The VASIMR Engine: Benefits, Drawbacks, and Technological Challenges

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Abstract: Literature research has been performed to identify the benefits, drawbacks, and main technological challenges of the VASIMR engine: the good, the bad, and the ugly about the concept. VASIMR is arguably the most flight-ready high-power space propulsion system anywhere in the world at a current technology readiness level of 6. The throttling ability, propellant choice freedom, relative high thrust, and electrodeless design make the engine very attractive for drag compensation, satellite repositioning, lunar/martian cargo, and/or interplanetary missions. Efficient only at high powers, the size and complexity of the RF, power, and thermal systems represent important challenges that have kept the engine grounded since originally proposed ready-for-flight in 2004. This paper presents a critical analysis of the current status of the engine and the major technological roadblocks and uncertainties towards flight by late 2014.

Nomenclature

AARC = AdAstra Rocket Company
CPT = Constant Power Throttling
EATCS = External Active Thermal Control System
HEMP = High Efficiency Multi-stage Plasma thruster
HiPEP = High Power Electric Propulsion Ion Thruster
HSF = Human spaceflight
ICRH = Ion Cyclotron Resonance Heating
ISS = International Space Station
LSS = Life support system
PPT = Pulsed Plasma Thruster\
VASIMR = Variable Specific Impulse Magnetoplasma Rocket

I. Introduction

The present work focuses in the Variable Specific Impulse Magneto-Plasma Rocket –VASIMR- engine; one of the most promising electric propulsion technologies today. After little more than 70 years since the successful firing of the V2 rocket in 1943, humanity has seen an incredibly fast development of rocketry opening the doors to the space age. In less than 1% of recorded history, humans have managed to place spacecraft as far as the edges of the solar system, send astronauts to and back from the moon, and most recently retired the first partially re-

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usable spacecraft in history. Today, the space industry is a 72 Billion dollar industry [29] spanning Earth Observation, Telecommunications, Space Science, and Human Space exploration efforts which all rely on propulsion technologies to access and exploit the space environment.

Starting with Arcjet thrusters in the 1970s, electric propulsion entered the market of GEO station-keeping applications. Electric propulsion is slowly becoming a standard for long-range exploration missions (i.e. Hayabusa, Dawn, Bepi-Colombo) due to its propellant mass savings, flexibility, large ΔV capabilities, and especially due to the advances on space power generation broadening power availability aboard spacecraft. Most flight proven electric space propulsion engines have relatively high Isp, but their thrust is much smaller than their chemical counterparts (see Table1 below). VASIMR is trying to bridge the gap between high-thrust propellant-needy thrusters and the propellant- efficient low-thrust electric propulsion systems. Under the new NASA's vision for space exploration, the development of new space propulsion VASIMR engine enjoys great importance[15].

Its inventor, Franklin Chang Diaz –a nuclear fusion researcher by training-, developed the concept of the engine back in 1979 with hopes to lay the basis for a nuclear fusion rocket of the future. The VASIMR concept uses fusion technologies to ionize, contain, accelerate, and detach large densities of plasma to generate relatively large thrusts. Furthermore, it offers the advantage of throttling which would allow optimization of trajectories and reasonable abort options for manned missions. However, since the early 1980s, VASIMR remains in the drawing boards and laboratories. It was proposed for flight aboard experimental spacecraft by mid-2004 and targeted for implementation in ISS slipping from 2006, 2011, 2013, to currently mid-2014[4, 15]. The present report critically reviews the accessible literature on the VASIMR and identifies the technological challenges that need addressing towards successful demonstration and future long-term operation of the engine.

II. The VASIMR, a peak under the hood

In the following hopelessly inadequate three paragraphs, a brief qualitative introduction of the operational concept of the VASIMR is presented (more details in [1,2,3,4]). The goal is to exclusively introduce the operational basics for sake of clarity during the rest of the publication. Figure 1 below illustrates the main stages of the engine:

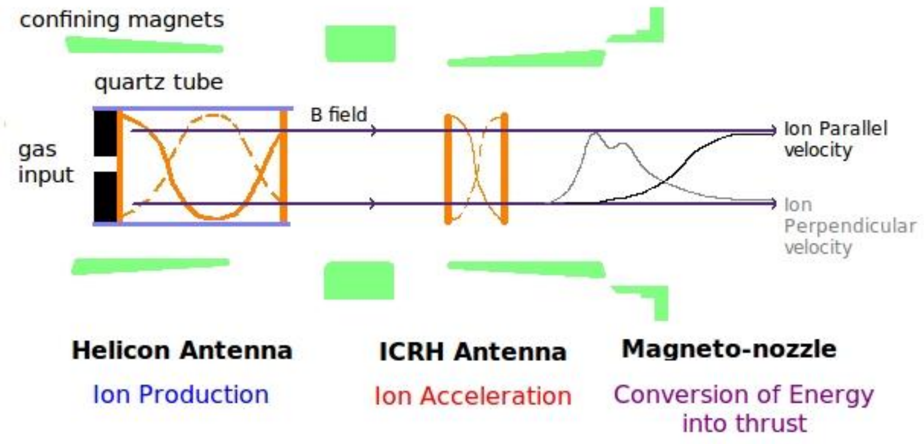

Figure II-1. VASIMR Engine schematic

Figure II-1 above shows the main three stages of operation of the VASIMR engine. First, the helicon antenna ionizes the incoming gas and produces low temperature plasma. Secondly, the single-pass Ion Cyclotron Resonance Heating (ICRH) antenna 'heats' the plasma by exiting the ion population to resonance. Finally, the magneto-nozzle takes the hot plasma's transversal (perpendicular) velocity and transforms it to longitudinal (parallel or axial) kinetic energy in the desired thrust direction. Throughout all stages, there is a strong axial magnetic field that confines the plasma and is imperative to the operation of each stage.

After neutral gas is injected into the core, initially confined by the quartz tube, the first step is plasma production through the helicon antenna. It introduces right-hand circularly polarized electric fields, which in the presence of an axial magnetic field, incite helicon or whistler-mode waves into the media. The electromagnetic oscillations at frequencies of 10-50 MHz energize free electrons in the gas. The electrons quickly multiply by ionizing other gas molecules through collisions. The process creates a chain reaction that can achieve large ionization ratios (close to 100 % [12, 2]) due to the variable temporal and spatial quality of this unique antenna.

Once the gas is ionized into plasma, it is confined by the magnetic fields. The ICRH antenna then heats the plasma by driving the ions to resonance. Much like the house-hold microwave which excites water molecules in food to resonance and causes heating in the food through friction, the ICRH antenna emits left-circularly polarized radio waves that match the natural frequency of ions and increase the plasma temperature upwards 10,000,000 °C . The mostly transverse plasma's kinetic energy is then transformed into axial (thrust-producing) velocity by the magneto-nozzle. The latter consists simply of an adiabatic (slow) variation of the confining magnetic field and relies on the physics of magnetic constriction. At some point downstream, the growing plasma β (ratio of plasma pressure to magnetic pressure) allows a super-alfvenic transition to detach the plasma from the rocket without allowing perturbations to propagate but downstream. More details can be found in [1, 13 and references therein]

III. Benefits, the Good

A. Constant power throttling

The Variable Specific Impulse Magneto-plasma rocket has *throttling* written on its very name. This capability can prove quite valuable in interplanetary flight when high thrust is needed to quickly escape a planet's gravity field and low thrust is ideal for long coasting periods when fuel efficiency is paramount. Emergency conditions in human space flight missions also praise the ability of the VASIMR to quickly turn around in high-thrust mode to return to safety as soon as possible. The secret to the variable specific impulse lies on the power management to both the helicon and ICRH antenna stages. Isp changes occur at constant power, fully utilizing the power source in the spacecraft at all times.

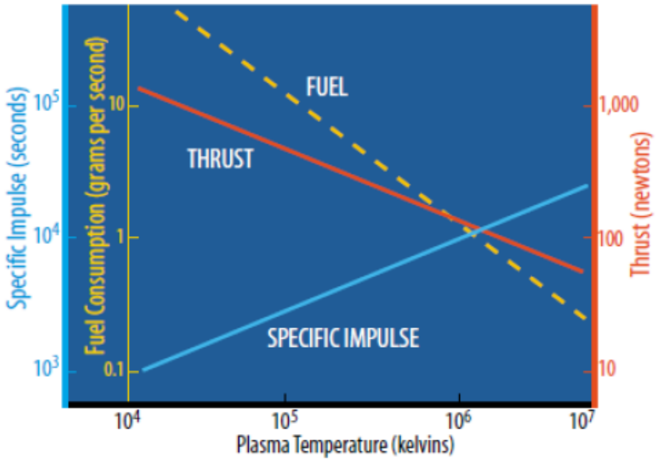

Figure III-1Constant Power throttling thrust and fuel-consumption specs. Thrust and fuel use are seen to decrease as specific impulse is increased. Adapted from Chang-Diaz (2000) credited to John de Santis.

In low-thrust-high-Isp mode, the bulk of the power is directed towards the ICRH antenna ensuring large energy transfer and very high kinetic energy in the exhaust plasma. However, the decrease in power to the helicon stage implies smaller plasma density and gas flow; therefore, less material is ejected with the concomitant reduction in thrust. Conversely, in high-thrust-low-Isp mode, a larger portion of the energy is routed towards the helicon antenna. Therefore, more propellant is injected and successfully ionized resulting in a denser, richer, plasma bulk being heated by the ICRH antenna. Since the heating/acceleration stage would not have enough power to heat all ions in the dense plasma, it would consequently accelerate the plasma to a smaller exhaust velocities. Because more propellant is ejected in this case, the thrust is higher. These two modes are graphically summarized in figure III-1 above.

Even though Isp throttling is also possible in low-power electric propulsion technologies such as PPTs or HEMPs, the VASIMR is the only EP engine in the 100kW-range with such capabilities today [15]. The VASIMR offers the unique advantage of constant power throttling. In the case of variable-trust PPTs, for instance, the thrust is increased with a concomitant increase in input power and potential lifetime decrease through increased electrode erosion. The VASIMR, however, makes full use of the power supply and draws the same power constantly. Also, assuming a sound range of Isp throttling is experimentally confirmed (see section V), VASIMR's variable Isp offers a unique advantage over competing Hall-effect, conventional ion engine, or electro-thermal technologies in the kW range. Commercial versions of Hall Effect engines quote a constant thrust and efficiency levels at a given power. Running these engines off their rated values could result in drastic efficiency drops, faster element erosion, or permanent damage to components.

Another advantage of CPT is the flexibility to abort manned-interplanetary missions. Chemical propulsion systems that put man on the moon made single burns to enter/exit lunar orbit and spent most of their time coasting. If anything goes wrong inside the manned spacecraft, as in Apollo 13, astronauts can only wait till the next scheduled burn to correct their path and direct themselves to safety. Moreover, traditional electric propulsion systems targeted at a single small-thrust and high Isp levels, could easily be used to return to Earth in emergencies; however, the long burn times required to change the trajectories could further jeopardize human life in case of urgent emergencies. The VASIMR is the only space propulsion device to-date *conceptually* capable of turning around and entering high thrust mode to return the crew to safety as soon as possible. Finally, CPT could be used for creating artificial gravity environments and acclimatize astronauts to the destination's gravitational field before their arrival.

B. Electrodeless design

Another advantage of the VASIMR engine is the lack of direct contact between antennas and confining magnets with the hot plasma. The engine is therefore fully re-usable. During the ionization stage, there is a quartz tube used to hold the neutral gas becoming ionized (figure II-1), yet it leaves the plasma to freely flow along the B-field lines shortly after the helicon stage. The quartz tube is thus only exposed to the cold plasma. Neither the ICRH antenna, nor the superconductor magnets, nor the magneto-nozzle ever come into contact with the hot accelerated plasma, which can achieve about 1.8Million Kelvin [29, 15]. Furthermore given that the core of the engine is evacuated, heating can only occur through radiation and/or neutral gas bombardment, which are far less efficient heating processes than convection or direct contact. Other electric propulsion designs rely heavily on elements that come into direct contact with hot plasma, which causes ion erosion and lifetime reductions. Gridded ion, Hall Effect, (i-)MPDs, and electro-thermal thrusters are very good examples of engines where accelerating grids, chamber walls, and nozzle surfaces come into direct contact with the hot plasma experiencing erosion that eventually impedes their operation.

C. Propellant choice freedom

Currently the VX-200 uses Argon as the main propellant. In Carter et.al. [3], it is shown that lighter propellants (H, He, D) are a better choice for interplanetary missions. Lighter propellants result in mass savings that increase the payload size and available mass for power supplies, thus increasing the potential Isp. According to Carter, lighter propellant elements also reduce burn times and power required to achieve a certain ΔV. Argon (18 in periodic table) is clearly not a light gas versus Neon, Helium, Lithium, or Hydrogen. According to a personal communication with Tim Glover [3] (2011), V.P. for Development at AARC, the development effort is focused in Argon because it has an exhaust velocity that is a good match to space operations in earth orbit and other near-term applications. The latest performance report (Cassady, 2010) indicates an exhaust speed of 50km/s, which is indeed relatively high (Table 1)

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[3] Email exchange 20 February 2011.

in the current Earth-orbit market. According to Glover, lighter gasses are certainly the best performers still and would be preferred in the future when high-power supplies are available aboard spacecraft. The VASIMR is therefore capable of using any propellant from Hydrogen, Helium, and Lithium to heavy Xenon and Argon. It is envisioned that either the magnetic field strengths or the antenna driving frequencies would require changes when switching between propellant types. However, the hardware would remain more or less the same and since electrodes do not come into contact with the plasma, the configuration, coating, and/or material hardware concerns can be disregarded.

A favorable consequence of this flexibility allows VASIMR to utilize refuse gasses from open or hybrid life support systems as propellant for propulsion. VASIMR could be installed aboard the international space station (Petro, 2002) and use the waste hydrogen gas from the station's LSS to perform orbit maintenance. According to Petro (2002), drag compensation consumes 60 metric tons of propellant in a ten-year period, while the VASIMR would require as little as 3 metric tons for the same job. Also, the constant thrusting nature of VASIMR could improve the microgravity environment.

D. Neutral Plasma output

In contrast to other high-power electric propulsion technologies such as Hall Effect, and/or Ion engines, the exhaust of the VASIMR engine is neutral plasma. Even though complete plasma detachment from the magneto-nozzle without ions or electrons clinging to magnetic field lines remains to be experimentally confirmed [30] (see section V) the current design has no need to neutralize the output plasma. The latter simplifies the operation reducing the number of parts and ensures a neutral spacecraft as well. MPD, PPT, and electro-thermal thrusters also eject neutral plasma, so this advantage is not unique. Nonetheless, it represents a relevant advantage.

E. Relative High Efficiency

The latest performance reports from the AdAstra company[9, 30] quote a efficiency of 72% at 211kWs input power, above their own semi-emprical models expecting efficiencies aounr 60%. Although a myriad of performance parameters remain to be experimentally confirmed (see section V), the VASIMR ground tests show superior efficiency than Arcjet, HEMP, Hall Effect, PPT and MPD technologies only to be overwhelmed by resistojet, FEEP, and few Ion engines [31]. Table 1 below shows a comparison of the VASIMR with other EP counterparts

Table 1. Electric Propulsion thruster comparison. The high thrust and competitive Isp of VASIMR illustrates the efforts to bridge the thrust gap between chemical and electric propulsion technologies.

Engine	Exhaust velocities (km/s)	Power kW	Thrust (N)	Specific Thrust N/kW	Efficiency	Source
Hall effect engines	16 - 25	1.4 - 20	0.1 - 1	0.07	45-60%	SPT-100 and T-220A [21]
Ion engines	25 - 80	0.8 - 5	0.03 - 0.2	0.04	40-60%	Qinetiq Q, [21]
Resistojets	3 - 5	0.5 - 0.8	0.5 - 1	1.25	50%	TUDelft (HiPEHT-MR 508) [
Arc jets	5 - 16	0.7 - 100	0.1 - 10	0.14	~35%	[21], [38], [35]
Pulsed Plasma Thrusters	6 -50	0.002 - 6	0.00003 - 0.1	0.016	44%	[21], [30]
HEMP	30	1.5-7.5	0.05-0.25	0.03	46-50%	T 3050, T 30250 [32]
VASIMIR VX-200	50	210	5.4	0.03	72%	[9]
RL-10 (Biprop-Chemical)	5	N/A	109900	N/A	N/A	Pratt and Whitney [38]

F. Radiation shielding

The VASIMR could provide two kinds of shielding to humans or sensitive payload aboard interplanetary spacecraft: light-gas propellant tanks, and strong DC magnetic fields. Firstly, the propellant of large interplanetary missions using VASIMR is likely to be lighter than Argon, possibly hydrogen or helium given their higher Isp and mass efficiency. Light gasses are known to be formidable shields against space radiation[1,2] and given the relatively large amounts required for a large mission moving heavy spacecraft, the propellant tanks could be positioned around the cockpit providing natural protection. An example of such configuration is shown below in figure III-2 below:

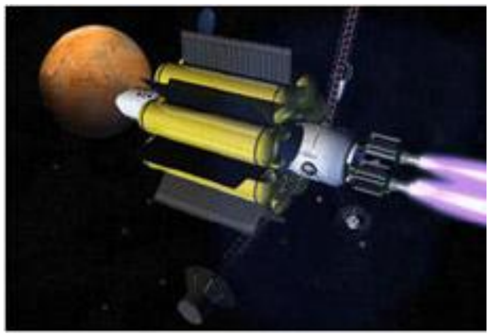

Figure III-2. VASIMR Interplanetary spaceship concept. Courtesy of NASA

Furthermore, as seen above in section II, the VASIMR uses superconductor magnets to induce very strong magnetic fields at peaks of 2 Tesla [30] to constraint the plasma inside the core. A group of international researchers lead by Ruth Bamford [19] disproved the long-held theory that kilometer-long and 100s of Tesla magnetospheres are required to shield astronauts from interplanetary charged particles. By using modern simulations and laboratory experiments, they concluded that a spacecraft could in fact be protected by a magnetic bubble just some 100-200 meters across, which can be created by fields of about 1 Tesla. Very high energy cosmic rays are still a concern, but these fields have the potential to deflect solar wind particles and keep the core of the VASIMR and the surrounding crew/sensitive equipment completely free of external charged solar particles.

IV. Drawbacks, the Bad

A. Complexity and size

The VASIMR is a big engine. A pioneer of fusion rocketry, it is inherently bulky (~1.5m long by 0.5m wide), complex, drives very strong magnetic fields, and requires large amounts of power. Due to the need of high magnetic fields generated with cryogenic superconducting coils, high-power RF sources to ionize and accelerate the plasma, and big power supplies, the VASIMR is no competitor to conventional EP technologies serving the micro, small, or middle-sized spacecraft market. Instead, bigger is better for this engine. Bering et al.[7] state: *"VASIMR is best suited for high power operations. The critical factor that limits efficiency at low power is the amount of antenna loading that can be obtained with the ICRH system."* With the increased interest in microsatellites and minituarization[31], the current complexity of the engine makes it unfeasible for such markets in the near term.

B. Large B fields and strong EM interference

The large magnetic fields and RF waves necessary to run VASIMR could be considered a disadvantage for various subsystems such as telecommunications, instrument payloads, and attitude control systems. Additionally, for HSF applications, even though shown to protect the crew from the space environment, long exposures to large magnetic fields and microwaves in the GHz range can have serious repercussions to the health of astronauts.

The magnetic fields required to run VASIMR represent serious amounts of electromagnetic interference to telecommunication systems and instrumentation measuring the electromagnetic space environment. Magnetic field instrumentation with resolution in the nano tesla regime would be severely challenged by both the large DC fields constraining and the GHz RF waves emanating from the antennas. Shielding and modulation might solve this issues, but increase the complexity and limit the range of possible payloads.

The large magnetic field in the VASIMR could also pose complications to the attitude control system due to the torques induced in the superconducting coils when the external field changes. It is widely known that a conducting loop of wire exposed to a magnetic field would experience a torque due to the Lorentz force. Specifically, if the VASIMR was used to raise a payload from LEO to GEO, the superconducting loops of wire would experience varying degrees of torques as they travel through Earth's dipole magnetic field. The loop's magnetic field would repeatedly attempt to be aligned with the Earth's field, and hence attitude control would require consistent corrections to maintain a certain heading. The current solution as proposed by VASIMR scientists [15] is to strap two twin engines with opposing magnetic field directions. The idea is defined as a zero-torque magnetic quadruple. Such a configuration would have no dipole moment and pose a B-field that drops as r^4 (instead of normal dipole B fields dropping as r^2). Instabilities of such magnetic configurations represent important risks that need to be mitigated theoretically and experimentally. The concept is shown below in figure 8:

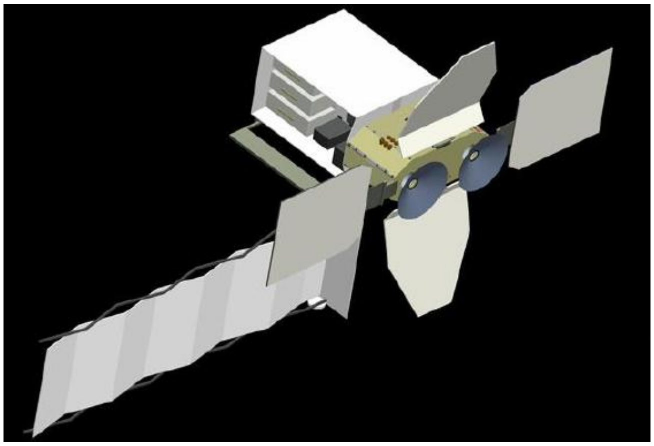

Figure IV-1)VF-200 VASIMR flight unit's to be implemented aboard ISS in 2014. The image shows the twin engines aiming at zeroing the torques induced by Earth's Geomagnetic Field. Courtesy of Ad-Astra 2011.

Finally, the World Health Organization Electromagnetic Fields Project investigating potential health risks associated with technologies emitting EM fields published results indicating severe complications in both short and long term involved with exposure to fields above 100uT (WHO, 2007). They concluded short term effects include nerve and muscle stimulation and changes in nerve cell excitability in the central nervous system. Long-term effect results are not conclusive but show patterns towards childhood leukemia and possibly cancer. The fields under study were; however, 10,000 times weaker than those in the core of VASIMR. Therefore, effective, fail-safe EM shielding must be a high priority in HSF spacecraft design.

V. Current challenges, the Ugly

A. Successful plasma detachment and plume directivity

The concept of efficient plasma detachment through a transition from sub to super-alfvenic flow (similar to a sub to supersonic flow phases in chemical rocket engines) has been theoretically derived and very recently experimentally confirmed [13, 30]. The latest performance reports of full power VX-200 operation demonstrated that the geometry of the plume is consistent with the occurrence of plasma detachment. Retarding potential analyzer (RPA) [30] data shows a tightly collimated plasma jet where a substantial amount of ions flow axially; however, it also shows some ions following along the magnetic fields. Unfortunately, due to thermal control and vacuum pumping limits, the longest test lasted only about 5 seconds. Longer burns are required to ensure:

- Ions clinging to B fields do not charge the spacecraft significantly,

- Electrons escape together with ions and also do not cling to magnetic field lines charging the spacecraft, (electrons are more prone to cling to B field lines given their lower masses)
- Magneto-hydrodynamic currents, cross-field diffusion, or other plasma instabilities do not affect detachment,
- Expanding plasma after sub-super Alfvenic transition contains enough directivity to propel spacecraft in a controlled and stable fashion
- Ensure sub-super Alfvenic transition is maintained over useful Isp throttling ranges occurring at sufficiently large distances from the spacecraft to ensure directivity and nozzle efficiency.

B. Thermal control

"*Thermal control is the most significant engineering challenge in the design of the flight version of the rocket*" (Petro, 2002). The thermal control system needs to ensure continuous operation of the engine maintaining superconductor magnets, helicon quartz pipe, RF antennas, and engine walls within operating temperatures. Even though the plasma never comes into direct contact with the magnets, antennas, or walls, non-ionized neutral gas bombardment and hot plasma radiation present pressing challenges. The current approach is to passively conduct heat from the core to radiators via thermally conductive materials. Specifically, heat pipes are employed in the antennas to transport heat due to their extreme currents and close proximity to the plasma. At current power levels and efficiencies [8, 9] considering the efficiency of RF energy generators and transmission systems, thermal control systems need to dispose of about 70.5kW of heat during full-power operation.

An interesting analog to this power level is he ISS External Active Thermal Control System (EATCS). It is capable of rejecting around the same 70kW[24] with circulating liquid ammonia. The ISS EATCS total surface area is about 3800 m^2 and weighs about 54 metric tons. Each radiator measures 23 by 4 meters, about 90 times bigger than the VF-200 shown in figure IV-1 above. Petro (2002) has suggested the use of phase-change materials where wax absorbs excess heat during thruster operation and dissipates it during periods where the thruster is not operating to decrease the size of the radiators. The small radiator size seen in figure IV-1is thus justified. In the latest laboratory version of the engine, thermal control restricts testing pulses to less than one minute due to thermal limits of glues in seals and joints in the rocket core [8, 30]. The thermal control systems of the VASIMR require a great deal of attention. As seen above rejecting waste heat with conventional radiators is likely to add unfeasible complexity, size, and weight to the engine. Continuous constant-power thrusting to take real advantage of VASIMR's variable Isp capabilities is a rather distant goal as long as thermal systems are concerned.

C. Power Hunger

The energy problem is currently the most pressing challenge to a sustainable economy. Space projects are not the exception. Since the VASIMR is intrinsically a high-power device, it relies heavily in advances in this area. If it is to be operated continuously for long-duration missions, at current powers, there are only two solutions[22]: photovoltaic arrays and nuclear reactors.

Solar arrays are the most common method of space power generation. Assuming the use of highly efficient space-qualified Ga-Ar solar cells (efficiency of 19%) with a degradation of about 4% per year for a 3 year mission, and considering missions around Earth orbit (L1, L2, Moon missions), the following table was generated:

Table 2. Size and mass of solar array power system. Based on Wertz and Larson Chpt1[23]

Version and Power	Size of Solar Arrays [m²] (GaAs-19%)	Rough Power System Mass [kg]
VX-10	80	300
VX-50	405	1500
VX-200	1680	4900
VF-12000?	97000.0	27000

As seen above, for powers under 100kW solar panels are very feasible. However, when reaching the VX-200 power level, the size and weight of the arrays becomes excessively large with current solar technology: 7 tennis courts. Using the ISS analogy again, surprisingly, the total power that can be continuously drawn from the large solar array system currently in place is 110kW (Phillips, 2001). Even though the ISS power system is designed for LEO and 20 years of service, it gives an idea of the size of the power systems required to run VASIMR continuously at full power. Furthermore, the last row in table 2 demonstrates that traditional solar cell technology is absolutely unfeasible for engines in the MW level; a 1.2MW system would take up nearly 24 futbol (soccer) fields! Other futuristic solar options are solar concentrators and solar dynamic engines, yet these could not be discussed here because of their lack of flight heritage performance data.

The other main option is space nuclear power. According to Tolyarenko[22] low temperature reactors with static conversion reaching powers of up to 10s of kW have been built and flight qualified (Topaz I). Bigger programs such as the SP-100 fission reactor targeted at 100kW electric power were planned but later cancelled[26]. Therefore advances in nuclear power generation in space scaling to big engines would be required to continuously power an interplanetary VASIMR. Chang-Diaz speculates that advances in nuclear reactors would be required for MW-range power operations of the engine[1]. A complication that becomes clearly apparent with the use of nuclear reactors is the efficiency transformation of energy from thermal to electric. The Topaz reactor mentioned above had an efficiency of 7% and generated a total power of 150kW thermally, while only extracting 10kW of electric power at 320 kg. If these efficiencies and masses are linearly scaled upwards to the 200kW VASIMR electric power need, the thermal engine must generate 3 MW of power at a weight of 6.4 metric tons needing to radiate 2.8MW of waste heat on top of VASIMR's 70.5kW explained above. For a MW-range VASIMR capable of taking humans beyond LEO, energetic efficiencies/mass should improve, but at the current state of technology such spacecraft concepts are at best highly futuristic (see figure III-2).

D. Space Qualification

There are many innovative technologies on-board the VASIMR that have never been flown into space. The successful timely demonstration of the engine requires brisk engineering efforts to space qualify both the superconducting magnet array and the RF generator electronics. The VX-200 utilizes two solid-state RF generators developed by Nautel Limited of Canada specifically for the VASIMR. Their specific mass of the helicon generator and ICRH source are 1kg/kW and 0.5kg/kW respectively, which is quite promising from the mass standpoint. However, they are currently not located within the vacuum chamber and require re-design for compatibility with EEE parts and testing in vacuum. Similarly, the custom-built superconducting magnet array provided by Scientific Magnetics of the UK requires changing the driver electronics and transforming materials to high-temperature superconductors to ease the job of the heat-rejection systems and operate in the vacuum of space[8].

E. Funding

The complexity of the VASIMR engine requiring large amounts of power, specialized RF electronics, plasma testing equipment, superconductor magnets, and gigantic vacuum chambers entail a large economic investment. Back in 2005 when the Advance Propulsion Laboratory at NASA JSC hosted the VASIMR effort, funding for the program was withdrawn due to Constellation program costs. This cancellation forced Chang-Diaz to propose NASA the privatization of the technology, which had an unexpectedly positive outcome. Ad-Astra Co. secured investments from the US, Europe and Costa Rica summing several tens of millions of dollars. Chang-Diaz indicates this figure to be 10 times more than what NASA ever spent on the project. The company has then achieved great milestones in power capability and efficiency, raising the flight readiness level from 2 to 6 over the five year period[15]. It is quite an important achievement considering the concept went from 0 to 2 TRL since the early eighties up to 2005: nearly 25 years. With the new Obama plans pushing development of new propulsion systems and Chang-Diaz close relationship with Bolden, NASA has renewed interest in contributing to the VASIMR effort. Thus economical support for the VASIMR looks bright today, but it must deliver up to its promise and remain competitive in the harsh environment of the space market.

VI. Potential Missions

The present section briefly addresses the proposed missions for VASIMR. As seen above in sections II and III, AdAstra presents the VASIMR as ideal for drag compensation of space stations (really large payloads), interplanetary cargo transport, and robotic or human exploration missions to the Moon, Mars, asteroids, or beyond. Thus, it is mainly a candidate for primary propulsion roles. VASIMR's electrodeless design makes it ideal for cargo applications back-and-forth the moon because it is fully reusable. Such missions put a premium on high Isp to reduce propellant mass and fair amounts of thrust to reach their destinations within fair timelines. Also at such high powers, efficiency is paramount in order to limit the size and mass of thermal control systems. Mission designers and system's engineers perform extensive trade-offs when choosing a certain technology for flight. Table 3 below compares the current VX-200 power input and performance with other current high-power electric propulsion engines.

Table 3. Comparing VASIMR with equivalent (un)clustered versions of other high-power eletric propulsion concepts

Engine	No. Thrusters	Thrust (N)	Isp (sec)	Power (kW)	Efficiency	Source
VX-200	1	5	5000	211	72%	[10]
BHT-20K	10	11	2800	200	72%	[33]
HiPEP - 50kW	5	3.4	9620	196	80%	[34]
RIT-50 -103kW	2	3.6	10340	207	88%	[40]
HEMP - 7.5kW	20	5	3000	150	48%	[35]
HP-PPT - 82kW	3	3.6	5300	246	38%	[36]
MPD LAJ-AF-2	10	5.36	5470	208	69%	[37]
Arcjet X-1	1	7	2211	216	36%	[38]
Resistojet	6	36	846	180	83%	[39]

Table 3 above shows that VASIMR is competitive, but it is not the only choice around 200kW. The BHT-20K engine already enjoys flight heritage, and in spite of the lower Isp and clustering, it doubles the VX-200 in thrust. Also, only 2 RIT-50 engines have better efficiency and double Isp with a slightly smaller thrust by 1.4N. Future work should attempt to fully identify the TRL of each engine to further enhance the ability to compare these.

There are also missions the VASIMR cannot perform. As any electric propulsion engine[10]so far, its weight to thrust ratio is too low to be used for lifting payloads from the Earth's surface. Also, as presented in section III, its complexity and size make it unfeasible for small and microsatellite applications. Furthermore, the steady nature of the thrust disqualifies VASIMR for precise attitude control, spin-axis control, or formation flying missions. Without Isp throttling data, there are no means to determine its minimum thrust and consider it for secondary propulsion missions.

Ultimately, current limitations in space power generation and thermal control systems limit the full deployment of VASIMR (as well as its high-power competitors) to high-caliber missions. Unfortunately, the real show-stopper for VASIMR is not the engineering, but the destination. Large magnitude exploration missions that would truly benefit from the breakthroughs of VASIMR are envisioned for the next decade at the earliest. If our species is to escape extinction, we must venture outside the cradle. When the time has come, the early efforts of a few visionaries would make the world of a difference.

VII. Conclusion

Contemporary VASIMR literature has been critically reviewed with the goal of identifying the mayor technological roadblocks that need addressing towards successful testing and long-term operations. These are best summarized in the risk matrix below:

Table4. Risk matrix VF-200 flight

	Consequences				
Likehood	A - Insignificant	B - Minor	C - Moderate	D - Major	E - Severe
5 Almost Certain	🟨	🟧	🟧	🟥	🟥 α, β,
4 Likely	🟨	🟨	🟧 δ	🟧	🟥
3 Possible	🟩	🟨	🟨	🟧	🟥 γ
2 Unlikely	🟩	🟨	🟨	🟨	🟧 ε
1 Rare	🟩	🟩	🟨	🟨	🟧 ζ

The matrix assumes that the ultimate goal of the VASIMR is to operate continiously and vary its specific impulse over fairly large ranges without severe drops in performance

α) Incomplete plasma detachment with spacecraft charging,

- 5E, ground tests show some ions clinging to B-field lines, electron distribution unknown. Ground test-times so far very short. Flight model must perform long tests in space vacuum to confirm complete plasma detachment over wide experimental Isp ranges.

β) Plume uncontrollable over ambitioned Isp ranges,

- 5E, ground tests have only tested performance at 28kW- helicon, 172kW-ICRH setting (Bering et al., 2011). Flight model must perform tests in full space vacuum over wide range of specific impulses to confirm engine provides thrust in single direction by maintaining sound distance between physical nozzle and detachment point.

γ) Plasma instabilities over operational Isp ranges,

- 3E unknown or known-unseen plasma instabilities which could have a great impact on the reliability of the technology. Ground tests are currently inconclusive by firing for only 5 seconds at a time. Unprecedented instabilities likely to occur at new power levels.

δ) Overall efficiency of engine drops below a competitive level (i.e., >50%) over ambitioned Isp ranges,

- 4C moderate severity if the engine under-performs at certain points. There is a rather high likehood of occurrence as efficiency has changed drastically with increased power over the years. No data has been published addressing the relationship between thruster efficiency and Isp. Experiments must be performed.

ε) Magnetic quadrupole zero-dipole-moment stability over changing magnetic fields,

- 2E, Very severe condition where instabilities could result in uncontrolled magnetic oscillations and torques severely disturbing attitude control system. Yet, the likehood of instabilities not experienced in the lab or ground tests is very small. Experiments must be performed

ζ) Constraining magnetic field and/or RF antennas interfering with telecommunication and/or payload

- 1E, Very severe repercussions in other subsystems which could imply utter mission failure. However, shielding techniques and EMC ground tests should iron these issues out.

Even though somewhat subjective, the above table shows the criticality of the technical challenges. The matrix above assumes an ideal VASIMR engine that burns continuously without long pauses between firings as those suggested by the VF-200 model.

There is plenty of engineering work to-do before the VASIMR is successfully tested in space. Fortunately governmental funding and support is secured for the next 3 years. Privatizing the concept was a smart move; yet performing a successful test in the ISS carries even further pressure from private investors. The talented team at Ad-Astra has demonstrated a continuous effort towards improving the VASIMR and with a PDR and CDR just 6 months and 1 year ahead respectively, the flight deadline is fast approaching. Let us remain optimistic about the tests in 2014 that would prove the technology readiness and in the long-term bring humanity a step closer to the stars.

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