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THE PHYSICS AND ENGINEERING OF THE VASIMR ENGINE

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ABSTRACT

The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high power, radio frequency-driven magnetoplasma rocket, capable of I_{sp}/thrust modulation at constant power. The physics and engineering of this device have been under study since 1980. The plasma is produced in an integrated plasma injector by a helicon discharge. However, the bulk of the plasma energy is added downstream by ion cyclotron resonance. The system features a magnetic nozzle, which accelerates the plasma particles by converting their azimuthal energy into directed momentum. A NASA-led, research effort, involving several teams in the United States, continues to explore the physics and engineering of the VASIMR, and its extrapolation as a high power, in-space propulsion system. These studies have produced attractive results in a number of areas, involving plasma theory and experiments, systems engineering and mission analysis. A conceptual point design for a 10 kW space demonstrator experiment has been completed.

INTRODUCTION

The development of advanced propulsion is a key element in the implementation of a robust space exploration program. Moreover, for human missions, spacecraft must possess some key features, which are not often required of their robotic precursors, but which are essential for the preservation of human life. Human vehicles must be fast, reliable, "power rich," and be capable of reasonable abort options for crew survival in the event of unexpected malfunctions; their propulsion systems must be capable of handling, not just the cruise phase of the journey, but also provide sufficient maneuvering authority near the origin and destination planets.

Several new and promising concepts are being investigated in order to address these issues. Many explore the intrinsic gains in performance afforded by plasma-based systems over their chemical counterparts. Advanced concepts such as VASIMR, the Hall Effect thruster, the Gridded Ion Engine, the Lorentz Force Accelerator and others are in various stages of development and field test and offer great promise for the future of space exploration.

However, with these requirements in mind, it is important to examine the operational advantages of high power magnetoplasma rockets, which are also capable of constant power throttling (CPT,) a technique where thrust and specific impulse can be varied, while the total jet power is kept constant. As we shall describe in this paper, this capability is afforded by a magnetoplasma rocket such as the VASIMR, where the modulation of the exhaust is done by a number of complementary techniques implemented on several of its system elements.

THE VASIMR SYSTEM

Research on the VASIMR engine dates back to the late 1970's, as a spin-off from fusion technology research on magnetic divertors[1]. These early studies were motivated by the intriguing properties of expanding magnetoplasma jets and their potential application to power generation and, of course, advanced propulsion. For example, with a properly shaped magnetic field, a plasma jet could be generated, heated and accelerated to produce attractive rocket performance. Moreover, the exhaust properties of this jet could be continuously modulated to better match operational requirements for various mission phases. In a varying gravity field, the ship would start at high thrust for rapid acceleration,

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then gradually increase its exhaust velocity (for greater fuel economy) as its speed increases. Because the power of a rocket is a constant fixed by the design, increasing the exhaust velocity always comes at the expense of thrust and vice-versa. The plume variability allows the continuous optimization of exhaust parameters in concert with the motion of the ship itself.

The above technique is called constant power throttling (CPT.) It is similar to the function of the transmission in an automobile in seeking an optimum utilization of engine power through hills and valleys. While CPT does not result in the lowest propellant use, it achieves the fastest possible trip with a given amount of propellant. Fast trips are important for human missions, as they reduce the deleterious physiological effects on crewmembers caused by prolonged exposure to micro gravity, isolation stress and the harsh radiation environment.

The VASIMR Engine, shown in Figure 1, consists of three linked magnetic cells, each with a specific function. The forward cell handles the main injection of propellant gas and its ionization; the central-cell acts as an amplifier to further heat the plasma; the aft cell is a magnetic nozzle, which converts the energy of the fluid into directed flow. During operation, neutral gas (typically hydrogen) is injected at the forward cell and ionized. The plasma ions are accelerated in the central cell with radio frequency power at the ion cyclotron resonance. After the ions have gained energy from the RF wave, they are exhausted out the aft cell to provide thrust. The aft cell is a magnetic nozzle, which converts the cyclotronic motion of the particles into axial velocity.

The full concept of the VASIMR engine also embodies the properties of magnetic mirrors. In these systems, the plasma particles can be energized and accelerated by electromagnetic waves launched from strategically placed antennas. In the VASIMR, three of these magnetic structures are linked into a continuous multi-stage duct, where each stage serves a unique purpose.

In the forward most stage, a relatively cold $(\approx 5\mathrm{eV})$ and dense $(\geq 10^{18}\mathrm{m}^{-3})$ plasma is produced with a device known as a helicon[2]. In it, radio waves ionize the gas in the presence of a magnetic field. The resulting plasma flows along the field into the central cell, where additional radio waves further energize it. The waves in the central cell resonate with the natural cyclotronic ion motion around the magnetic field lines. This process, known as ion cyclotron resonance heating (ICRH,) is widely used for heating plasmas in fusion devices. The central cell thus acts as a power amplifier. Presently hydrogen or deuterium is the propellant of choice, due to their low atomic weight, low radiation losses and suitability for wave heating.

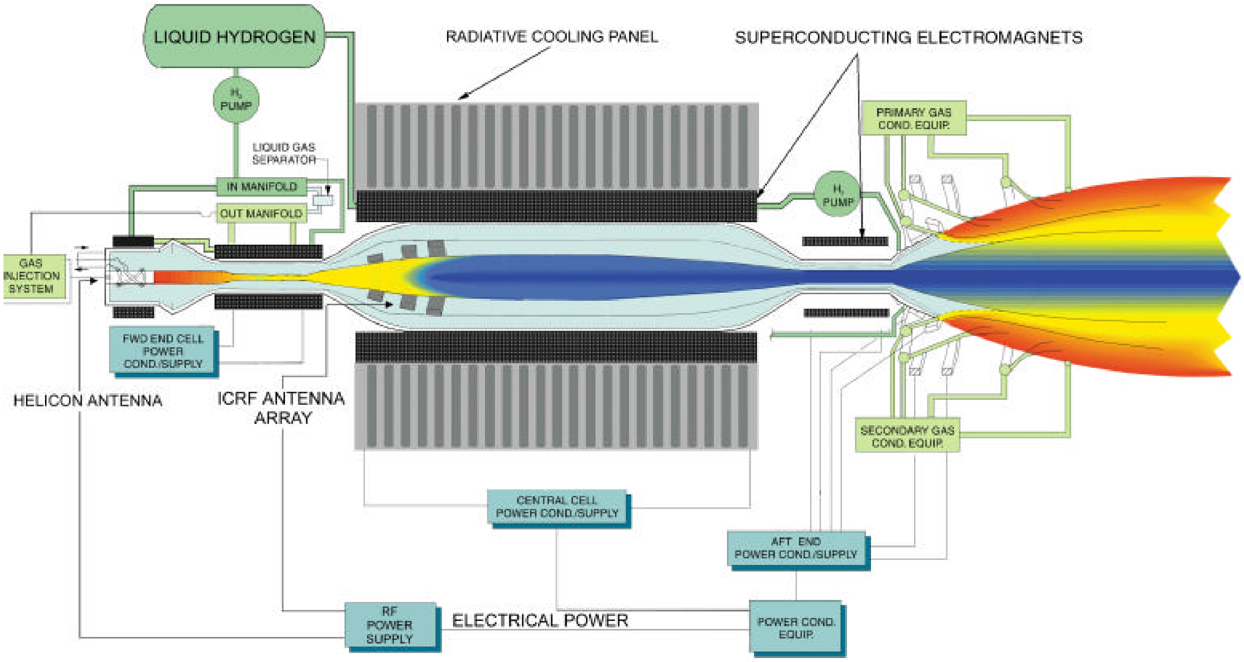

Figure 1. The VASIMR concept

THE BASIC PHYSICS

The Lorentz force on the ions in a magnetized plasma forces them to follow circular paths defined by a quantity known as the Larmor radius,

$$r_L = \frac{m_i v_\perp}{q_i B} \qquad (1)$$

where m_i, q_i are respectively the ion mass and charge, $v_\perp$ is the component of the ion velocity, which is perpendicular to the magnetic field, and B is the magnitude of the magnetic induction. Associated with this radius, the frequency of particle rotation about the lines of induction is known as the cyclotron frequency and is given by

$$\omega_i = -\frac{q_i B}{m_i} \qquad (2)$$

The frequency of the RF power matches that of the gyrating motion of the ions. It deposits the wave energy in motion perpendicular to the magnetic field. This motion must be redirected into axial momentum in order to provide thrust. The magnetic nozzle, the third and final stage of the VASIMR, does this. Here, the diverging nature of the magnetic field implies a magnetic mirror. As long as the expansion is small over scale lengths comparable to the ion Larmor radius, the particles exchange perpendicular motion for axial motion through the adiabatic conservation of the magnetic moment. The energy partition of ions as they move through the resonance and accelerate at the nozzle is shown in Figure 2. The total energy increases due to the RF power added to the particles, but the partition of energy between the perpendicular and axial directions changes as the particles move down the magnetic gradient.

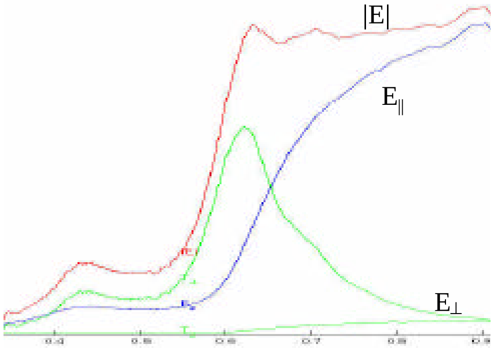

Figure 2. Energy partition for particles in the VASIMR (arbitrary units.) $|E|$ is the total energy while $E_\perp$ and E_z are respectively the perpendicular and axial components.

Figure 3 shows a comparison of the various scale lengths of interest in the expansion physics.

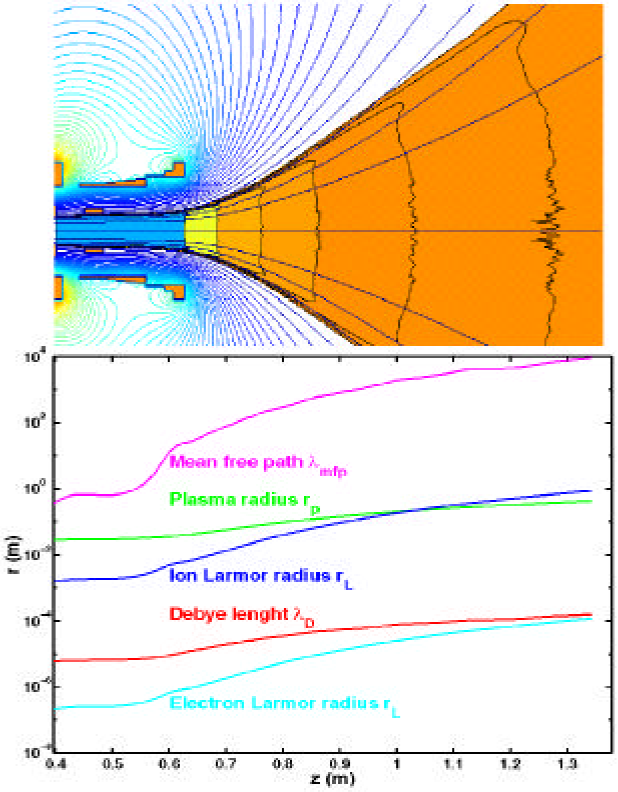

Figure 3. Scale lengths of interest in the expansion of the VASIMR magnetic nozzle.

The topology of magnetic fields dictates that the lines of force must close onto themselves. If the ions were to cling tightly to them, no thrust would be possible. Fortunately, the ions can only follow the field lines as long as these do not curve sharply, a principle known as adiabaticity. Moreover, as they move away from the magnets, the strength of the field decreases very rapidly and so does its force. The detachment of the plume from the field takes place mainly by the loss of adiabaticity and the rapid increase of the local plasma β, defined as the local ratio of the plasma pressure to the magnetic pressure.

The motion of the plasma electrons must follow that of the ions, since the ions carry the bulk of the momentum; however, the electrons tend to cling more tightly to the magnetic field and their detachment may affect the dynamics of the plume, or even induce a local distortion of the magnetic field. Recent theoretical calculations[3] have considered the detachment problem by looking at the transition from sub-alfvenic to super-alfvenic flow. This perspective is akin to the sub-sonic to super-sonic transition in a Laval nozzle, beyond which the dynamics upstream are decoupled from the downstream conditions. The transition occurs at the Alfven speed v_a, where

$$v_a = \frac{c}{\left(1 + \frac{\rho_m}{\varepsilon_o B^2}\right)^{1/2}} \tag{3}$$

In equation 3, ρ_m is the mass density, ε_o is the permitivity in vacuum and c is the speed of light.

These calculations show that the plasma will carry only a small amount of frozen magnetic field away from the jet. Laboratory experiments and further theoretical studies are underway to further refine these physics models. Under certain operational conditions involving low exhaust velocity, a hypersonic neutral gas blanket is being considered downstream of the nozzle to enhance plasma detachment while producing an afterburner effect[4].

Experimentally, two major facilities are investigating plasma performance. Both have obtained attractive results with hydrogen and helium, the two propellants of choice and more recently with deuterium. In helium, densities of 10^{19} m^{-3} have been obtained at frequencies near the lower hybrid resonance. Slightly lower densities, in the range of 10^{18} m^{-3} have been obtained with hydrogen and deuterium. Further investigations using other gas mixtures are envisioned. Theoretically, the dynamics of the magnetized plasma are being studied from kinetic and fluid approaches. Plasma acceleration by the magnetic nozzle and subsequent detachment has been demonstrated in numerical simulations.

ENGINEERING ASPECTS

The implementation of CPT protocols in the VASIMR engine is done through a number of mechanisms. The most important of these is the selective partitioning of the RF power for plasma production (in the helicon injector) vs., ion heating in the central cell. For high thrust operation, a greater fraction of the total RF power is vectored to the helicon injector, making a "rich" more dense plasma, but not heating it as much. For high I_{sp} operation, the bulk RF power is routed instead to the ion heating central cell, creating a "lean" higher I_{sp} flow, with concomitant reductions in thrust. In either case, it is important to achieve a high level of ionization and to minimize the power losses at the helicon source. The total RF input is constant and kept at a maximum for efficient utilization of the electric power source.

High temperature superconductors will produce the magnetic field. Currently, the Bismuth Strontium Calcium Copper Oxide (BSCCO) compounds are feasible at field levels of about 1 Tesla. These magnets will operate in a regenerative mode utilizing the cryogenic propellant as a coolant as well as Multi Layer Insulation (MLI) for thermal control. Preliminary designs for a small magnet prototype have been completed and one of the magnet sections will be fabricated and delivered for laboratory testing in early 2001. While the critical temperature of these materials is above 100 Kelvin, the magnet will be kept at 35 Kelvin in order to provide ample operational margin. Figure 4 shows the configuration of a current design.

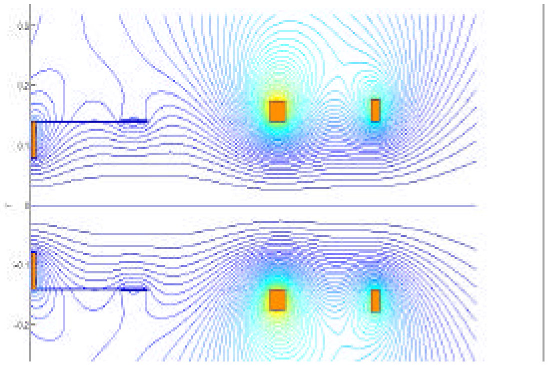

Figure 4. Magnetic configuration of a current superconducting magnet design.

Another important area of engineering involves the miniaturization of the RF power generation and delivery system (amplifiers, transmission lines and antennas.) Presently solid-state technology is being used to produce systems capable of up to 50 kW. The transition to a high power VASIMR will require the use of vacuum tube technology. Laboratory tetrode tubes at power levels of 100-200 kW have been available for many years. However, these devices have not been manufactured to operate in the space environment, so considerable engineering research remains to be done to explore this application.

At any rate, the present limitations in available space electric power will force the low power application to be developed first. Consequently, our research team has developed modular solid-state RF amplifiers at the kW level. These units are presently being tested in laboratory experiments. A water-cooled 1 kW steady state amplifier capable of operation from 2-50 MHz is shown in Figure 5.

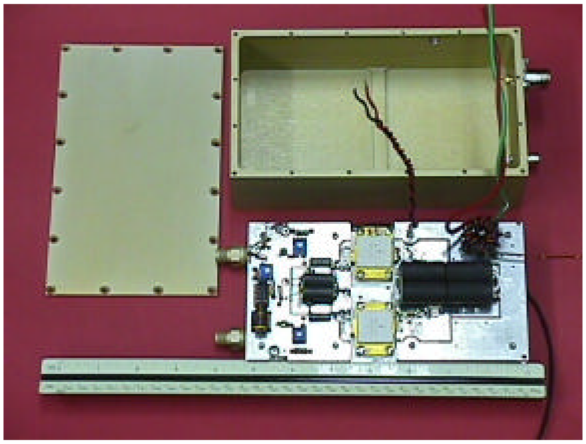

Figure 5. Solid-state 1kW steady state RF amplifier.

Research activities have focused on a number of key areas as embodied in the first flight demonstration experiment. This device is called the VF-10 thruster and forms part of an advanced propulsion technology spacecraft known as the Radiation and Technology Demonstrator (RTD.) This 10kW, solar powered spacecraft will feature a VASIMR engine operating at a constant I_{sp} of 10,000 sec and a thrust level of .1 N. A conceptual design of the RTD is shown in Figure 6.

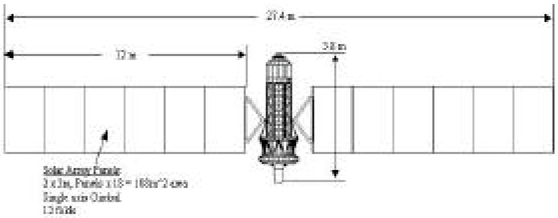

Figure 6. General layout of the RTD spacecraft.

The VF-10 will utilize newly developed, high power, solid-state RF amplifiers and a high T_c superconducting magnet, operating at a maximum field of .6T. This study supports an early flight demonstration of VASIMR technology in mid-2004.

HUMAN MISSION APPLICATIONS

A parametric comparison of the VASIMR with NASA's Nuclear Thermal/Chemical design reference mission has been completed[5]. The study shows the operational capabilities and tradeoffs of the VASIMR system for human missions to Mars. In this context, the outbound and return piloted mission can be carried out in just over 200 days with a three-engine and nuclear reactor cluster, operating at a combined power level of 12MW. A special feature of these missions is the capability to support powered aborts scenarios in the event of contingencies. This feature is of great interest for human missions. Figures 7a, b and c show the outbound piloted mission strategy. A 188 mT piloted ship departs LEO on May 6, 2018 and delivers a 60.8 mT payload (including the crew) to Mars in 115 days. The propulsion strategy is divided in three parts. A 30day Earth spiral (a) followed by a heliocentric trajectory to two Mars encounters at 85 and 216 days respectively (b). The crew lands on the first encounter. On the second encounter, the mother ship gradually spirals into low Mars orbit to await the completion of the surface mission and the return of the crew (c).

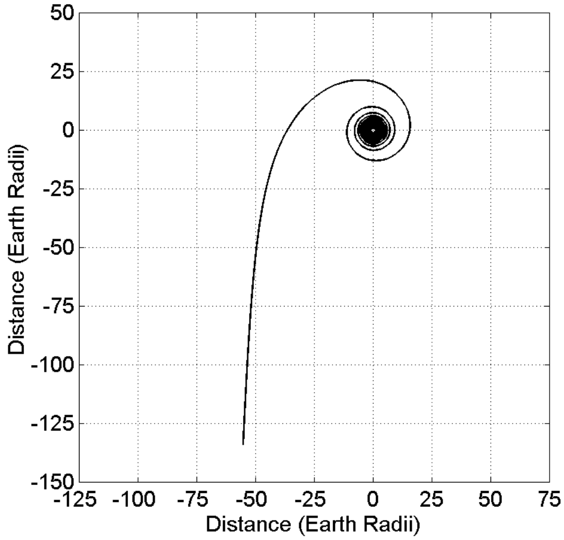

Figure 7a. Piloted mission 30-day constant I_{sp} spiral

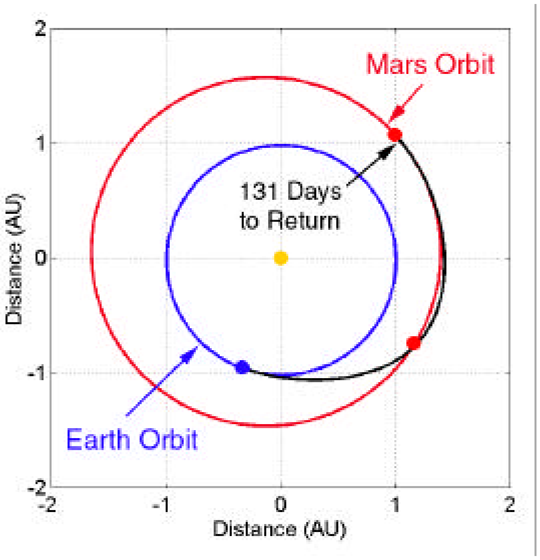

Figure 7b. Heliocentric piloted trajectory to two Mars encounters. The first one at 85 days delivers the crew for an aerocapture maneuver and landing.

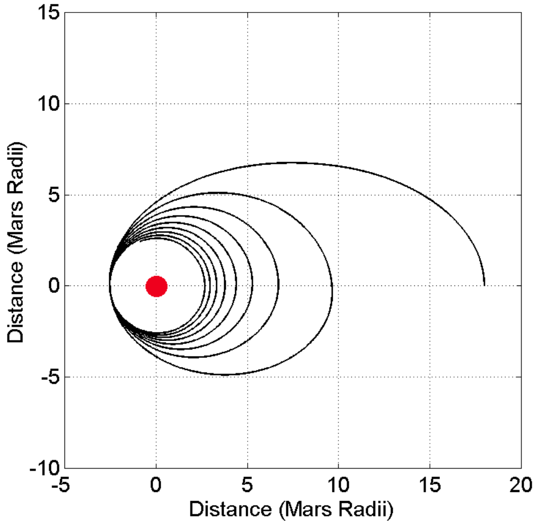

Figure 7c. A 7 day inward elliptic spiral follows at the second Mars encounter. This maneuver delivers the return ship automatically to a low Mars orbit to await the return of the crew.

During the outbound spiral, the engines operate at a constant I_{sp} of 3000 seconds. This maximum thrust climb is followed by an optimized, variable I_{sp} and thrust schedule, which delivers the craft to Mars at a relative velocity of 6.8 km/sec. Figure 8 shows the I_{sp} schedule for the piloted mission. Maximum power is maintained throughout. Figure 9 shows one possible architecture of such a ship. In this configuration, the hydrogen tanks are used as an effective radiation shield to protect the crew during the trajectories.

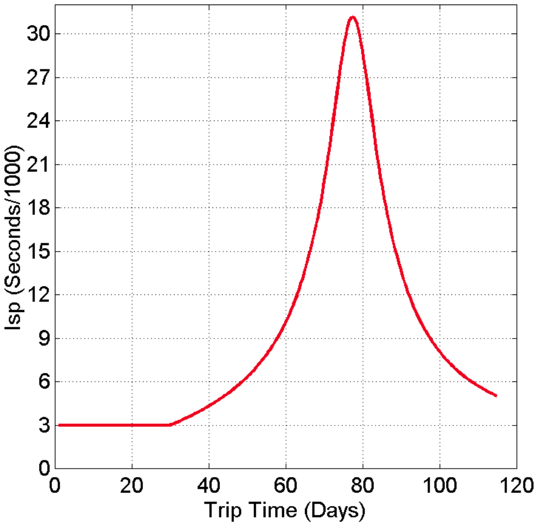

Figure 8. I_{sp} schedule for the outbound piloted mission

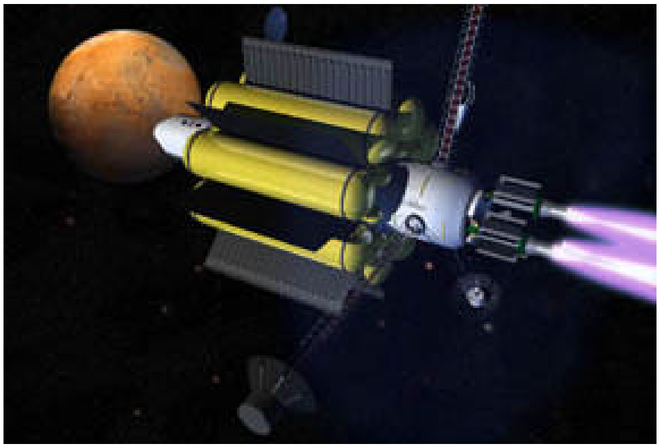

Figure 9. A possible architecture for the human Mars vehicle.

The return mission is similar in nature. The Mars outbound spiral is only 4 days due to a combination of factors, including a lighter ship and a lower gravity. The heliocentric portion is also 85 days. At Earth arrival, the crew executes a direct atmospheric entry with an aerocapture maneuver. The mother ship is either left on a high parking orbit or delivered for disposal to the Sun or on an escape trajectory out of the solar system.

The importance of abort options for human missions can not be overemphasized. The present study has taken an exploratory look at these maneuvers and possible scenarios under which they would apply. Generally speaking, the VASIMR engine is reconfigured to react to propulsion system failures limiting engine power, propellant available or critical failures not related to the propulsion system. Figure 10a shows that a rapid return to Earth is available for a propellant system failure where 1/3 of the remaing propellant has been lost on day 39. For a non-propulsion related failure on day 44, a longer trajectory to Eearth is still available. This is shown on Figure 10b. Finally, an abort deep into the heliocentric trajectory results in very long return time and strong consideration should be given to an emergency landing on Mars. This is shown in Figure 10c.

The very long abort trajectory shown in Figure 10c merits additional discussion. While it may be unlikely that a crew may choose to abort to Earth on day 80 of the heliocentric trajectory, a number of malfunctions could occur on the surface of Mars and within the space vehicle that would preclude a landing. In these cases, the 430day return is the only option available. While these trip times may seem excessive, they are short in comparison to the design reference mission (DRM,) which requires in all cases to await the opening of the return window, either on orbit or on the Martian surface. There is no possibility of returning to Earth early.

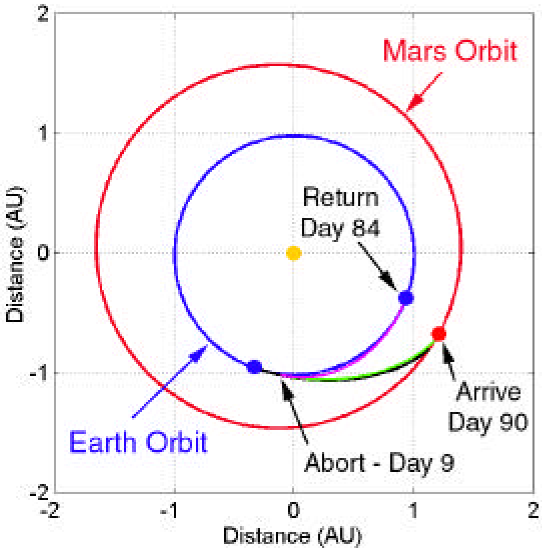

Figure 10a. A return to Earth abort due to a loss of 1/3 of the remaining propellant on day 9 of the heliocentric trajectory.

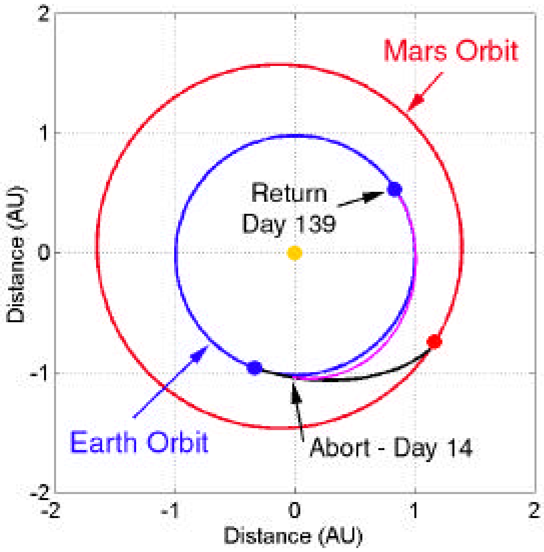

Figure 10b. A return to Earth abort on day 14 of the heliocentric trajectory is still possible with a full propulsion system.

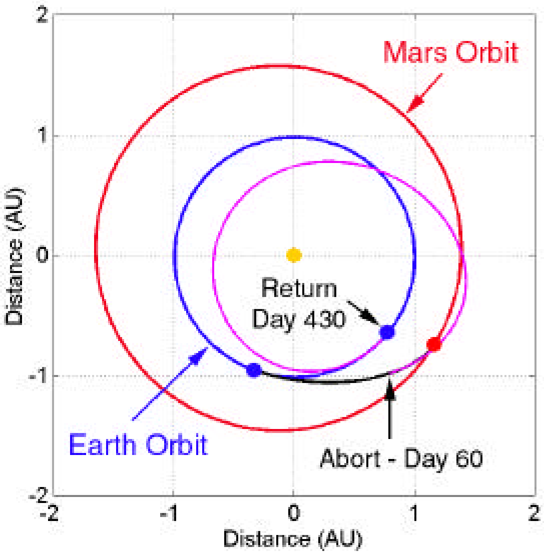

Figure 10c. An abort deep into the heliocentric trajectory results in a long return time.

CONCLUSION

A great deal of progress has been made in the understanding the basic physics of the VASIMR engine. Nevertheless, the research continues on many fronts. In plasma theory, a better understanding of the physics of light gas helicon discharges is required in order to better optimize the plasma generation stage. In the ion heating area, better ICRH models are needed, which include the effect on the plasma electrons. At the magnetic nozzle, MHD fluid models are being generated to understand the plume separation and develop magnetic field design criteria.

These theoretical studies go hand in hand with laboratory experiments to verify the physics. These experiments are providing critical insight on the operation of these devices and serve as validation benchmarks for the theoretical models. The laboratory activities are being focused on the definition of the parameter space for the RTD spacecraft. These experiments are set to achieve a steady state laboratory demonstration of the plasma parameters required for the VF-10 flight demonstration device.

Spacecraft engineering and mission studies are also ongoing, and help define the relevant questions and priorities in order to achieve a viable space demonstration of the technology. Already, the use of a high temperature superconducting magnet appears feasible, and the generation of kW level RF discharges with compact solid-state technology has been experimentally demonstrated in the laboratory.

Finally, mission studies have been conducted which provide useful comparisons with other competing technologies. These results show attractive mission performance with multi megawatt nuclear electric power and open up a number of abort options to conceivable failure scenarios of great importance to human crews.

ACKNOWLEDGMENTS

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REFERENCES

1. F.R. Chang and J.L. Fisher; "A Supersonic Gas Target for a Bundle Divertor Plasma", Nuclear Fusion, Vol. 22, No. 8, 1982.

2. M.D. Carter, F.R. Chang-Díaz, A.V. Ilin, D.O. Sparks, F.W. Baity Jr., R.H. Goulding, E.F. Jaeger, J.P. Squire, "Radio Frequency Plasma Applications for Space Propulsion", *Proceedings of ICEAA99* (1999).

3. R. Sagdeev, University of Maryland, East West Space Science Center; private communication. March, 2000.

4. F.R. Chang Díaz, "Research Status of the Variable Specific Impulse Magnetoplasma Rocket", *Transactions of Fusion Technology*, **35**, 87-93 (1999).

5. L.D. Cassady and F.R. Chang Díaz, "Parametric Study of Mars Trajectories Under Variable Specific Impulse" Advanced Space Propulsion Laboratory, NASA, Johnson Space Center, Houston, TX 77059 (USA). Internal report in publication.