Solar Electric Propulsion (SEP): Comparing the Power Niches for SEP-VASIMR® and SEP-Hall Technologies

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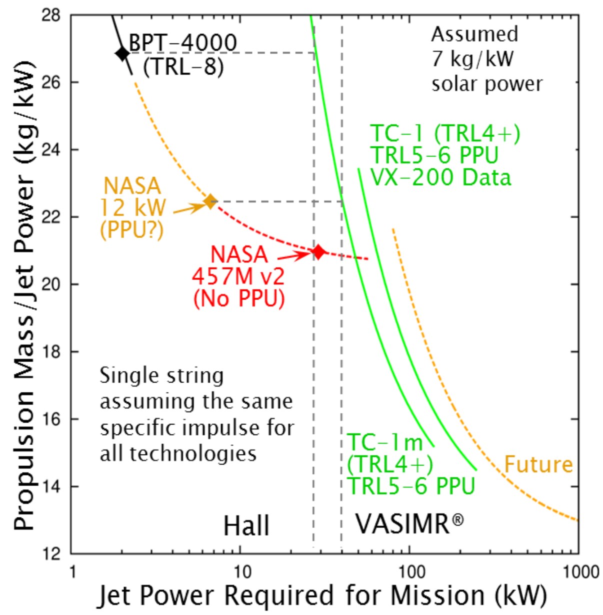
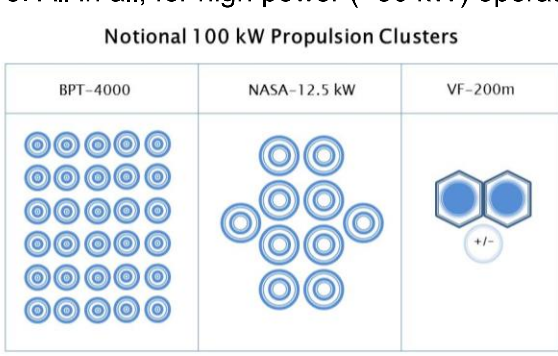
June 15, 2014



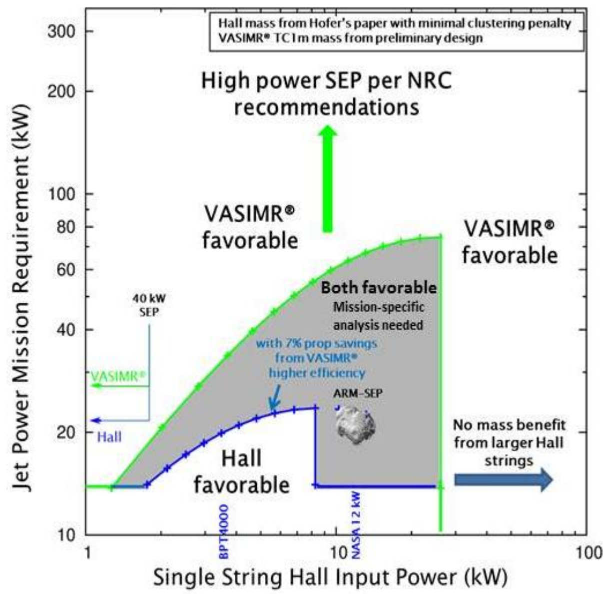
A convenient way to visualize the natural power niches of SEP-VASIMR® and SEP-Hall technologies is to plot the "propulsion mass/jet power" vs the jet power required to accomplish the mission under consideration. The propulsion mass is the total mass of the propulsion system, including the solar array, the power processing unit (PPU) and the thruster itself. The goal is, of course, to reduce that "system" mass as much as possible. By assuming the same specific impulse (I_{sp}) for both systems and the same weight for the solar array at 7 kg/kW, the salient features of the two technologies can be assessed side by side and the favorable power niche for each can be identified.

The Power Niche - From the figure at right, it is evident that both technologies "shine" in different power regimes with a small overlap at about 50 kW. At power levels below 50 kW, the Hall system shows a clear advantage in terms of propulsion system mass, while above that value, the VASIMR® system is the better choice. The controlling physics of each technology are responsible for the trends exhibited by the curves. SEP-Hall propulsion systems have a lower power density, so their "propulsion mass" reaches an asymptotic value at approximately 20 kg/kW as the power increases. Large clusters of Hall thrusters are required to accomplish high power missions. For SEP-VASIMR®, the "propulsion mass" is a steeper function of power, which renders this technology uncompetitive at low mission power but gives it a strong advantage at power levels above 50 kW.

Technology Readiness – For high power (>30 kW), both SEP-VASIMR® and SEP-Hall have achieved rough technological parity in the whole, though not in the parts. For example, the 200kW, VX-200 VASIMR® laboratory prototype has been successfully fired at high power more than 10,000 times with extreme reproducibility and excellent performance (>70% thruster efficiency, 5000 sec I_{sp} and 6 N thrust); however its integrated thermal management subsystem is still to be fully demonstrated. On the other hand, the NASA 12 kW Hall thruster has the technological heritage of its lower power cousin, the BPT-4000, but its Power Processing Unit (PPU) is not yet available and remains a challenge. In contrast, the SEP-VASIMR® PPU is at a high state of maturity at a technology readiness level (TRL) of ~5. All in all, for high power (>30 kW) operation, it could be said that both systems are at TRL~4-5.

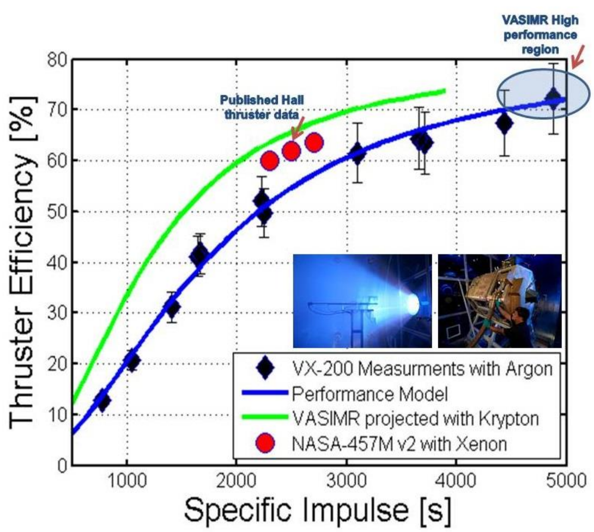


Thruster clustering – In addition to building up to the total mission power requirement, clustering thruster strings is a way to build propulsion system redundancy; however, as mission power increases, so does the optimum thruster size for the cluster. A typical single fault tolerant, SEP-VASIMR® propulsion cluster such as the VF-200m, includes two thruster cells (TCs) and a field-cancelling coil. In this configuration, a full thruster cell string failure can be tolerated with no significant impairment of the propulsion system performance, as the other cell is capable of handling all of the power. In a "per kW" basis, low power thrusters tend to be generally heavier than higher power ones. On this basis, SEP-Hall and SEP-VASIMR® show regions of favorable mass in the (log-log) power space of the image at right. The green trace shows the boundary between Hall and VASIMR® favorability, assuming equal I_{sp} for both. Hall systems gain favorability against VASIMR® with increasing power up to a maximum single string power, beyond which VASIMR®'s higher power density always results in a lighter string. For the Hall systems considered in this study[1] this maximum is about 25 kW. At low power, VASIMR® systems below ~15 kW of jet power are technologically unattractive. Recent experimental data also show a 7% thruster string efficiency advantage for the VASIMR®, which brings the issue of the propellant effect on the propulsion mass budget front and center. For example, if the difference in efficiency is traded for a higher I_{sp}, the end result is a 7% reduction in the propellant component of the mass, thus reducing the region of Hall favorability as shown by the blue trace. The green and blue traces define a "favorability grey area" where further mission-specific analysis is required to assess the best technological choice. NASA's approximate point design for its 40 kW ARM-SEP mission is illustrated for reference.



Storing the propellant - Arguably, in a mission-specific sense, differences in overall spacecraft mass due to the impact of the required propellant tankage could have an effect on the general picture emerging from this visualization. We have not included these differences in our study and we now elaborate on the reasons compelling us to make that choice.

First, long-term cryogenic storage will greatly reduce those differences. Noble gases are only "mild cryogens" and propellant storage at much lower temperatures is already a strategic technology requirement in the current all-chemical or nuclear-thermal propulsion architecture envisioned for human Mars exploration (DRA-5.0) and is being vigorously pursued, in parallel and independently of SEP.



VX-200 performance data, (Inset: VX-200 engine, and VX-200 plume at 200 kW)

Second, the added cost of a higher pressure Argon tank, as compared to Xenon, would be offset over time by savings in the cost of the propellant itself. Argon is about 1/200 the cost of Xenon, so an increased development expense in an Argon tank to carry a cheaper propellant at a higher pressure, would be amortized, beyond the ARM-SEP mission, on evolvable tank technology for Mars.

Third, for SEP-VASIMR®, Krypton is also an attractive propellant with ideal gas storage properties closer to those of Xenon and, with higher field magnets, Xenon itself could also be used, eliminating entirely the propellant tankage difference.

[1] Hofer, R.R. And Randolph, T.M., "Mass and Cost Model for Selecting Thruster Size in Electric Propulsion Systems", *AIAA Journal of Propulsion and Power*, Vol. 29, No. 1, 2013, pp. 166-177.