Plasma, Ion-Thrusters, and VASIMR

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University of Colorado-Boulder, ASEN 5053, Fall 2011

I. Introduction

For decades, rocket propulsion has been studied intensively in order to explore the expanses of the solar system and the hope is, eventually, the universe. In that quest, many different designs and techniques have been researched. While the main types of engines today are solid rocket motors, liquid rocket engines, and hypergolic engines, there are other types of thrusters that have recently become another focus of research. Plasma thrusters and ion thrusters, which fall under the category of electric thrusters, are being studied with the applications of using as orbital boosters or potentially long-distance missions to objects in the solar system. These propulsion systems have advantages over the traditional chemical rockets and will be discussed in more detail in the following.

II. Plasma Thrusters

While chemical rockets use liquid and solids to expel the products produced during a controlled explosion, plasma thrusters expel the plasma without an explosion taking place. Plasma is the fourth state of matter and is characterized by an electrically neutral gas, that is, all positive and negative charges in the gas have a combined net charge of zero.

A. Pulsed Plasma Thruster (PPT)

Pulsed plasma thrusters produce a high-specific impulse and have low power consumption (like most electric thrusters to date). These thrusters are not suited for applications where a high thrust is needed. They are more suited to low-thrust situations such as attitude control for small spacecraft.

1. Operation

The basic idea of this system is to form a plasma and expel it out of the nozzle, much like any other rocket system. However, a PPT does it in a much different way. First off, the PPT system is made up of a power source, a processing power unit (PPU), an energy storage unit (ESU), and the thruster itself. The power source can be anything that provides electrical power, although solar cells are usually used because the thruster operates at low power levels. The PPU converts the spacecraft power to charge the thruster's ESU, which applies high-current pulses through the thruster to do work, thus giving the Pulsed Plasma Thruster its name.

It has two electrodes that are located close to the propellant source in solid form. An ESU or possibly a capacitor in parallel with the electrodes is then charged to a high voltage by the thruster's power supply. The thruster's igniter, which is also close to the solid propellant, produces a spark which discharges the ESU between the electrodes to create plasma, called the main discharge. The surface of the solid propellant is then ablated and ionized, becoming a plasma propellant. Using the Lorentz force (created by electromagnetic fields in the thruster), the plasma is accelerated out of the thruster and propels it forward. A spring behind the solid propellant forces it into the position vacated by the plasma, thus providing a constant fuel source.[1]

2. Applications

The very first use of a PPT was in 1964 by the Soviet Union on a spacecraft called Zond 2. Four years later, the U.S. launched the LES-6 satellite which used a PPT system. Other systems such as the Transit

Improvement Program (TIP) spacecraft and the Navy Navigation Satellites (NNS) also used PPTs. The Earth Observing 1 (EO-1) spacecraft makes the use of a dual-axis PPT to control its pitch and momentum. This PPT can produce a thrust of 860 μNand an exhaust velocity of 13,700 m/s (which is almost twice that of the space shuttle) while it consumes only 70 watts of power. This is the appeal of electric propulsion systems. Going forward, research will continue to be done to develop more efficient and longer-life PPTs that will ultimately allow for precise, efficient maneuvers as well as extended mission times.[1]

B. Magnetoplasmadynamic Thruster (MPD)

The MPD thruster is the most powerful form of electromagnetic propulsion to date. This system has the capability to convert large amounts of electric power (in the megawatt range) into thrust making this technology a great prospect for space exploration, specifically for taking cargo to lunar or mars bases as well as deep space exploration. These also have the high velocities that are associated with ion propulsion, which will be discussed later.

1. Operation

Like a PPT, a MPD thruster has two electrodes, one being a central cylindrical rod (cathode) and the other a hollow cylindrical shape (anode) that surrounds the cathode. The anode acts as part of the nozzle itself. The thruster works by creating high-current electric arc between the two electrodes. The cathode heats up, emitting electrons that collide with the propellant gas to produce plasma. The current running through the cathode back to the power supply induces a magnetic field. The magnetic field and the electric current interact to create a Lorentz force that propels the plasma out of the thruster, producing thrust.

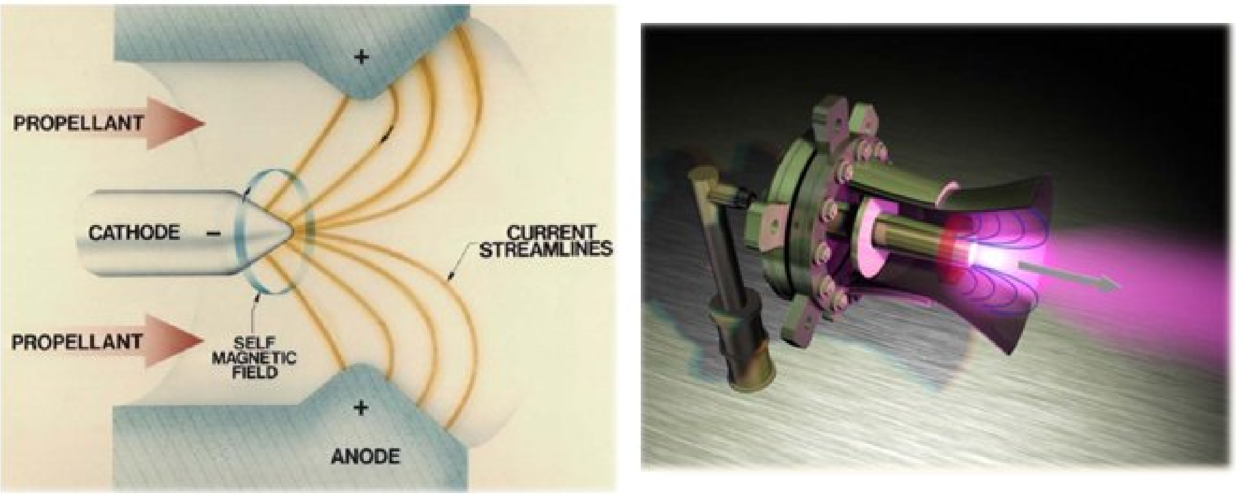

Figure 1. A diagram of the electrodes and currents lines as well as a 3D model. Credit: NASA

Depending on thruster design, external magnets are sometimes used to provide more acceleration to the plasma while also stabilizing the flow.

2. Applications

Research of high-power MPD thrusters started in the 1960s and its performance has slowly improved over since then. Different designs and propellants have be studied with lithium vapor being able to provide the most efficient operation to date. Facilities such as the NASA Jet Propulsion Laboratory, Princeton University, and the NASA Glenn Research Center are currently researching lithium-fed and hydrogen-based MPD thrusters. While lithium is the most efficient, it has its drawbacks. Namely, lithium is a condensable propellant that can coat the spacecraft surfaces and power arrays. On the other hand, noncondesable hydrogen propellant eliminates the problem of coating and also can provide a higher exhaust velocity. A hydrogen MPD thruster of the mega-watt class is being developed by researchers at the Glenn Research Center. They have demonstrated that exhaust velocities, thrust levels, and power levels of 100 km/s (just over 10 times the top speed of the shuttle), 100 N, and 1 MW, respectively, can be obtained. The hope for this and similar systems is to reduce costs and flight times of missions. As larger and larger amounts of power become available in space, these could potentially be the future of manned missions to other planets in the solar system.[2]

III. Ion Thrusters

Ion proplusion has long been the subject of science fiction movies, books, and other media. With advances in technology, these systems have become a reality and are currently used for satellite station keeping as well as the main propulsion component of deep space exploration systems.

A. Ion Propulsion System

Ion thruster common today use inert gases as for propellant. Xenon is the most widely-used propellant. It is injected from the downstream end of the thruster and flows toward the upstream end. The reason this method of injection is chosen is to increase the time for which the propellant is in the chamber. Most modern ion thrusters use electron bombardment for ionizing the propellant, however, an alternative method called electron cyclotron resonance (ECR). This technique uses high-frequency radiation such as microwaves with a large magnetic field to heat electrons in the propellant atoms. This heating causes the electrons to break away from the atoms, creating a plasma. The ions used for thrust are then extracted from the plasma. In electron bombardment, electrons are produced by a hollow cathode, named the discharge cathode, located in the center of the chamber on the upstream end. The electrons then flow out of the discharge cathode. The power supply of the thruster charges the chamber walls with a high positive potential and attracts the electrons to the walls. Refer to the diagram below for a visual aid of the setup.

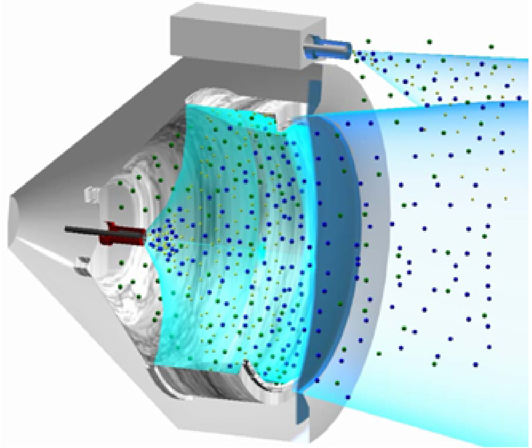

Figure 2. An overview of the operation of an ion thruster using electron bombardment. Credit:NASA

These electrons ionize the propellant by electron bombardment. Using a magnetic field induced by high-strength magnets along the discharge chamber walls, the electrons are directed into the discharge chamber. This maximizes the time the electrons are in the chamber. Therefore, since the time the electrons spend in the chamber as well as the time the propellant spends in the chamber is maximized, the chance of the propellant being ionized is maximized which makes ionization as efficient as possible. Now comes the task of accelerating the ions out of the nozzle. To do this, electric fields produced by electrodes that are at the downstream end of the thruster are used. Each electrode set, called grids or ion optics, have thousands of coaxial apertures. The apertures as a lens would, except that they *electrically* focus the ions.

In the ion thrusters of NASA, a two-electrode system is utilized with a highly-positive charged electrode upstream, known as the screen grid, and a highly-negative charged electrode downstream, called the accelerator grid. Because the ions are produced in a highly positive location and the accelerator grid is negative, the ions are accelerated toward the accelerator grid where they are focused through the apertures, generating many ion jets. All of the ion jets together are called the ion beam. The thrust is the force existing between the just-produced upstream ions and the downstream cathode, while the exhaust velocity is determined by the voltage applied to the grids. The exhaust velocity of an ion thruster is only limited by the voltage applied to the optics. Theoretically speaking, an infinite amount of voltage could be applied which implies that there is no limit to the speed that could be obtained by ion thrusters. Located at the top of the thruster in Figure 2 is another hollow cathode called the neutralizer. This is there to expel the amount of electrons needed to keep the exhaust beam neutral since large amounts of positive ions are expelled during its operation.[3]

B. Projects

The NASA Solar Technology Application Readiness (NSTAR) project was the first ion propulsion system to act as the main component of propulsion for a mission. It was used on the Deep Space 1 (DS1) from 1998 to 2001. By the time the mission had been completed, the NSTAR logged over 16,000 hours of operation and 200 starts.

The NASA Evolutionary Xenon Thruster (NEXT) project has been in development of a high power solar-powered ion propulsion system that is capable of missions to other planets, Mars and Saturn being two points of interest. The integration test of NEXT was done in 2003 and it demonstrated that the thruster was a complete ion thruster.[3]

The Jupiter Icy Moons Orbiter (JIMO) project, which had been in the early stages when it was canceled in 2005, was a proposed to use an ion propulsion system as its main drive. The thrusters would have been powered by a small, on board nuclear reactor. NASA officials claimed JIMO, with its nuclear powered ion thruster, was too ambitious for an initial demonstration.[5] Its mission was to orbit Europa, Ganymede, and Callisto, three of Jupiter's moons to study their interior structure, the evolution and current state of their surface and subsurface, how the components of these systems integrate and operate, as well as their habitability. The moons could potentially have subsurface oceans and could possibly contain the ingredients for life. Unfortunately, the project lost its funding which caused its cancellation.[4]

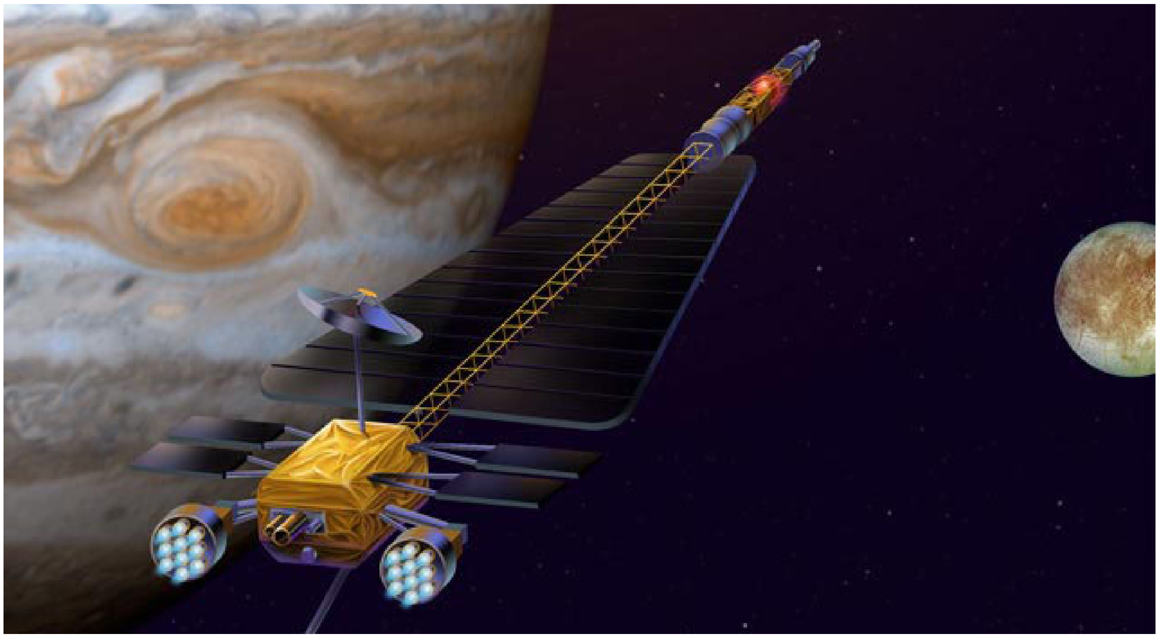

Figure 3. An artist's conception of the proposed JIMO. Credit: NASA

IV. VASIMR

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) could potentially fill in the gap between high-thrust, low-specific impulse systems (chemical rockets) and low-thrust, high-specific impulse systems (ion thrusters). The 'variable' part of its name is very important. It allows the engine to operate as one of the two types of systems or somewhere in between. The concept was created by former NASA astronaut

Dr. Franklin Chang-Diaz, who worked on it while at NASA and later started his own company, Ad Astra Rocket Company, to develop the engine further after retiring from NASA in 2005.[6]

Ad Astra Rocket Company currently has two versions of VASIMR. One, named VX-200, is a prototype whose purpose is to test flight-like hardware and other technology in a vacuum. In a performance test in November 2010, VASIMR was able to operate at full power for 25 seconds. While operating with an RF power of 200 kW it produced a thrust of 5.7 N and an exhaust speed of 50 km/s (which is an equivalent of an specific impulse of 5000 s) with a thruster efficiency of 72%.[7]

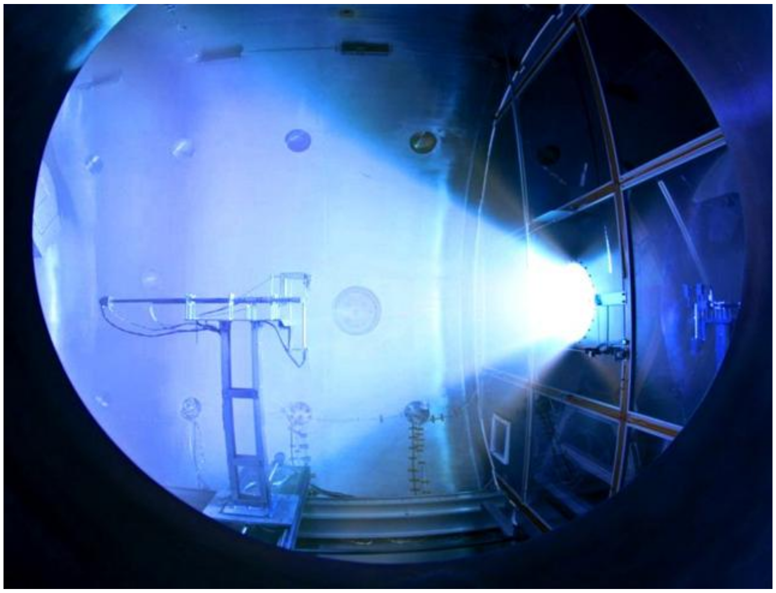

Figure 4. VASIMR operating with argon propellant at full power in a vacuum chamber. Credit:Ad Astra Rocket Company

The second version, called VF-200, is the flight unit of VASIMR. In 2008, Ad Astra Rocket Company signed an agreement with NASA to test VF-200 on the International Space Station (ISS)[12] and the launch is anticipated to happen sometime in 2014.[11] VF-200 that will be launched and attached to the ISS will consist of two 100 kW thrusters in a single engine box (this is so that a zero-torque magnetic quadrapole will exist, the for this will be explained in the Advantages/Disadvantages section). It is currently being designed to reach the steady-state operating temperature to show that it can operate for an indefinite amount of time. It will use electrical power on ISS to charge a battery that can power the thruster for about 15 minutes if operating at full power.[7]

A. Principles of Operation

Much like an ion thruster, VASIMR uses a gas such as argon or xenon, however, it is also capable of using hydrogen. It works by injecting the propellant into a tube surrounded by magnets and two radio wave (RF) antennas. The first RF antenna converts the gas into the plasma used for propulsion by ionizing it. This is called the helicon section due to the way the antenna is shaped which allows it propagate helical waves through the gas to ionize it into a cold plasma. The cold plasma, which is actually at a temperature of around 5,500 K (close to the temperature of the surface of the Sun), interacts with the magnetic fields produced by the magnets along the tube. The magnetic field can be visualized as lines that are through the rocket with ions orbiting around each line, giving the ions an orbiting momentum perpendicular to the rocket's direction of travel. The second RF antenna, called the Ion Cyclotron Heating (ICH) section, heats the plasma to extreme temperatures (on the order of one million degrees Kelvin). This section works by producing radio waves that hit ions and electrons along their orbits at resonances producing their acceleration and temperature increase. With this done, the plasma is primed to be ejected from the nozzle to produce thrust. However, the ions are orbiting perpendicular to the rockets motion. VASIMR's magnetic nozzle induces a magnetic field and as the field lines expand, the spiral paths of the ions elongate which produces very high exhaust velocities on the order of 50 km/s.

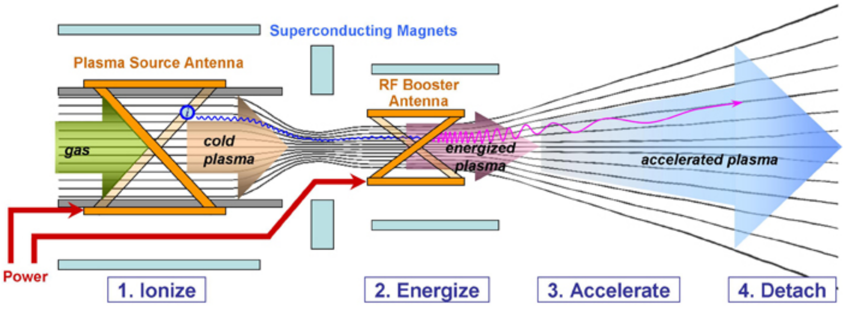

Figure 5. A 2D schematic of the VASIMR engine. Credit: NASA

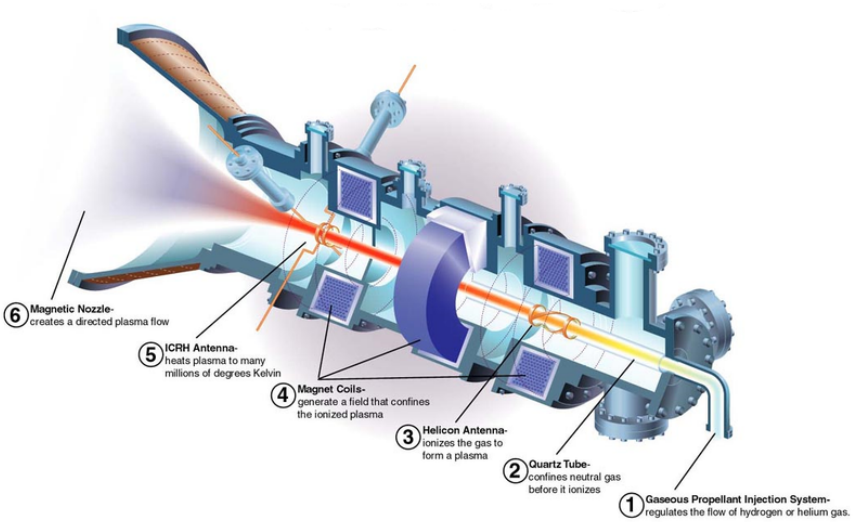

Figure 6. A 3D visualization of the VASIMR engine operation. Credit: NASA

There are three distinguishing features of the VASIMR engine that makes it a highly desirable engine should it put in use. As stated before one of the most appealing aspects of the engine is that it can vary its thrust and specific impulse exhaust parameters to match many different mission requirements in an optimal way. This can reduce trip time while also delivering the highest payload for a certain fuel load. The second standout feature is that it uses RF waves to create the plasma and energize the plasma. This procedure allows the VASMIR system to have no physical material electrodes in contact with the plasma. Because of that, it has a much longer life span and a higher reliability since erosion has been minimized. This also allows a much higher power density than any other electric thruster designs. The final distinguishing feature, which makes use of the second one, is that VASIMR is able to process a large amount of power and that leads to a higher amount of thrust generated. Because it can produce more thrust, it can transfer bigger payloads to low Earth orbit (LEO), the moon, and even other planets in the solar system efficiently. VASIMR is also high scalable so that more powerful version could be designed depending on the mission requirements.[7]

B. Power Sources

Each electric propulsion system must have power source. This is one of the biggest problems not only for VASIMR, but for other electric propulsion systems as well. VASIMR is a high-power thruster and therefore, requires a large amount of electricity being able to be generated in space. Even with the rapid growth of modern technology, there are really only two different options: solar power and nuclear power.

1. Solar Power

Solar power can be used in conjunction with VASIMR efficiently for near-Earth missions, such as boosting the ISS and transporting cargo to a lunar base. While solar power is not extremely efficient, Entech Solar Inc. in a partnership with NASA's Glenn Research Center has successfully produced a ultra-light, high performance solar concentrator. The Stretched Lens Array (SLA) makes the use of a thin film lens to concentrate a large amount of sunlight onto and small area of photovoltaic (PV) cells. It also uses a thin sheet of thermally conductive material underneath the cells to reduce the waste heat produced.

This type of array is said to be capable of 30% efficiency in a space-optimized design. Because the sunlight is concentrated on a small area of PV cells, PV material will be reduced (by about 90%) which leads to a significant reduction in cost per watt. Because of these capabilites and the need for minimization of mass in space applications, the VASIMR project is very interested in using it as a power source. Again, this could only be used for near-Earth missions.[8]

2. Nuclear Power

A nuclear reactor is an great power source, but with the notions a nuclear reactor mission going bad, NASA and other companies have been wary about using it. The capabilities are available, it is just a matter of deciding whether the risks are worth it and it is not yet worth it for NASA and others. While nuclear power is definitely usable in today's rockets, the mass of the reactors are still a limiting factor and must be reduced to be able to power something with a power requirement of VASIMR.

C. Advantages/Disadvantages

Unlike conventional cyclotron resonance, VASMIR ejects the ions immediately through the magnetic nozzle, which does not give the ions enough time to become a thermalized distribution. From theoretical work, almost all of the energy in an ion cyclotron wave (ICW) would be transferred to ion perpendicular energy in a very small volume at a point on the magnetic nozzle gradient. This model is non-linear and predicted a very high absorption ratio and showed that all of the ions would receive nearly the same energy increase. Therefore, the ions would be ejected through the nozzle with a narrower energy distribution than a thermalized distribution which allows for a much simpler and compact magnet orientation.[10] VASIMR also does not have nearly as many moving parts as a chemical rocket which not only maximizes its lifetime, but it increases its reliability as well.

While there are quite a few appealing characteristics of VASIMR, like any other system, it has its drawbacks. With its relatively large operational power, it creates larges amounts of waste heat that must be dispersed somehow. Without properly taking care of this waste heat, unnecessary stress may be put on the materials used in the engine which could lead to malfunction or failure. As mentioned earlier, it uses powerful superconducting electromagnets to contain the plasma so that physical contact is not needed. However, the magnetic fields generated by these magnets are in the tesla-range.[13] These fields can potentially affect and disrupt operation of other on-board devices. Also, because the magnetic fields are so strong, it can interact with the magnetosphere producing unwanted torques on the spacecraft. This is the reason for their planned use of two 100 kW thrusters when testing the VF-200 on the ISS. By orienting the magnetic field of one thruster opposite to that of the other's, a zero-magnetic quadrapole is created eliminating the possibility of unwanted torque.[14]

D. Skepticism

Whenever a new idea comes along that says it could revolutionize the way something is done, there is always some skepticism until it has actually been proven to work. VASIMR is no exception. One would probably expect a technology like VASIMR, one that could reduce the flight time to Mars and one that has support from NASA, to be welcomed by the advocates of human-mission Mars exploration. However, at an International Mars Society Convention in 2010, these advocates were not only skeptical about VASIMR but they thought that technologies like VASIMR could even delay the prospect of human missions to Mars.[9]

1. VASIMR claims

In an interview with Lee Billings from *Seed Magazine*, Diaz, when asked what was needed to push the development and use of a nuclear reactor in space, he referred to the story of the first nuclear submarine. In 1958, the USS Nautilus was able to navigate under the north polar ice cap and surface on the other side using a nuclear reactor. This enabled many different types of missions that were not able to be done before and now, nuclear submarines are common. Diaz said that for space programs to accept and widely use a nuclear reactor as a power source, something similar must happen. He went on to say that with the power close to what a nuclear submarine can generate, VASIMR could get humans to Mars in only 39 days compared to around eight months of a chemical rocket. Because of this shorter travel time, astronauts will be subject to less cosmic radiation and weightlessness which are both negative influences on the body in and extended period of time.

2. Opposition

Not everyone is so optimistic about VASIMR. Robert Terry, a physicist that worked in the plasma physics division of the Naval Research Laboratory for more than 20 years, was present at the convention and he was concerned about the reduction in effectiveness from leaks and losses in the VASIMR design. Referencing an analysis that studied the impact of specific impulse versus the impact of the aeroshell on the usable payload that could be sent to Mars, he said that improving the aeroshell's mass fraction had a much larger impact than increasing the specific impulse, even to very high values said to be obtainable by VASIMR. From this data, he was skeptical that VASIMR would have a spot in the Mars picture.

One of the biggest concerns for the VASIMR project in general is that, to be able to travel to Mars in a short amount of time, it needs a nuclear power system that is capable of delivering 200 kW to the engine. A system with this capability coupled with the compactness needed for space exploration has not been developed yet and there is no promise that it will happen anytime soon. Robert Zubrin, organizer of the convention and the president of the Mars Society, said that mission designs centered around VASIMR had unrealistic expectations about the mass of the nuclear power system needed. The Topaz nuclear reactors, which were developed by the former Soviet Union, were the largest nuclear power system for space. They were able to generate 10 kW and had a specific power of 100 kg/kW. NASA's now-canceled Prometheus project had hopes of getting this specific power down to 65 kg/kW. Zubrin believed obtaining somewhere around 20 kg/kW is optimistic to say the least. Zubrin would be one to know as well. He holds a B.A. in Mathematics, a master's degree in Aeronautics and Astronautics, a master's degree in Nuclear Engineering, and a Ph.D. in Nuclear Engineering. He said that the VASIMR Mars mission concepts were based on a specific power of 1 kg/kW. To put that in perspective, he related it to "steel with the weight of Styrofoam." He analyzed it further and assumed that 20 kg/kW was obtainable. For a reactor to generate the 200 kW required for VASIMR at full power, it would need to be 4,000 kg. In comparison, the VASIMR mission concepts that had the 39-day travel time assumed a total mission mass of 600 kg. The mass of the reactor required is almost seven times that. If the total mass was assumed to be 4,000 kg for a VASIMR Mars mission, the mission time would be six to eight months which is comparable to how long it would take using a chemical rocket.

Another problem brought up by Zubrin was that VASIMR could easily be perceived to be a necessity for a human Mars mission in order to reduce the risk of mission failure (the longer the travel time, the higher the chance of something going wrong during the trip) as well as radiation exposure. Zubrin is concerned that VASIMR is being used as a reason why a Mars trip can't happen now. He also believes that radiation concerns are overblown by some. He pointed out that the exposure for ISS crews is about half the exposure that one would get from space, the reason being that the Earth blocks out about half of the radiation on the ISS. Zubrin said that traveling to Mars in a conventional chemical rocket would have exposures of what crews on the ISS would receive over a decade. His reasoning is why expose crews to that radiation without going anywhere (on the ISS) rather than exposing them to the same amounts of radiation while traveling to Mars and ultimately allowing human exploration of Mars.

One would have been hard-pressed to find someone that was optimistic about VASIMR at this conference but Geoffrey Landis, a scientist at NASA's Glenn Research Center, said it depends on where we are going and what we want to do. If human exploration for Mars is the ultimate and final goal then the development of VASIMR and the nuclear power source is "overkill." He said if on the other hand Mars is only the beginning of exploration of the solar system, then VASIMR may be worthwhile.[9]

V. Conclusion

At this day in age, rocketry is focused on the best-performing systems to complete missions and to explore our solar system. While chemical rockets are not going anyway anytime soon, plasma and ion thrusters are becoming widely used for satellite-orbit keeping, deep space exploration devices, and other missions that do not have a hard time constraint. As research continues, these thrusters will only become more efficient, more powerful, and more versatile.

The prospect of VASIMR being able to perform to its claims has excited many human exploration advocates, while others remain skeptical. VASIMR could potentially be the break-through technology that was needed to get the manned space program going again or it could be just another plasma propulsion system on the market that was not able to live up to its expectations. One thing is for sure: without a powerful space nuclear power system, VASIMR's future seems doubtful. Regardless of what happens, space exploration will only become more exciting and surprising as time goes on. On the quest of exploring the solar system, new technologies are bound to be discovered that might just revolutionize the way exploration is done.

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