scalability to Human Spaceflight".

II. Objectives

The VX-200SS program will complete design verification, testing and lifetime estimates of a VASIMR® prototype engine, operating under thermal steady-state at power levels greater than 100 kW for at least 100 continuous hours. The testing will build on lessons learned from over 10,000 pulsed tests at power levels up to 200 kW in the uncooled VX-200™ experiments that were completed by Ad Astra Rocket Company (Ad Astra) in 2009 to 2012. The work will bring the integrated VX-200SS VASIMR® prototype to Technology Readiness Level of 5 (TRL-5), including RF Power Processing Units (PPUs), superconducting magnet, propellant management system, and internal thermal management subsystems. Performance measurements will verify that the upgraded VX-200SS system retains the power efficiency measured in the VX-200™ program. Steady-state testing will be carried out using argon propellant. The accumulation of significant operating time will allow a cost-effective measurement of the wear of plasma-facing components with sufficient accuracy to evaluate their expected lifetime to greater than or on the order of 10,000 hours. We plan to accomplish these objectives in three phases. We name these phases VX-200SSa, VX-200SSb and then VX-200SS. This is an iterative approach with incremental increases in operational demands. The operational phases are described in section V.

III. Thruster System

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 heating to efficiently couple RF power into ion kinetic energy and is referred to as ICH in this paper.

Basic descriptions of a VASIMR® engine's function have been included in several previous papers.[15, 16] Four unique elements of a VASIMR® engine are: the RF PPUs, the superconducting magnet, the thermal management system, and the rocket core (RC). The RF PPUs are based on a robust and highly efficient single-stage solid-state power amplifier design. These amplifiers have heritage from the radio broadcast industry, and have been proven to full power steady-state operation in the VX-200™ system. Magnet technology based on high-temperature superconductors is progressing rapidly for a wide range of terrestrial applications and is readily adapted to this application. The thermal management system is based on robust fluid-loop technology integrated into the rocket core. The rocket core element resides down the bore of the magnet and is designed to utilize the RF power in conjunction with the high strength magnetic field to create and accelerate a high power-density plasma stream. The rocket core also manages any waste heat from the plasma.

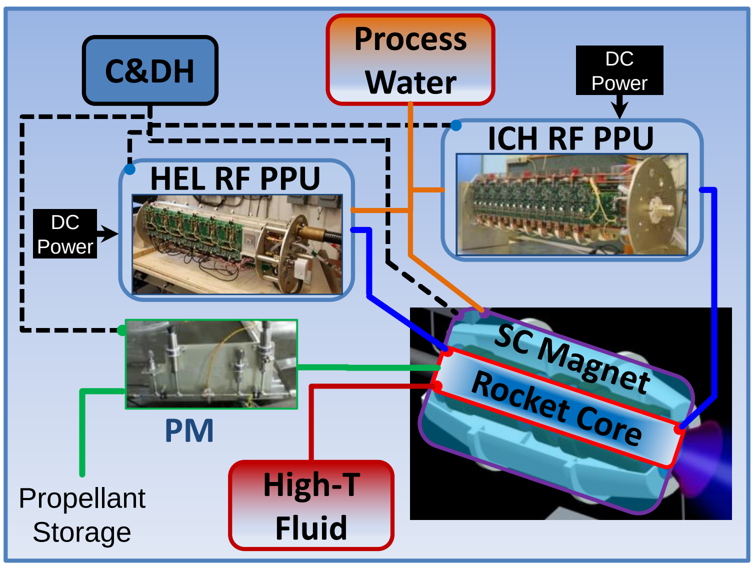

Figure 2 Simplified block diagram of the VX-200SS system.

The planned VX-200SS system comprises six basic subsystems: 1. Rocket Core (RC); 2. RF Power Processing, including both helicon (HEL) and ICH RF generators with impedance matching; 3. Superconducting Magnet; 4. Thermal Management, including process fluid heat rejection (at ~ 25 °C) and high temperature heat rejection fluid (up to ~ 200 °C); 5. Propellant Management (PM); and 6. Command & Data Handling

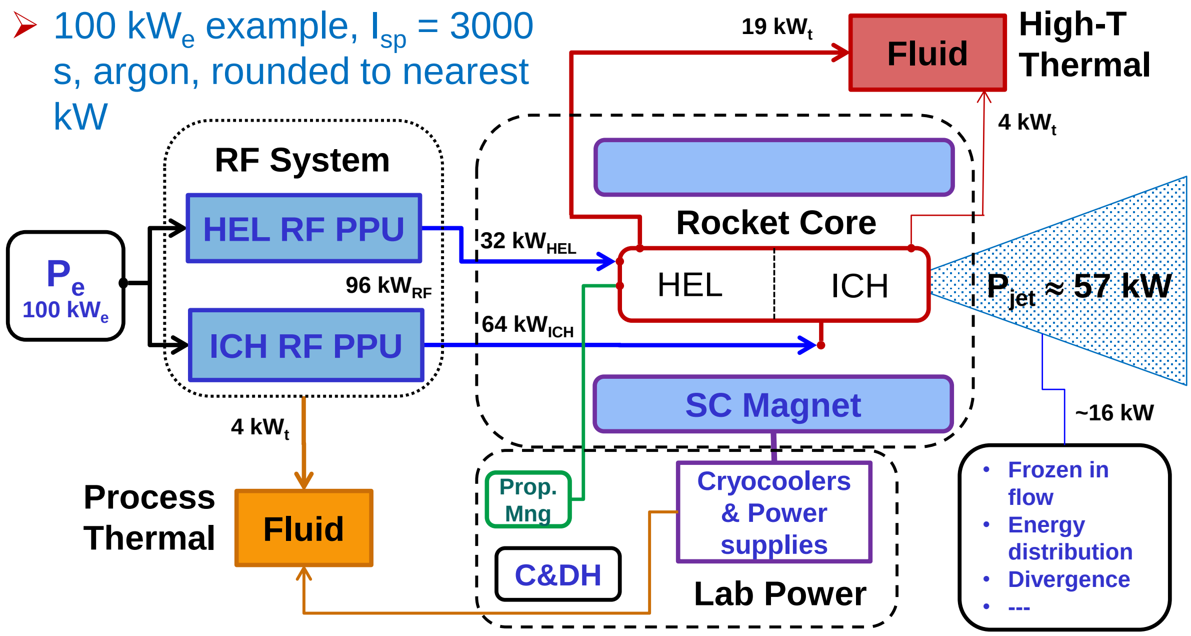

Figure 3 Flow diagram with an example at 100 kWe input power with argon propellant at I_{sp} of 3000 s.

(C&DH). Figure 2 contains a simplified block diagram of the VASIMR® VX-200SS 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,[13] particularly as to the mass scaling of an integrated propulsion system. To further illustrate the system in operation, Figure 3 contains a flow diagram and an example of the power flow at 100 kWe input power for argon propellant operation at the relatively low I_{sp} of 3000 s where the heat load is high in the design domain for this system. This power flow and heat are based on experimental data. Physics-based modeling predicts similar performance using krypton with an I_{sp} of 2000 s. The following elaborates on the system elements.

1. Rocket Core

The rocket core 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. It has no moving parts other than the cooling fluid flowing inside the ICE jackets. Heat loads used for design are based on infrared camera and infrared sensor data obtained during operation of the VX-100 and VX-200™ devices between 2007 and 2012. 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, heat transfer analysis predicts that system power level objective of more than 100 kW is safely handled per core design with an average heat rejection temperature of approximately 200° C. Manufacturing of the prototype rocket core is expected be completed in July 2016. Multi-layer insulation will be installed to protect the bore of the superconducting magnet from the hot rocket core.

2. RF PPUs

Modern solid-state RF broadcast technology has reliably operated in the custom experimental RF generator units (Nautel Ltd. models VX-200-1 and VX-200-2) for nearly 5 years. They have accomplished tens of thousands of pulses under varying conditions, which is harsh for power electronics. We frequently refer to the two units that drive the rocket as RF generators (or RF PPUs) 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 the 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. The generators alone do not comprise the entire RF Power Processing system. We must also have impedance matching circuitry that is rated for steady-state operation. This impedance matching, which is accomplished with high voltage low loss capacitors, further isolates DC voltages from the active switching components from the plasma load.

The existing VX-200™ RF PPUs have been recommissioned to full operational capability and calibration after nearly 5 years of service. These units will accomplish the VX-200SSa and VX-200SSb phases of the program. The impedance matching circuitry is already in vacuum, although modifications with low loss capacitors and precision electrical connections will be included to reduce parasitic losses and carry the small amount of stray heat away in steady state. A parallel, privately funded effort is underway to install modified versions of the RF PPU systems into the vacuum chamber by the end of the VX-200SS program.

3. Magnet

The VX-200™, in operation from 2009 through 2012, utilized a state-of-the-art low temperature superconducting magnet designed and developed by Scientific Magnetics, LLC of the United Kingdom specifically for the VX-200™.[17] The magnetic field is generated by a superconducting (Nb-Ti) magnet encased in a well-insulated cryostat surrounding the engine core and cooled by conduction to the cryocoolers heads without the need for any liquid cryogens. The magnet produces a peak magnetic field strength of 2 T. The spaceflight VASIMR® system will utilize high temperature superconducting magnet technology so that the heat-rejection systems that chill the magnet can operate with a high efficiency. The existing magnet has now operated reliably for over 10,000 hours, and has safely withstood several quenches, per its design, without degradation. Manufacture-recommended servicing and cryostat modifications have been made to allow robust operation during vacuum chamber pressure cycling and to tolerate continuous high temperature operation of the rocket core.

4. Propellant Management

We plan to use the same propellant management system that was successfully used in the VX-200™ program. This system regulates argon propellant flow through an injector plate into the helicon first stage using a high TRL-7 Moog propellant flow controller. The controller contains a proportional flow control valve, a low pressure transducer by Taber Industries, and a 0.041" diameter orifice. Choked flow enables regulated mass flow rates up to 5000 sccm (~ 150 mg/s). The mass flow rate is also verified using an in-line calibrated, NIST traceable, MKS-179 thermal mass flow controller.

5. Control and Data Handling

Control and data acquisition will be primarily accomplished using LabView programming and National Instruments hardware. This strategy was adopted for rapid and cost-effective implementation of control algorithms that can be later adapted to control systems with spaceflight heritage. In this effort, Ad Astra in collaboration with National Instruments has demonstrated the successful operation of a Compact-RIO system mounted on top of the engine test stand in vacuum during plasma operations.

6. Thermal Management

The new rocket core will be cooled independently with a closed fluid loop system with a heat exchanger to facility water. The RF PPUs, superconducting magnet and other ancillary components are cooled with a dedicated treated process water loop also having a separate heat exchanger to facility water. The rocket core will start operations using a closed loop treated water system to accelerate the performance testing at full power with plasma and to further measure heat loads. It is then a straight forward effort to transition to high temperature operation in the rocket core using common industrial technology at temperatures below 300 °C. The final configuration will run at spaceflight relevant temperature above 200 °C, and the fluid in the rocket core will be representative of that which will operate in space to verify realistic thermal performance. Detailed calorimetry will be performed with the fluids to confirm heat loads, design analysis and power flow.

IV. Test Setup

For economical testing of the VX-200SS device, Ad Astra plans to leverage the existing private investment in its large vacuum test chamber; and the same high power plasma laboratory used to successfully test the VX-200™. Figure 4 depicts the VX-200SS test setup, similar to the VX-200™ operational tests from 2009 through 2012, but with an improved chamber divider, the addition of a plasma dump to sacrificially intercept the plasma and continuously remove the heat of the rocket exhaust, and additional pumping capacity for long duration testing. The chamber divider seals the rocket plume pressure from the power electronics, uniquely made possible by the inductive coupling of RF power through sealed dielectric windows in a VASIMR® system. The chamber divider enables differential pumping so that the VX-200SS system components stay in high vacuum (~ 10^{-6} Torr) while the pressure on the plume side of the divider can rise to greater than 10^{-4} Torr. The high plasma pressure of the system allows the rocket operation to

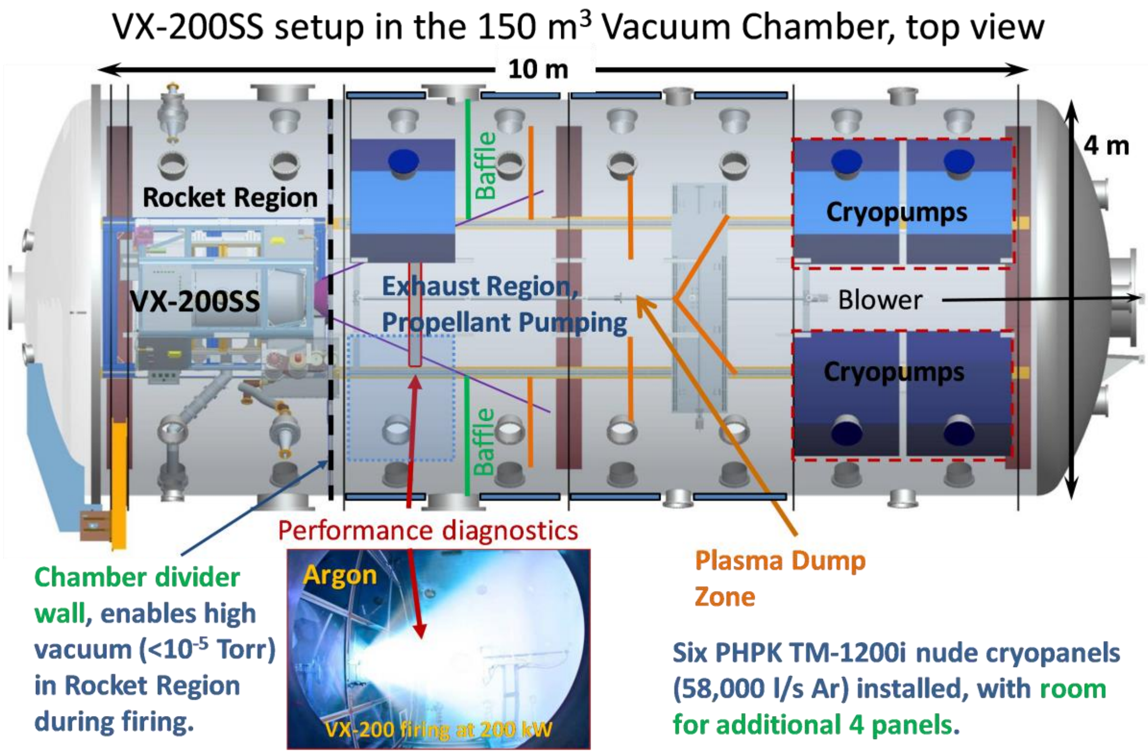

Figure 4 VX-200SS test set up.

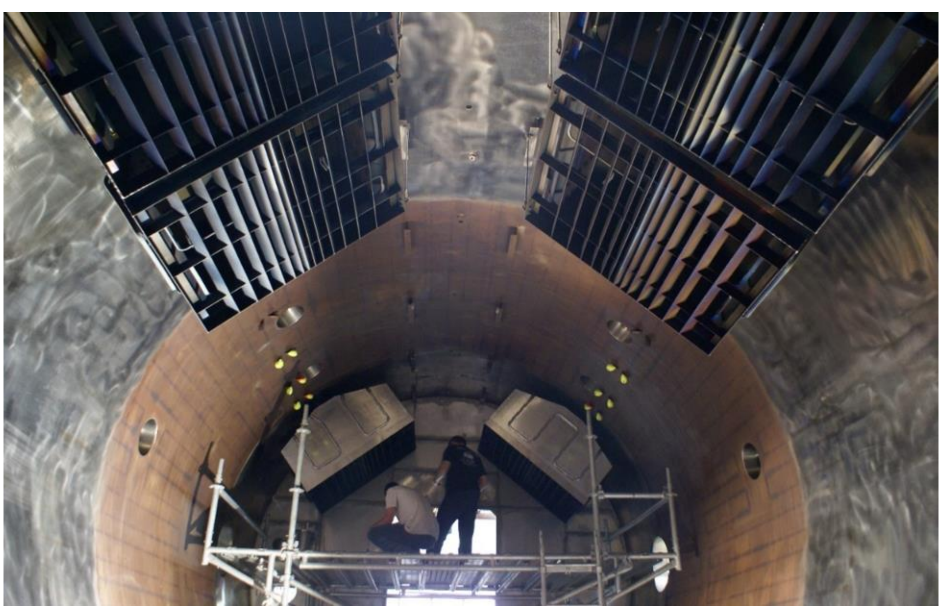

Figure 5 Cryopumps installed in the chamber

remain relatively unaffected by the elevated pressure, and greatly reduces pumping requirements relative to those typically needed for electrostatically driven devices. Presently six cryopanels are installed and operational.

Figure 5 shows the inside of the chamber looking from the exhaust end while pump installation was ongoing. The chamber provides locations and infrastructure for up to a total of 10 cryopanels on the plume side of the chamber divider for a total potential pumping rate of 580,000 liters per second with argon. Four original pumps have been serviced and two new cryopanels have been added, with two more pending, as 8 cryopanels are expected to be more than sufficient to meet the pumping requirements for testing. In the VX-200SSa phase, the chamber and pump shielding is drapes of grafoil, without active cooling. In this first phase, a diagnostics translation stage will be utilized to characterize the performance in a full power pulsed mode. Also, for helicon-only operation, Ad Astra has previously demonstrated that the helicon stage operates effectively at pressures over 1 mTorr. This could lead to much more economical thermal functional testing in the first phase. For long-duration testing, the plasma dump must be made more robust to withstand the power of the Ion Cyclotron Heating (ICH) second stage of the rocket, and the chamber actively cooled to extract the heat.

The exterior of the chamber shows water cooling channels welded to the outside to carry away the heat of the plasma exhaust during long duration testing. These channels will be completed over the next year to support increasingly long duration operation. The photo in Fig. 6 also shows the 180 kW ICH amplifier (left) configured for testing into a dummy load. The stainless steel dividing wall can also be observed just inside the open door of the chamber.

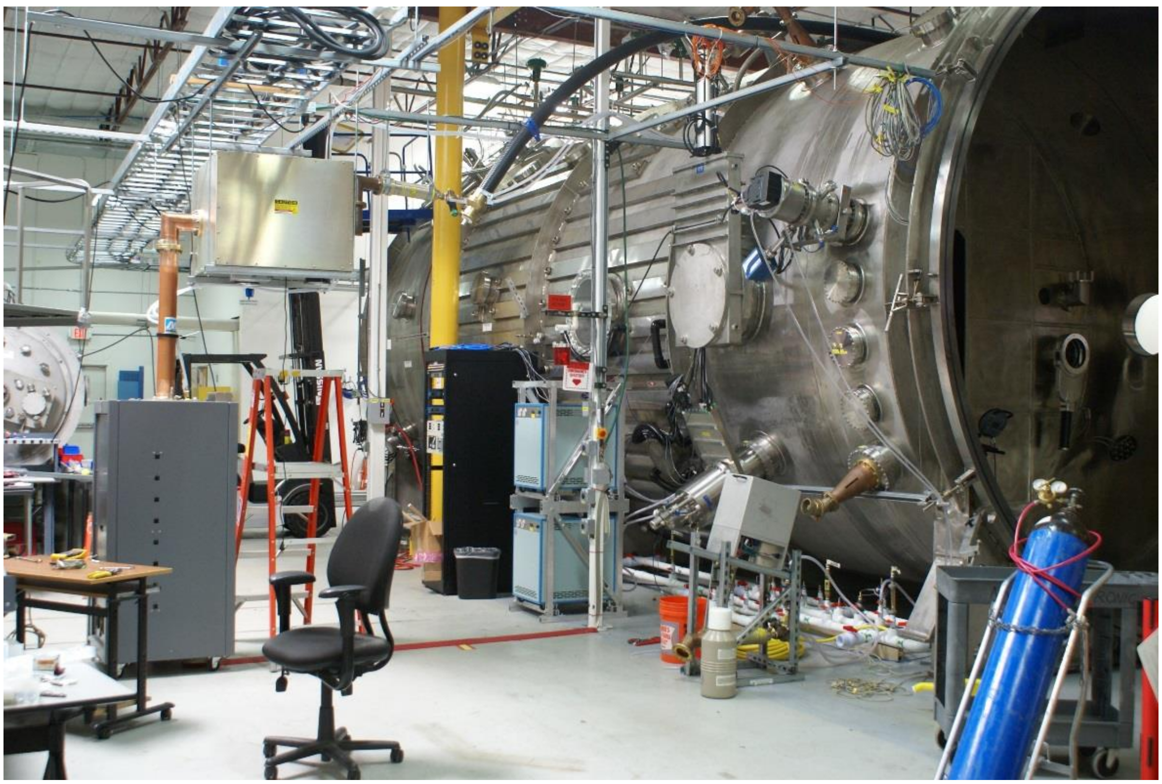

Figure 6 Exterior of the vacuum chamber, door open, with an RF PPU in the left foreground.

For plasma diagnostics, a calibrated plasma momentum flux sensor (PMFS) will scan through the diameter of the plume to accurately and economically measure the value of thrust, and adds information about the momentum density profile.[18] Ad Astra has proven that this technique accurately infers thrust with background neutral pressures in excess of 10^{-4} Torr. The data from the PMFS, Langmuir probes, and other existing sensors will confirm predicted power performance of the VX-200SS system. The VX-200SS thermal control advancement also enables long and/or rapid pulsing capability for thrust measurement at low background pressure. PMFS diameter scans can be completed in approximately 10 seconds with stable rocket core temperatures to enable extensive exploration of varying input parameter values. This new capability will allow rapid performance optimization and characterization of the planned operational envelope. This performance data set can then be correlated with input parameters, such as RF impedance, gas pressure and others, to determine that the rocket core and test setup are performing to specification before and during the long duration tests. The parameters that will be measured and methods for measurement are listed in the table below.

Parameters	**Diagnostics**
Propellant Flow	• MKS mass flow sensor • VX-200™ Moog TRL-7 gas flow controller
Input Power	Helicon and ICH RF PPU systems • DC voltage and current • Integrated and vendor calibrated RF power and impedance sensors. • RF power and impedance sensors at the Rocket Core interface.
Thrust	Plasma momentum flux sensor (PMFS). • Two redundant PMFSs scanned across the diameter per the published method.
Thermal Fluid Input/Output ΔT and flow rate.	Helicon coupler, Choke, and ICH coupler • Sensor wells with temperature sensors, e.g. RTD. • Flow rate meters
Thermal Structure	• Shielded temperature sensors, e.g. RTD. • IR temperature sensors for high RF field regions.
Plasma properties Flux, T_e, etc.	Langmuir probes scanned across the plasma diameter • Array of 20 planar Langmuir probes biased in ion saturation • Swept guard-ring Langmuir probe
Magnetic Field	• Superconducting coil currents • Magnetometer verification
Neutral Gas Pressure	• Commercial gas pressure sensors (convectron and ion gauges) on the chamber in the rocket region and at least two in the plume and plasma dump regions. • Residual Gas Analyzer (RGA) in the plume region to check for purity
Lifetime estimate	• Precision bore gauge map of the entire plasma facing surface. Diameter accuracy to within 0.0003" or 0.0076 mm.

V. Operational Plans

Ad Astra has selected the technical approach to achieve these objectives in three plasma operational campaigns in an iterative strategy. These three phases are named: VX-200SSa, VX-200SSb and VX-200SS. Figure 7 contains a high level schedule. In the first year, near completion now, Ad Astra is building a new high temperature steady-state rocket core per existing designs and service the existing RF PPUs and superconducting magnet. Ad Astra's vacuum chamber systems will also have shielding added to withstand helicon steady-state testing for shake-out firings lasting a few minutes. Ion cyclotron heating (ICH) for total power levels of 100 kW will then be added and baffling will be installed to improve pumping for better performance diagnostics. Early in the second year, about to begin, we will start integration and testing of VX-200SSa to characterize thermal and power performance using treated water cooling systems to expedite results.

For the VX-200SSb phase, the ICH systems will be modified for steady-state operation and a plasma dump capable of absorbing and removing approximately 100 kW of power from the chamber in steady-state for over 100 hours will be installed, applying lessons learned from the first phase of operation.

For the VX-200SS phase, Ad Astra will apply lessons learned and upgrade all systems to operate at full design temperatures in steady-state for 100 hours of continuous testing with more than 100 kW of power. After this duration of testing, high precision bore gauge instruments can then measure wear rate values in the rocket core that can be extrapolated to evaluate the lifetime with a goal of >10,000 hours of operation for a flight design. The background vacuum pressures for this ground test are more than adequate for thermal testing and are

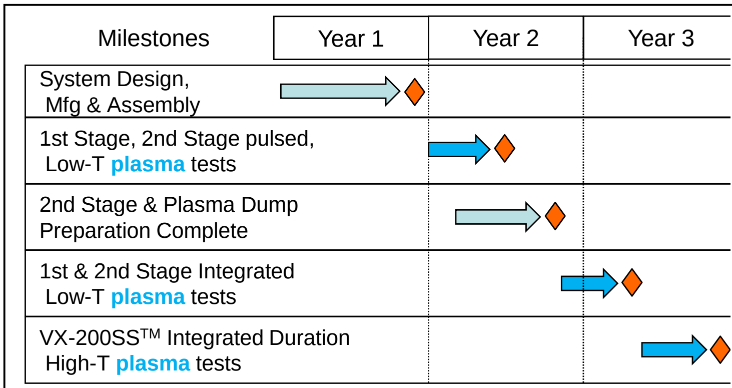

Figure 7 High level schedule for the VX-200SS program

expected to give pessimistic erosion results compared with in-space operation because of a small additional charge exchange load in the plasma acceleration section.

VI. Summary

The VASIMR® system technology has made tremendous progress in the development of a spaceflight ready application. The VX-200™ program has verified plasma and power performance as well as 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 shows a VASIMR® thruster string can achieve a specific mass below 3 kg/kW. Physics-based and benchmarked modeling shows system efficiencies with I_{sp} ranging from 2000 to 5000 s using argon and krypton. The use of other propellants makes it possible to further expand the operational envelope.

We are presently a year into implementation of the VX-200SS program to demonstrate thermal steady-state operation at input power levels exceeding 100 kW for over 100 hours of continuous operation. This involves manufacturing of a new rocket core and implementing significant upgrades to the RF subsystems, vacuum chamber, and performance measurement diagnostics. The VX-200SS program will enable duration testing that will be long enough to measure plasma facing wall erosion with a precision sufficient to evaluate component lifetime relative to the design goal of more than 10,000 hours of plasma operation. The program is to be completed in three years, with the first year consisting of mostly construction and upgrades to subsystems and components. The first year is nearly complete, so we are in the integration process in preparation for plasma operations. Integrated plasma testing at high power begins in the second program year and will be completed in three major operational campaigns.

Acknowledgments

NASA Next Space Technologies for Exploration Partnerships (NextSTEP) Broad Agency Announcement. Ad Astra Rocket Company would like to thank Nautel Ltd of Halifax, Canada for their excellent work in contributing the RF generators used in VX-200 testing.

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