Steady-State Testing in the VASIMR® VX-200SS™ Project

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The VASIMR® VX-200SS™ program has completed six years of development and testing under a NASA NextSTEP contract with the goal of demonstrating a steady-state, 100-kW engine at a Technology Readiness Level of 5. In July 2021, the VX-200SS™ operated at 80 kW for 88 hours continuously, exceeding by fifty-fold its previously demonstrated duration at this power level. Several upgrades to the rocket core enabled this new scale of endurance, including a new endplate geometry, new antenna and ceramic window assemblies, and improved gas sealing at ceramic joints. Surface temperature and residual gas analyzer measurements affirm the merits of these design changes. In addition to the rocket core, a TRL-5 power processing unit has facilitated the success of the project by quickly recovering from transients on the power circuit of the ion heating stage. Thrust measurements were consistent within ±10% throughout the 88-hour test, with no long-term trends. The VX-200SS™ ion heating stage is presently being modified to enable steady state operation at 100 kW in late 2021.

I. Introduction

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR®) is an emerging technology in the field of in-space electric propulsion. VASIMR® uses two stages of radio frequency heating in a strong magnetic field to produce an intense plasma exhaust. The ions are fully magnetized within the rocket core, allowing efficient power coupling from an electrical power system via ion cyclotron heating. Recent operations have used argon propellant, but deuterium, krypton, and neon have also been tested. Power coupling in both stages occurs through a ceramic window; there are no electrified surfaces directly exposed to the plasma. Because the plasma is quasineutral throughout the rocket core, there is also no need to neutralize the exhaust. The propellant flow, 1st stage power, and 2nd stage power can all be varied independently to change thrust and specific impulse.

The VX-200SS™ is a 100-kW, thermal steady-state variant of the earlier, 200-kW VX-200™ pulsed prototype, developed privately by Ad Astra Rocket Company. The VX-200SS™ program was initiated in 2015 as a public-private partnership between NASA and Ad Astra under the Next Space Technologies for Exploration Partnership (NextSTEP) Program. The goals of the prototype development program are to advance the VASIMR® technology to TRL 5 and to demonstrate the thermal management necessary for continuous, long-duration operation at 100 kW of direct current (DC) input power.

The VX-200SS™ is artificially limited in power and efficiency because it uses the legacy VX-200™ magnet. However, a steady-state rocket core and magnet which are designed for each other could potentially reclaim the

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performance demonstrated by VX-200™. Reference [1] details the thrust, efficiency, and specific impulse that future VASIMR® designs will aim to replicate. Reference [2] estimates the mass versus power of a spaceflight VASIMR® system.

A. Ceramic Surface Temperature Measurements

A conceptual schematic of a VASIMR® system is shown in Fig. 2. The 1st stage "Ionizer" is a helicon-type plasma source. The 2nd stage "RF Heater" is an ion cyclotron heating device. Figure 2 also shows the temperature measurement locations of plasma-facing ceramics in the VX-200SS™ prototype. The ceramic windows confine neutral gas and allow RF power to be coupled through to the plasma, but they must tolerate the associated heat load. Ceramic temperature measurements are therefore important for monitoring the performance of the thermal design. Ad Astra has been using infrared pyrometers to measure plasma-facing component temperatures since 2019. Earlier efforts were thwarted by the challenges of the ambient environment within the rocket core.

B. Power Measurements

Each stage of a VASIMR® thruster uses an independent radio frequency power system. Figure 3 shows a simplified schematic of the power circuit for the 2nd stage of the VX-200SS™ prototype. The circuit for the 1st stage is similar, except that the 1st stage power processing unit (PPU) is still outside the vacuum. Figure 3 also shows the locations where power can be measured in the circuit. In this paper, all presented power measurements were made with the DC current and voltage sensors located just to the left of the vacuum feedthrough. For the 1st stage circuit, the DC sensors are at the connection to the PPU.

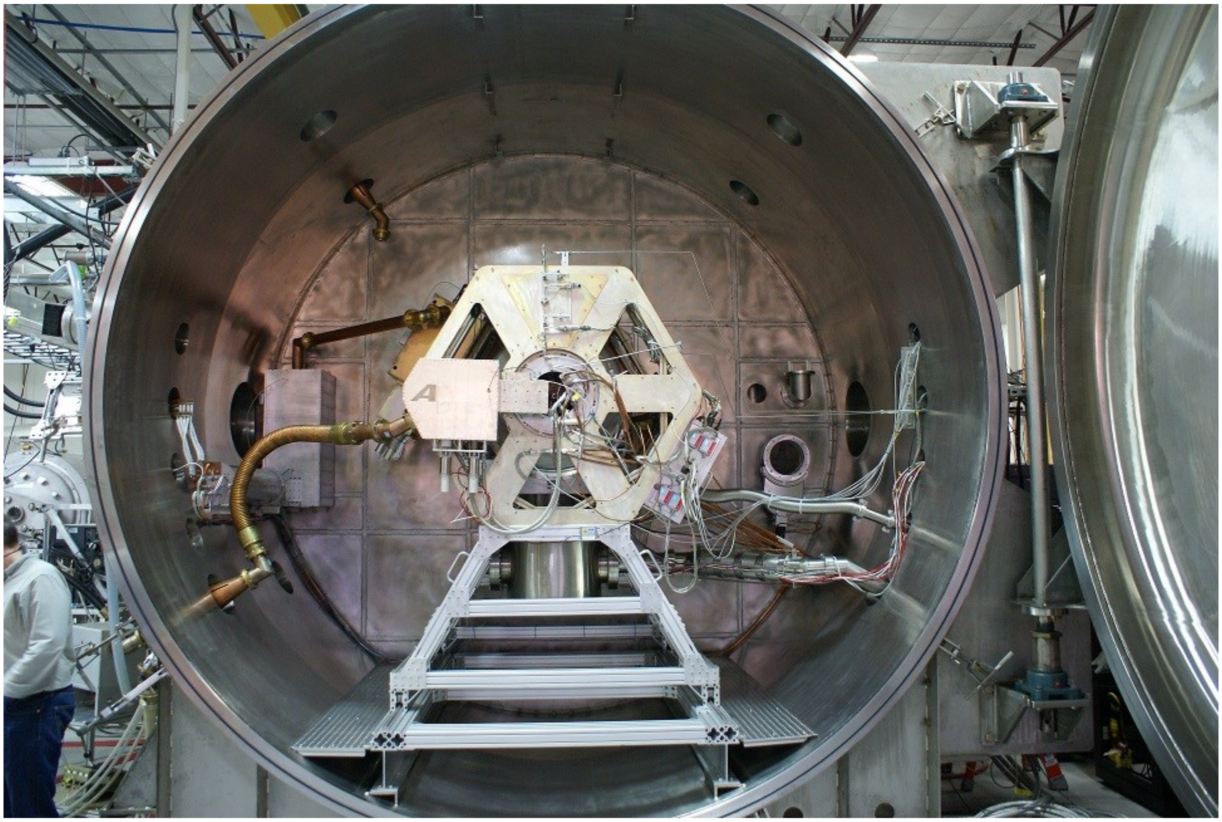

Fig. 1 Upstream view of VX-200SS™ testing facility in 2020.

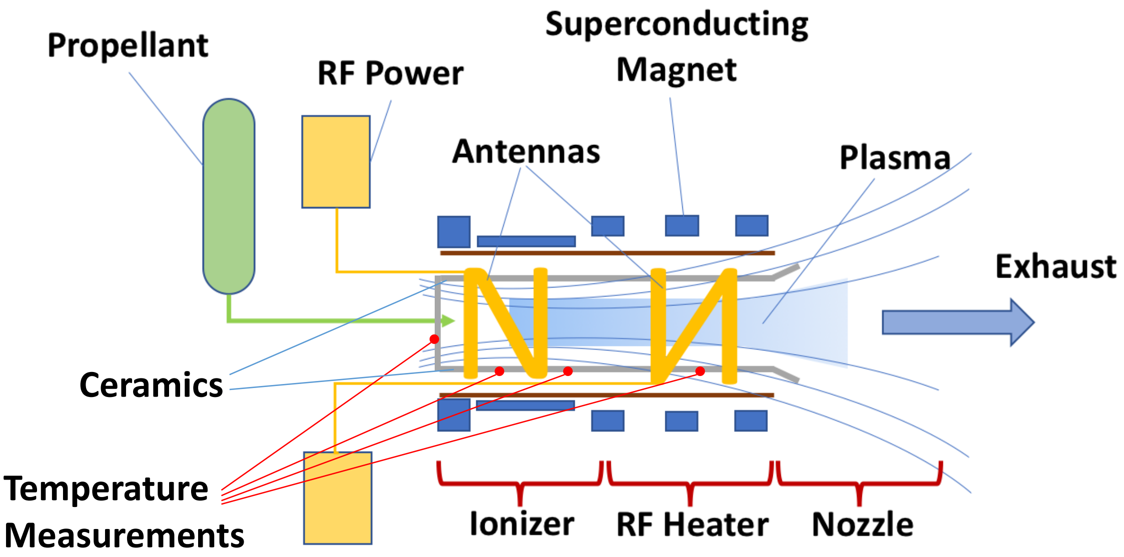

Fig. 2 Schematic of a VASIMR® system with temperature measurement locations in the VX-200SS™.

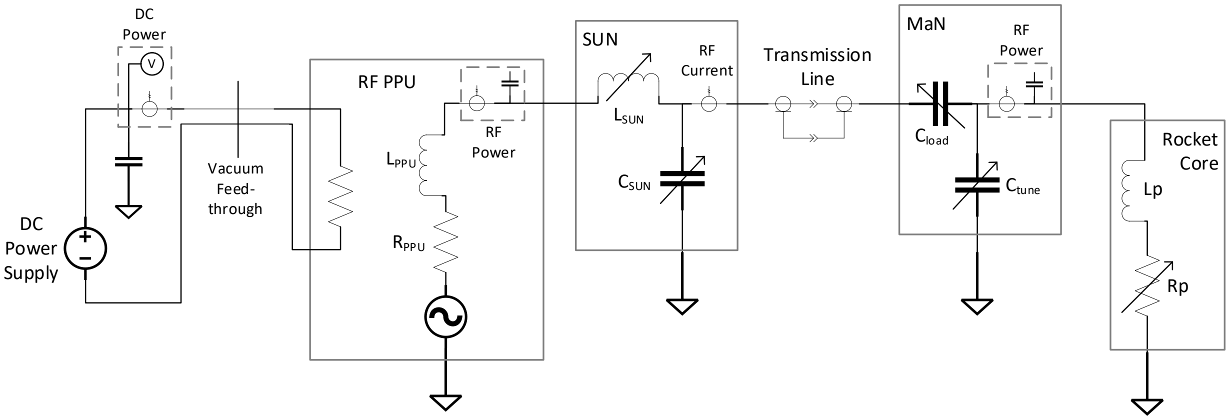

Fig. 3 Simplified VX-200SS™ RF power system with power measurement locations.

II. Evidence of Thermal and Sealing Design Improvements

A. 1st Stage Ceramic Interface

The interfaces between the coolant, the radio frequency antennas, and the plasma-facing ceramics are critical features of the VX-200SS™ rocket core design; the ceramics require sufficient cooling to survive radiant heating by the plasma. In early 2020, a new 1st stage antenna and ceramic assembly was integrated into the VX-200SS™. A major design goal of the new 1st stage was to improve the thermal interface between the active cooling and the ceramics at the operational waste heat load.

Figure 4 shows the operating temperature of the 1st stage ceramics at various power levels and across several testing campaigns. These temperatures were measured by an infrared pyrometer viewing the outer surface of the ceramic tube that surrounds the 1st stage plasma. Integration of the new 1st stage assembly in 2020 is correlated with a distinct reduction in temperature, indicating at least a partial success of the new design. In the subsequent testing of 2021, the 1st stage ceramics have remained within their operating temperature limit.

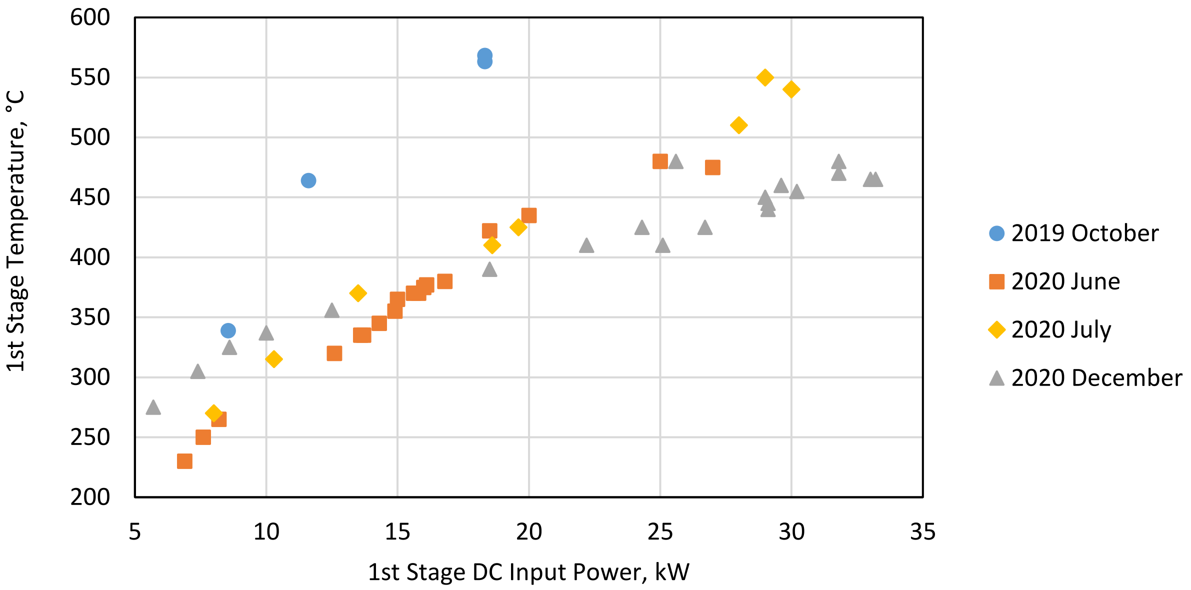

Fig. 4 VX-200SS™ 1st stage ceramic temperature vs. power, major upgrade implemented early 2020.

B. Endplate Geometry

The endplate of the VX-200SS™ is part of the ceramic assembly which contains neutral propellant before it is ionized. This component was a repeated failure point of the prototype prior to late 2020. Intense heating from the 1st stage plasma routinely stressed the ceramic to the point of cracking.

To correct this, the shape of the front end of the rocket core was changed to reduce the heat load on the endplate material. Figure 5 shows the dramatic change in operating temperature of the endplate with the new design, implemented in November 2020. The effect this change has on the 1st stage ionization performance has not yet been carefully studied, but preliminary observations suggest that any effects have been minor.

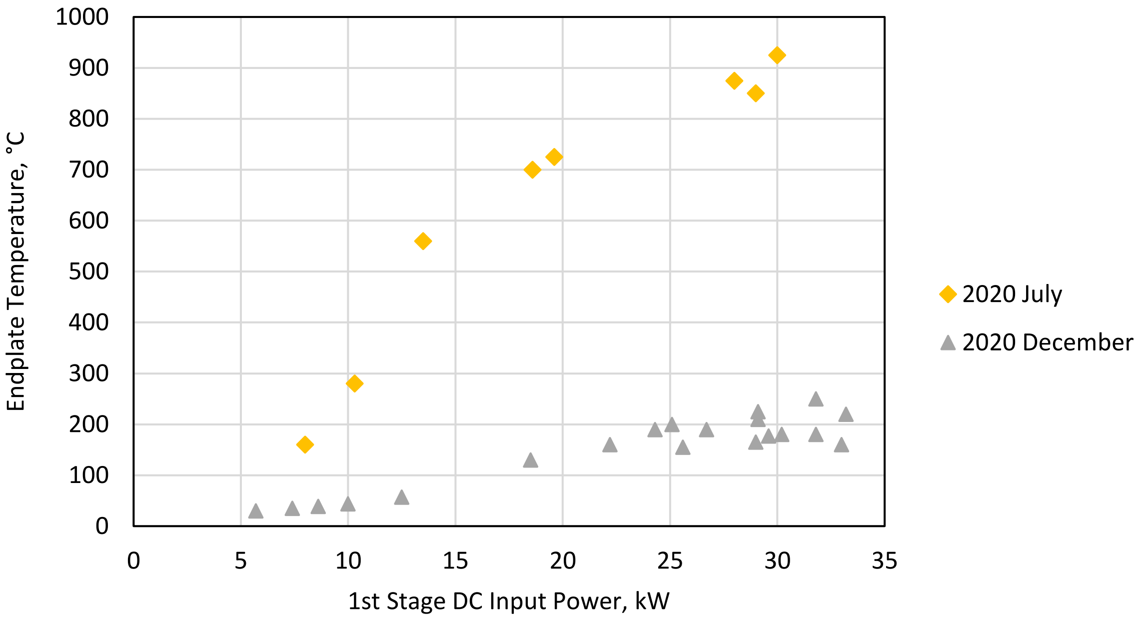

Fig. 5 VX-200SS™ endplate ceramic temperature vs. power, major upgrade implemented late 2020.

C. Propellant Sealing

The plasma-facing ceramics of the VX-200SS™ are an assembly of several manufactured components. The ceramic-to-ceramic joints in this assembly must be sufficiently sealed to prevent leakage of neutral gas into the space between the rocket core and the magnet cryostat. If the pressure in this annular space becomes too high, the operational power of the VX-200SS™ will be limited by Paschen breakdown at the RF antennas. Designing seals for this application has been challenging; the seals must tolerate the temperature cycles of the ceramics, electromagnetic fields in the proximity of the radio frequency antennas, and the static field of the superconducting magnet.

Figure 6 presents two measurements of partial pressure versus time during VX-200SS operation: one made in May 2021 and another in June. These mass spectra were measured by a residual gas analyzer in the upstream section of the vacuum chamber. During thruster operation, the upstream argon (40 u) pressure is due to a combination of argon exhaust leakage through the vacuum chamber partition wall and neutral propellant leakage from the rocket core seals. Since the vacuum pumping and partition wall seals are typically unchanged from one experimental campaign to the next, the evolution of ambient upstream argon pressure during thruster operation is a good indicator of the rocket core seal quality.

The May 2021 RGA plot in Fig. 6 shows an example of inadequate seal performance. During this test, the argon leakage from the rocket core degraded to the point where argon became the dominant gas species in the upstream section of the vacuum chamber. A Paschen breakdown eventually formed in the rocket core annulus and the test was terminated. The VX-200SS™ seal design was upgraded in the following month, and the June 2021 RGA plot shows a more favorable mass spectrum. The new seals were able to control the argon leakage to an acceptable rate throughout the temperature rise in the rocket core, thereby enabling long-duration testing.

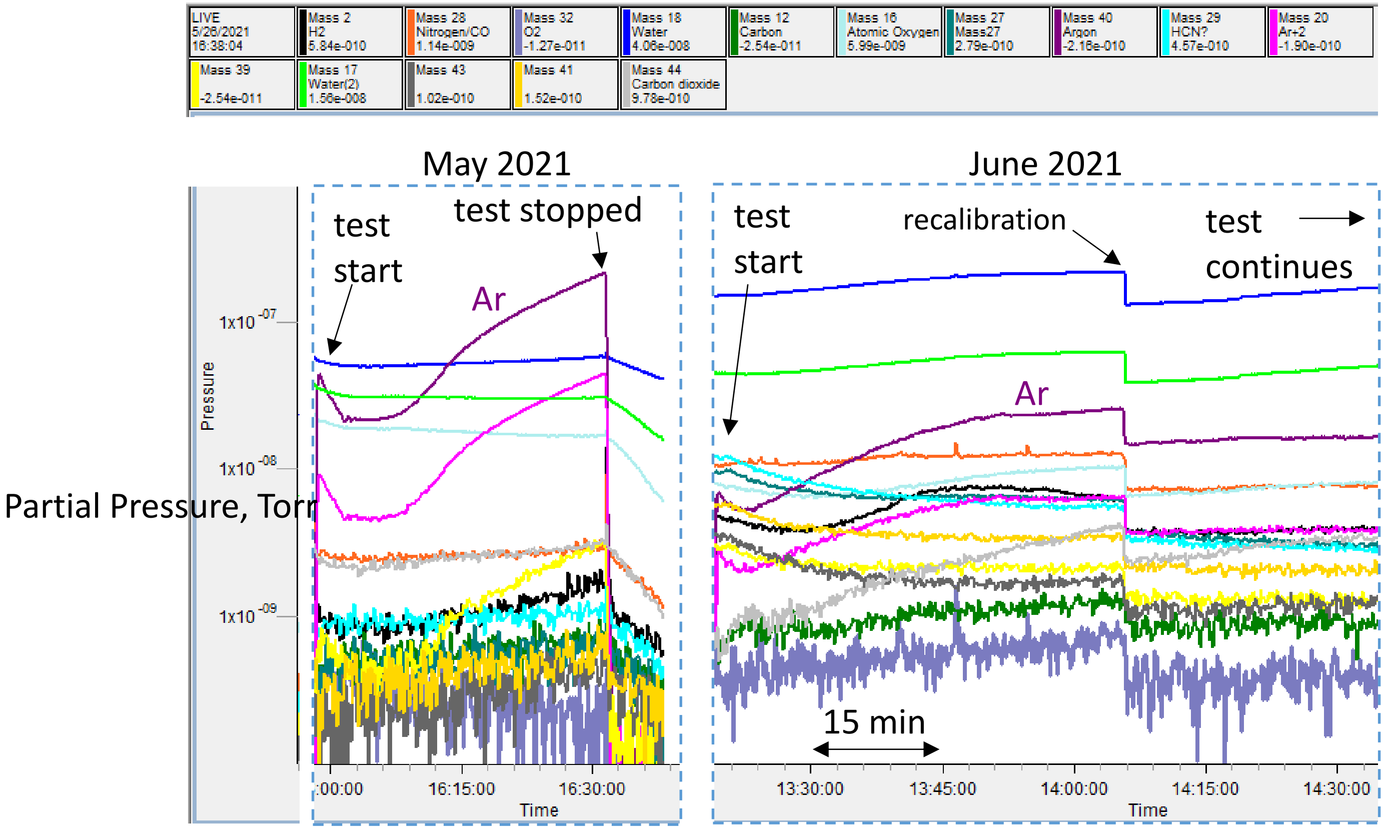

Fig. 6 Residual gas analyzer spectra measured while at power, before (May) and after (June) upgrades to the VX-200SS™ propellant seals.

III. Record Endurance Test

In June and July 2021, the VX-200SS™ demonstrated several record firing durations at total power levels of 70 and 80 kW. During this testing campaign, the prototype benefited from the design improvements evidenced in Figures 4, 5, and 6. Additional upgrades were made to the RF transmission lines between the matching network and antenna in both the 1st and 2nd stage power circuits. The 2nd stage antenna and ceramic assembly was also replaced, but a discussion of this upgrade will be presented in a future publication.

The most notable endurance test occurred from July 12 through July 16, when the VX-200SS™ operated at 80 kW for 88 hours. This operation was intended to demonstrate a 100-hour firing at the highest possible power, but a faulty sensor triggered an automatic shutdown by the thruster control system at the 88.1-hour mark. Despite the early termination, the July test demonstrated fifty times greater endurance at the 80-kW power level, and twenty times greater endurance at any power level, than previous VX-200SS™ testing campaigns.

Figure 7 shows the total DC input power and the rocket core surface temperatures vs. time during the 88-hour test. The commanded 2nd stage power was constant throughout the test; the 1st stage power was manually varied by less than one kW due to tuning operations on the RF matching network. The power balance during this test was approximately 30 kW from the 1st stage and 50 kW from the 2nd stage. Argon propellant flow rate was constant at 63.4 mg/s.

Momentary reductions in power were due to an algorithm which disabled the output of the 2nd stage PPU for 500 milliseconds during transient faults on the RF circuit. Following the 500 millisecond wait period, the PPU re-initiated its power ramp sequence, which for this test was programmed at 1.4 seconds. Post-test visual inspection of the thruster revealed the likely cause of the faults, and an appropriate design change is in progress.

The 2nd stage ceramic temperature typically dropped by about 2°C in response to circuit fault transients, which is not discernable on the scale of Fig. 7. The notable drop in 2nd Stage temperature around hour 7 and the sudden jump in temperature at hour 77 were likely due to unintended changes in the active cooling flow rate. Design changes now in progress will also mitigate this cooling flow instability.

In general, the 2nd stage ceramic temperature was too high for this power level. It predicted difficulty in achieving steady state operations at 100 kW, which was later confirmed by operational testing. The aforementioned redesign of the 2nd stage will also attempt to lower the ceramic operating temperature in late 2021.

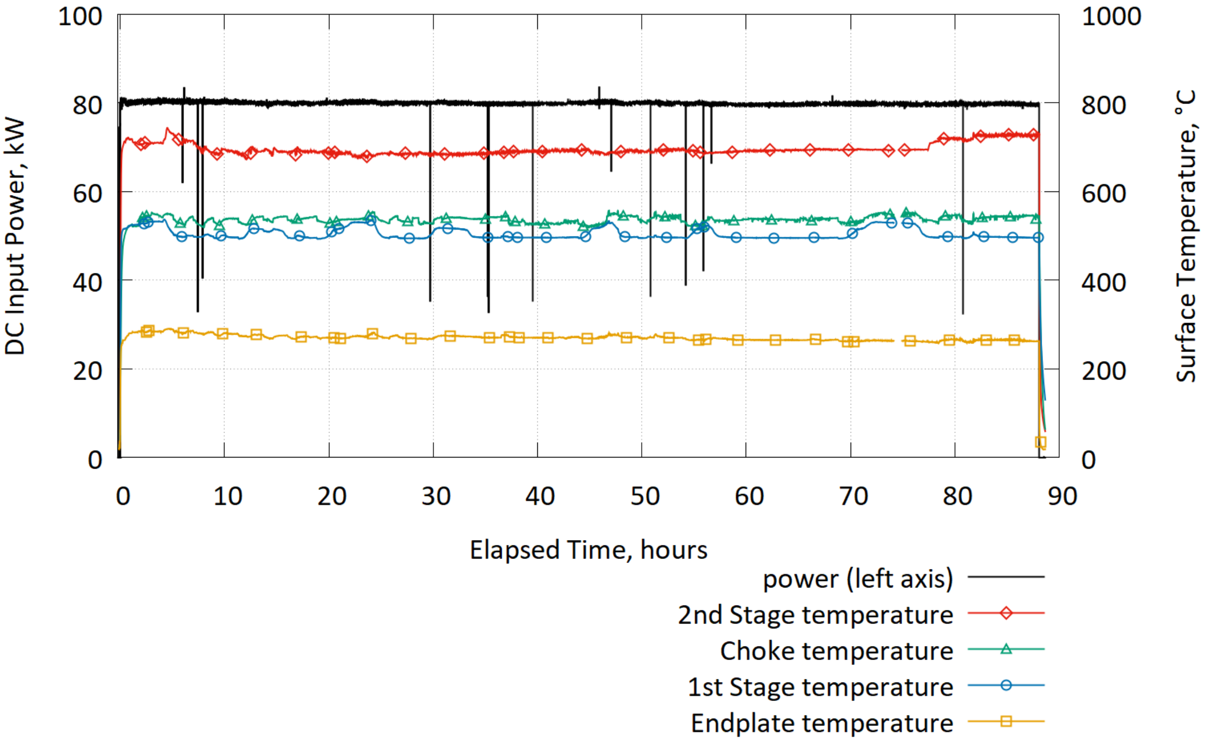

Fig. 7 Power and surface temperatures vs. time during the longest firing of the VX-200SS™, 12-16 July 2021.

The choke is the region between the 1st and 2nd stages of the rocket core. The choke temperatures shown in Fig. 7 are lower by approximately 100°C than they were in early 2021. This reduction was accomplished by improving the thermal interface between the active cooling and the ceramic surface. The reduced choke temperature has likely contributed to the improved gas seals demonstrated in the RGA spectra of Fig. 6.

A gap in the temperature data of Fig. 7 at hour 74 is due to operator error. Otherwise, the plot shows every power measurement and every twentieth temperature measurement. DC power was sampled every 2 seconds and temperatures were sampled every 1.6 seconds during this testing campaign.

A. Thrust Measurements During 88-hour Test

The VX-200SS™ thrust was measured ten times during the 88-hour test. In a similar way to the technique described in Ref. [3], thrust was measured using two redundant plasma momentum flux sensors translated radially through the plasma exhaust plume. Thrust density was integrated assuming azimuthal symmetry. New to this testing campaign, however, was the ability to incorporate the signal from a third momentum sensor that is radially offset from the thruster axis and the scan axis. The offset sensor reduces the uncertainty associated with the assumption of azimuthal symmetry.

Figure 8 presents the thrust measurements made throughout the July 12th-16th operation. Pairs of coincident measurements represent left and right-moving scans of the exhaust plume. There is no significant trend in the thrust measurements. However, the precision is not as good as previously demonstrated. A fourth sensor is out of commission and could reduce the uncertainty if repaired.

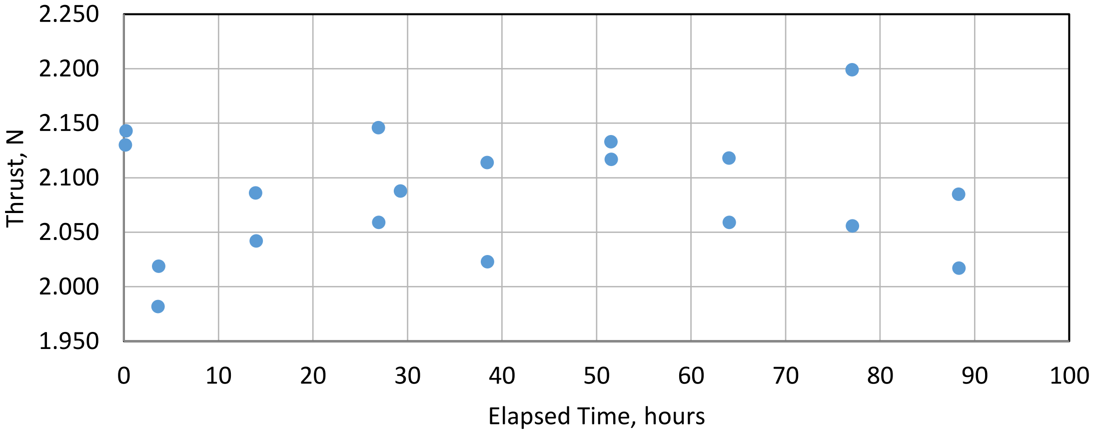

Fig. 8 Thrust measurements during the 88-hour test at 80 kW.

IV. Firing Durations through 5 Years of Testing

The longest test durations of the VX-200SS™ prototype are plotted against power in Fig. 9. This set is only a representative sample of the longest operations; some of the points represent many repeated firings at the same operating profile. Prior to the recent achievements in the 70-80 kW power range, there had been only gradual progress in power and duration. A collection of improvements was necessary to break through the two to three-hour endurance barrier: reliable coolant and gas seals, actively cooled RF transmission lines, robust thermal interfaces to the ceramic windows, and a modified endplate geometry. Together, these changes enabled the 1st stage to operate at 30 kW, roughly its full power, and the 2nd stage at 50 kW, about two thirds of its design power.

Figure 9 also shows the continued difficulty in achieving long-duration operations at 100 kW. The present configuration of the 2nd stage precludes further increases in steady state power. The near-term plan for the VX-200SS™ is a relatively straightforward modification of the 2nd stage assembly, with testing expected in late 2021. A more substantial re-design is also being investigated but would likely not be realized until early 2022.

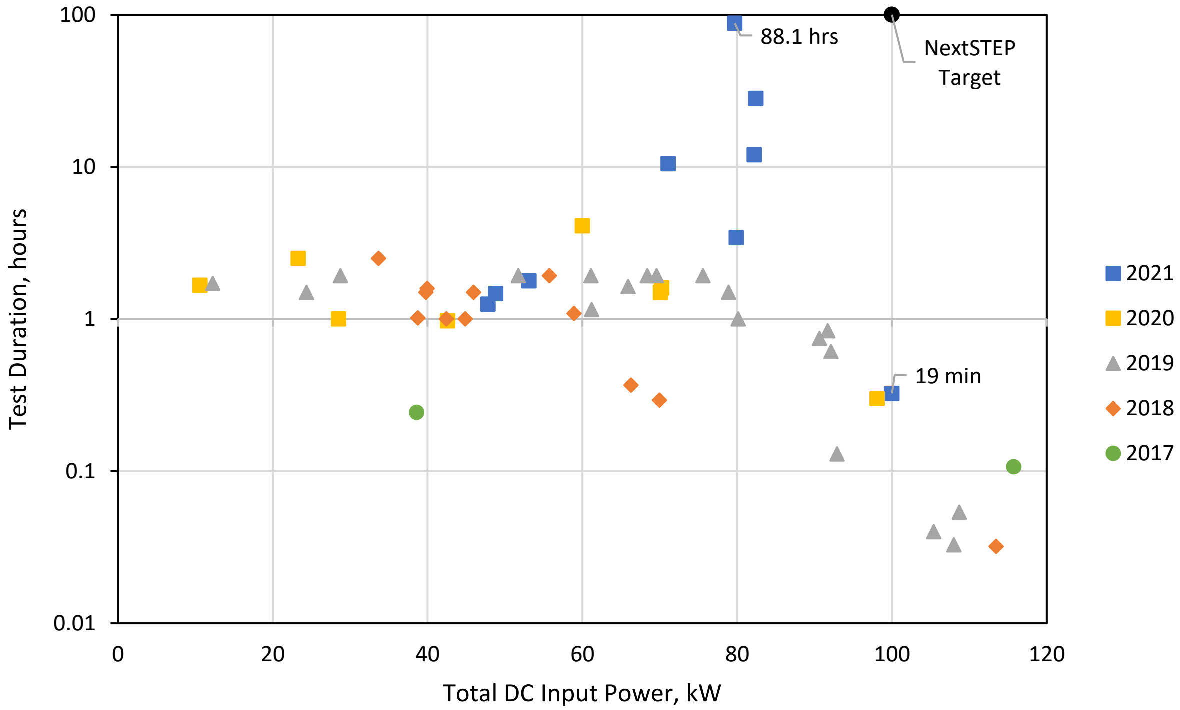

Fig. 9 Longest firings of the VX-200SS™ prototype versus power.

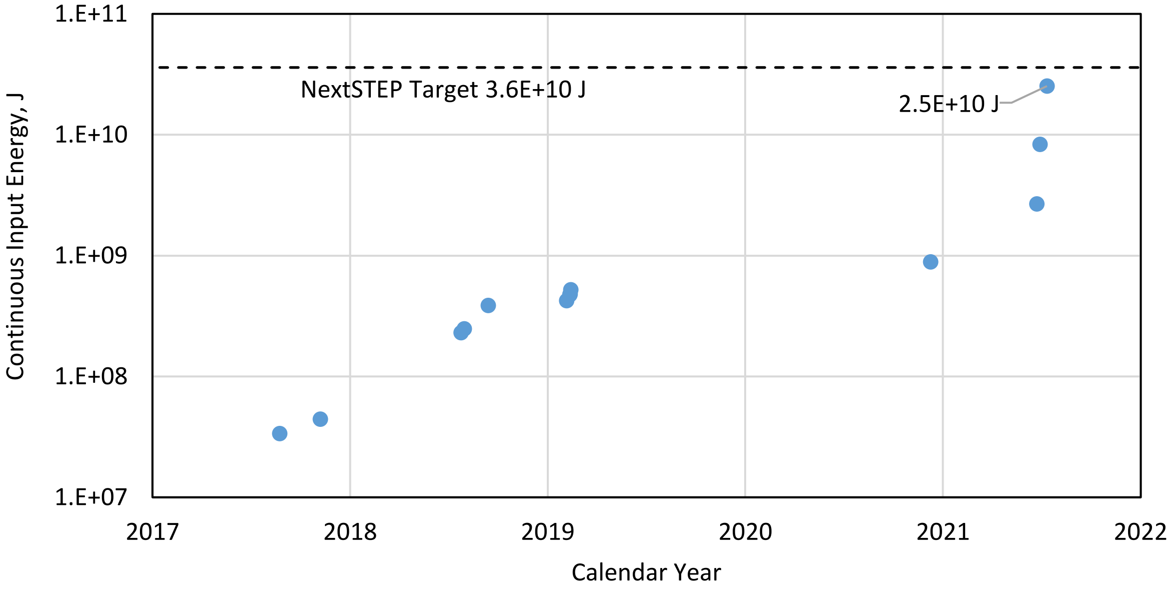

Fig. 10 Timeline of the VX-200SS™ maximum demonstrated continuous DC input energy.

V. Conclusion

The VASIMR® VX-200SS™ prototype demonstrated remarkable improvement in its steady-state operating power over the last 6 months, validating a series of design improvements to the rocket core and the RF power systems. Although the NextSTEP contract term has ended, Ad Astra continues to develop the prototype toward a demonstration of 100 kW in steady state. Nearly every component in the VX-200SS™ rocket core has been rebuilt since plasma operations began in 2016. An on-going rebuild of the ion heating stage will be completed in late 2021 with testing to immediately follow. Lessons from the last six years of development are being incorporated into the design of a TRL-6 system, as Ad Astra works to make VASIMR® part of the future of space propulsion.

Acknowledgments

Development of the VASIMR® VX-200SS™ has been supported in part by Ad Astra private funds and by NASA's NextSTEP Program.

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