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On the Development of a Magnetically Vectored Variable I_{SP} Plasma Rocket

Enectalí Figueroa Feliciano
Stanford University; Stanford, California

Franklin R. Chang Díaz
Advanced Space Propulsion Laboratory; NASA JSC, Houston, Texas

Jared P. Squire
Advanced Space Propulsion Laboratory; NASA JSC, Houston, Texas

Abstract

The development of a Magnetically Vectored Variable I_{SP} Plasma Rocket at the Advanced Space Propulsion Laboratory (ASPL) is in progress at NASA's Johnson Space Center. The facility is using a small, 3.2 m tandem mirror device to study the application of RF heated magnetically contained plasmas for space propulsion. The central cell radius is 0.1 m and fields of 0.2 T and 2 T are possible in the central and end-cell mirror sections, respectively. A magnetoplasmadynamic (M PD) injector has just been acquired and will be used along with other methods of plasma refueling. A 1 M W magnet power supply upgrade is being developed with full implementation by the spring of 1997. Two microwave systems for discharge initiation and plasma heating at 2.45 GHz and 14.0 GHz, respectively, are in operation. Additionally, RF systems with 200 kW and I MW of power are being modified and conditioned for operation. The concept provides electrode-less operation and variable thrush'specific impulse at constant power (200 -30 N / 5000-30,000 seconds at 10 M W with a 60% efficiency). Optimization for speed or payload are possible with the same engine, giving the rocket great flexibility. Missions to Mars in 90 days are described, and missions to Pluto are under study,

Introduction

Human and robotic interplanetary travel using conventional chemical rockets suffer from prolonged trip time. In the case of human missions, the exposure to weightlessness and radiation and their effect on the crew's health are the major concern. The possibilities for changing trajectories in mid-flight are very constrained, and the total maneuverability once the destination is obtained is limited to correction burns and orbit captures. In the event of an emergency, abort scenarios in human missions are very difficult and often involve long orbits and close solar flybys. For robotic missions, the years of coasting through interplanetary space while principal investigators wait to begin

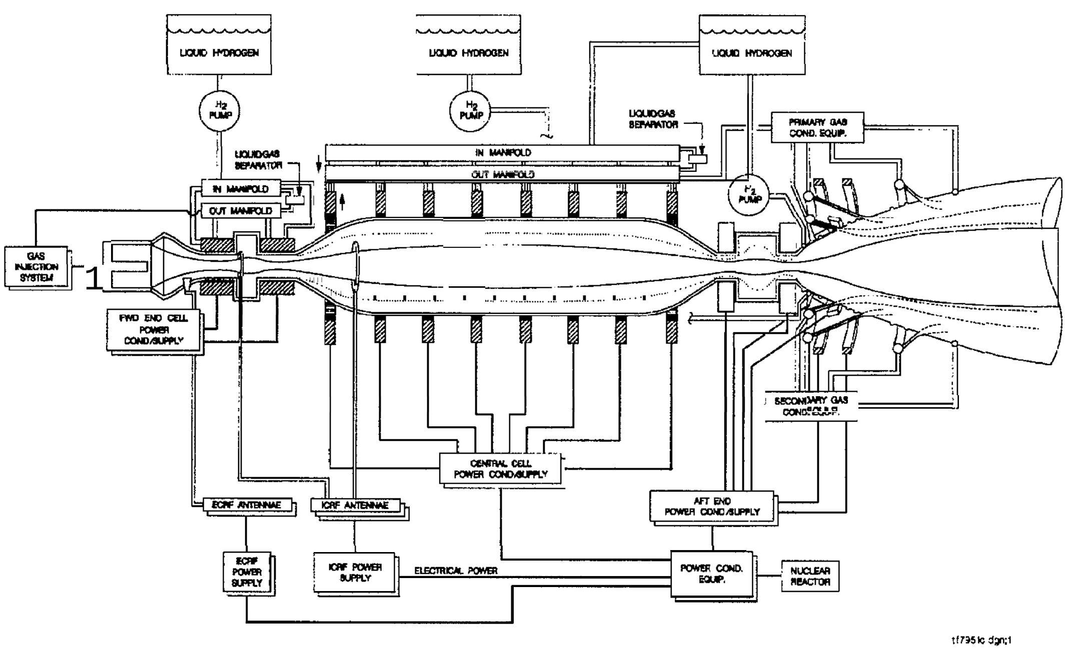


Figure 1. Schematic of the Magnetically Vectored Variable I_{SP} Plasma Rocket.

gathering their data makes involvement by scientists and students taxing, and raises the ground support and total cost of such missions. The acceleration time in conventional chemical rocket is negligible when compared to total trip time. This in turn puts constraints on the available launch windows, especially for long missions to the outer planets, reducing the versatility and error correction capability of the spacecraft. What is needed is an advanced propulsion system capable of optimization for high payloads, high speed, or maneuverability for the duration of the mission.

One such capable system is the Magnetically Vectored Variable I_{SP} Plasma Rocket.' This approach uses a tandem mirror configuration used in fusion research to magnetically contain a plasma heated by Ion Cyclotron Resonance Heating (ICRH). The high powered, electrode-less thruster can operate optimally over a large range of thrust/specific impulse (I_{SP}) combinations. This is accomplished via a variable magnetic nozzle with a coaxial gas injector near the throat that modulates the exhaust and protects engine materials from the hot plasma. A schematic is shown in Fig. 1.

Concept

A tandem magnetic mirror[2] consists of a collinear set of annular magnets divided into a solenoidal central cell, where plasma is contained and heated, and two higher field end mirror sections. These end-cell sections are high field magnets that tend to reflect the plasma at either end of the central cell and axially trap a fraction of it; thus the term "magnetic mirror." When used for propulsion, gas (typically an inert gas or hydrogen) is injected through one end and ionized into a cold, dense plasma by a device such as a MPD injector, a, hollow cathode discharge or by Electron Cyclotron Resonance Heating (ECRH) before entering the central cell, The central cell acts as an amplifier and heats the plasma by ICRH.[3,4] The device is operated asymmetrically, inducing a flow throttled by the exhaust nozzle magnetic field. At the nozzle, a thin, dense film of hypersonic gas is injected to aid the detachment of the charged particles from the magnetic field by diffusion, adding the benefit of insulating the engine materials from the hot plasma. Additionally, an AC component to the DC field maybe introduced at the nozzle to create instabilities and "shake" the plasma off the field lines. The magnitude of the AC component and the mass flow of the insulating discharge gas depend on the particular mode of operation, and are expected to be minimized at the low thrust, high I_{SP} mode.

Basic Equations

The advantages of variable I_{SP} propulsion have been known since the early 1950s.[5,6,7] The conceptual basics are developed here in the simplest but illustrative case of gravity-free space. For a variable I_{SP} rocket, the exhaust velocity with respect to a frame at rest with the vehicle departure point is made to match the vehicle velocity over the majority of the trajectory. Exhaust kinetic energy is optimally imparted to the vehicle when the exhaust leaves the rocket at rest, i.e., u = v, where the exhaust and vehicle velocities are denoted u and v, respectively.

Assuming no gravitational effects, the momentum balance for a rocket in free space is

$$\dot{v} = -\frac{u\dot{m}}{m} \tag{1}$$

where $\dot{v}$ and $\dot{m}$ are the time derivatives of the vehicle velocity and rocket total mass respectively, and *m is the* total mass. The total power flow off the exhaust is

$$P = \frac{u^2}{2}\dot{m} \tag{2}$$

and the relationships between the various masses are

$$m = m_o - m_f \tag{3}$$

where m_o *is the* total mass of rocket fuel at t = O, and m_f is the total mass of fuel exhausted through the nozzle at time t.

For a constant I_{SP} rocket, $u = I_{SP} * g$ = constant, and Eq. (1) can be integrated between **initial** and final velocities v and v_o to give

$$v(t) = v_o + u \ln \frac{1}{1 - y} \quad \textbf{(4)}$$

where

$$\gamma(t) \equiv \frac{m_f}{m_o} = \frac{\dot{m}}{m_o} t \quad \textbf{(5)}$$

is the mass fraction as a function of time. The mass flow rate $\dot{m}$ is usually considered a constant.

For a variable I_{SP} rocket, if we optimize efficiency so that $u = v$, integration of Eq. (1) yields

$$v = v_o \frac{m_o}{m} = v_o \left(\frac{1}{1-y} \right) \quad (6)$$

Equations (4) and (6) are plotted in Fig. 2. An exit velocity of $u = .5\, v_o$ was used for the conventional rocket, For the same mass fraction an optimally tuned variable I_{SP} rocket obtains a significantly greater velocity than a conventional rocket; for a given velocity, variable I_{SP} allows a far smaller mass fraction, thus granting larger payload capacity.

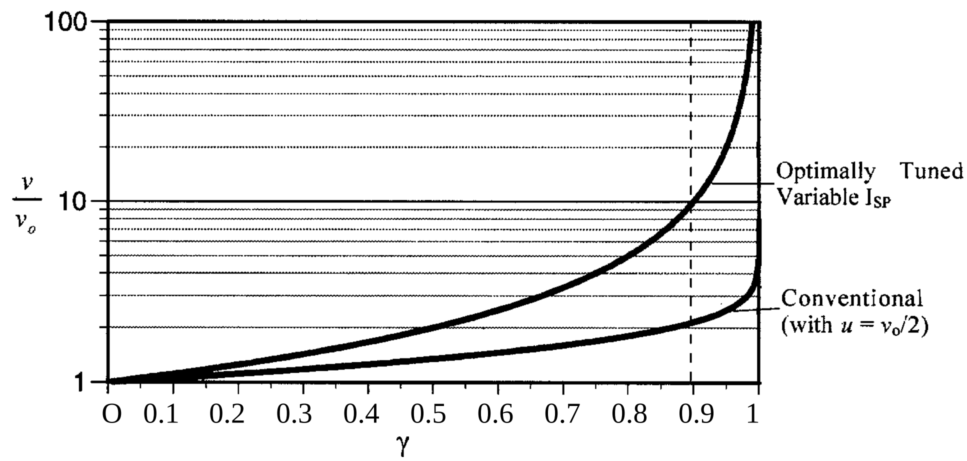


Figure 2. Velocity ratio as a function of the fuel mass fraction γ.

It should be noted that similar velocities can be achieved by high constant I_{SP} engines. However, when the distance involved is large,as in the case of interplanetary travel, variable I_{SP} reaches high speeds faster, and thus reduces the total trip time.[8]

Facility and Operation

To establish experimentally the feasibility and characteristics of the Variable I_{SP} Plasma Rocket, a tandem mirror plasma facility has been established at the Advanced Space Propulsion Laboratory (ASPL). The laboratory is located at NASA's Sony Carter Training Facility (SCTF), part of the Johnson Space Center in Houston, Texas. Plasma discharges have been created successfully at low energy levels.

The laboratory has dimensions of 96' x 48', The main experimental bed consists of a small tandem mirror machine, 3.2 m in length by 0.75 m in diameter. The vacuum chamber is a cylindrical assembly consisting of 9 stainless steel sections, with 24 ports available for diagnostics. A turbomolecular pump at the exhaust end easily maintains a 10-7 torr base vacuum. Back-filling to approximately 10^{-4} torr for plasma discharges is accomplished with a "10-100 seem gas flow. Our present pumping rate capability via turbomolecular pumps is 1,500 liter/s, although a cryopump is being considered that will boost the pumping rate to over 5,000 liter/s. An exhaust tank 1.5 m in diameter by 3 m in length has been fitted to the machine through a cone mating section and will permit high density discharges and study of the plasma plume in a simulated space vacuum. The cone section will later be an area of intense study as hybrid gas-magnetic nozzle experiments begin in 1997. The copper winding magnet set consists of two tandem mirror assemblies, each capable of 6,000 A each at liquid nitrogen temperatures, and the central cell, which has eight magnets capable of 1,000 A each at ambient temperature. To cool the end-cell magnets to liquid nitrogen temperatures, vacuum dewars have been designed into the machine; compressed air circulation

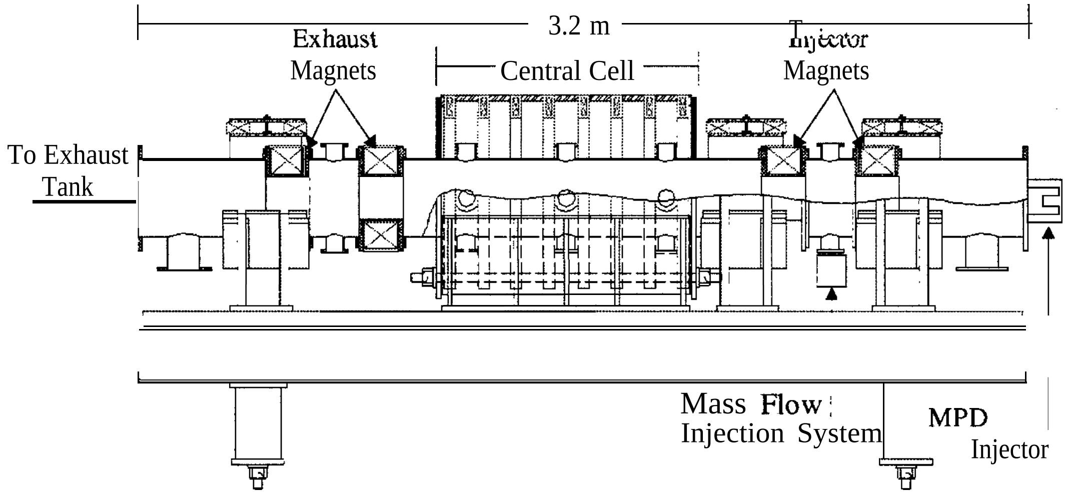


Figure 3. Tandem mirror machine at ASPL.

cools the central cell magnets. The magnets are presently powered by a 45 kW system consisting of three independent DC power supplies to regulate the current to each part of the machine and tailor the magnetic field for optimum flow, A 1 MW pulsed (10 seconds) DC power system is in the installation phase and should be operational by the time of this conference. Two microwave sources are used for ECRH: a 2.45 GHz microwave generator capable of delivering 800 W and a 2 kW, 14.5 GHz Klystron microwave generator that has been brought into operation this summer. For ICRH, two systems are currently being modified and conditioned for installation in the lab. One is a 200 kW RF transmitter, and the other is a set of three 1 MW RF transmitters that at one time powered the Arecibo Radio Telescope. They both have a frequency range from 1 to 10 MHz. For data acquisition, 5 CAMAC crates with a total of over 100 channels are connected to a data highway providing 2 Mbytes/s down loading rate into a Power Macintosh. A summary of the laboratory setup is shown in Table 1.

System Parameters

Overall length	3.2 m
Central cell length	1.15 m
Central cell radius	0.36 m
Exhaust tank	d-1.5 m x 3 m
Vacuum level	10^{-7} torr
Central cell field (B_c)	2 kG
Maximum field (B_{max})	3 T
DC power	1 MW
Plasma density (variable)	10^{19} m^{-3}
Plasma temperature	0,01 -1.0 keV
Plasma heating power:	
ECRH	2 kW
ICRH	1 M W

Table 1. System Parameters for ASPL equipment.

A brief overview of current operation follows. After the desired base vacuum is achieved (104 tom), a mass flow control system is used to inject Argon or Helium into the chamber in the injector end of the machine. By adjusting the flow, a pressure of 2x 10-4 torr is established, which is the optimum pressure for plasma breakdown in our current system. Three separate power supplies are used to selectively modulate the magnetic field in the injector, the central cell and the exhaust. Plasma discharges can now be generated in two modes, low and high power, For the low power mode, the 2.45 GHz generator is used to induce ECRH in the gas and generate a plasma. This mode, which produces a density of 7x1O^{16} particles/m^3, is used to test the equipment and purge the vacuum tank of impurities, since it can be run at steady state. Currents of 150 A in the injector and 30 A in the central cell magnets are typical for this mode, generating magnetic fields up to 0.1 T. The high power mode uses the 14.5 GHz Klystron in conjunction with the 2.45 GHz generator to achieve densities of 2x1O^{18} particles/m^3. This mode can be operated only for 30 second pulses, and liquid nitrogen refrigeration is needed for the end-cells. Part of the activities of this summer included the design of a Programmable Logic Controller (PLC) system for automating the operation of the machine, which is now done manually.

Development

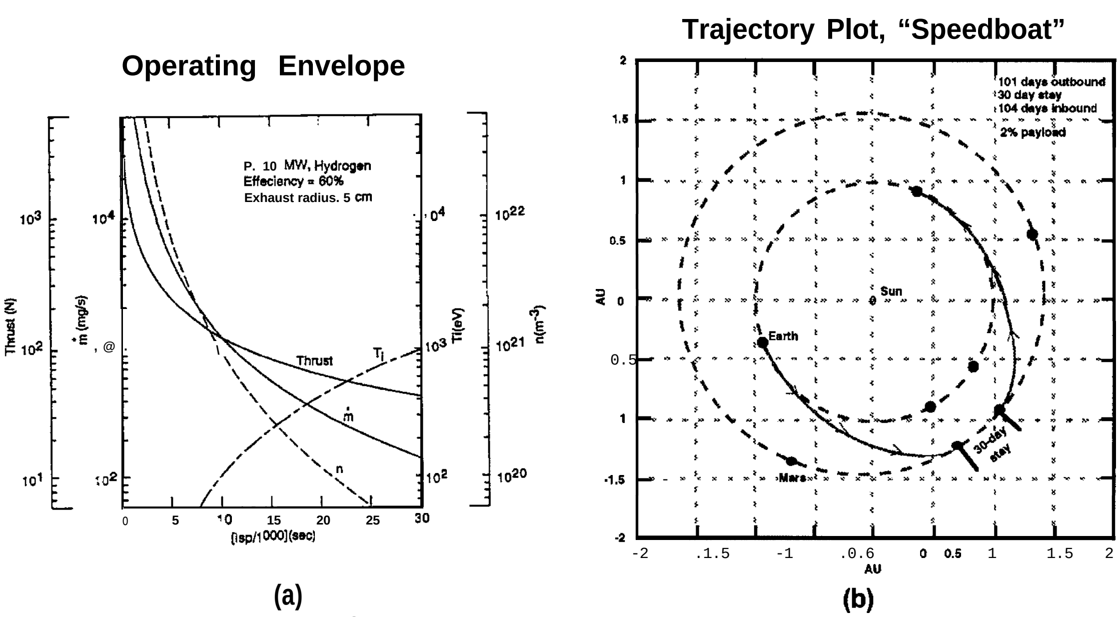
Several exciting prospects await ASPL in 1997. The completion of the system installation and fill on-line status in expected, at which point the major focus of the lab will shift into experiments and data collection. There are still numerous questions to be answered and concepts to be proven, and there are plenty of opportunities in engineering and plasma physics to follow. Several diagnostics will be installed, including an array of Langmuir probes to measure the temperature and density of the plasma at the edge. A laser fluorescence system at 6563 Å will determine the neutral density of the exhaust, and a microwave interferometer operating at 100 mW will be used to map the plasma density. Also, a retarding potential analyzer for the plasma exhaust is under development. Further studies will be conducted, especially in the nozzle section, where magnetic field decoupling effects have to be ascertained. A general empirical performance envelope for the concept must be developed, and scaling laws for different power regimes determined.

Proceeding into the next step of development, a small, 30 kW engine is being designed to fly as a shuttle mission in the coming years. Powered by batteries, it would be a free flying satellite deployed and controlled from the Shuttle and would perform many 1 to 2 minute pulses. It would carry superconducting magnets and its own communication system. The goal of the mission would be to prove the general principle of the concept and test the process in the vacuum of space. Thrust and I_{SP} would be monitored, along with a host of plasma diagnostics and video feed to have visual contact with the engine and plasma while in operation.

Next a 100 kW demonstration rocket is envisioned. This would be very similar to a full scale version, possibly nuclear powered, with superconducting coils. Once operational, it could be used to launch magnetosphere mapping missions in a outward spiral around Earth; or to take cargo, such a GPS transceivers or supplies, to the moon; or to send small probes to the outer planets in record times.

Future

The full scale Magnetically Vectored Variable I_{SP} Plasma Rocket would be a high redundancy, high power platform able to carry large payloads in a "tugboat" mode, or to safely and quickly carry a crew in a low payload "speedboat" mode. A recent study[9] examined scenarios for human and robotic missions to Mars. The mission is a split sprint consisting of a robotic mission that would carry supplies and landing modules, and a fast light mission carrying the crew. The same type rocket would be used for both, and would be a 10 M W version of the demonstration rocket



(a) (b)

Figure 4. a) Operating Envelope for a 10 MW rocket. b) 101 day human mission to Mars for a 30 day stay. Travel times of 90 days with 14.49% inbound payload capacity and 18.12°/0 outbound payload capacity are possible for extended duration (two year) missions,

mentioned in the last section (Fig. 4a). For the robotic mission, a 66.66% payload mass fiction and 180 day trip is projected, at which time the craft will enter Mars orbit. Check outs will be done and a robotic lander deployed with a habitat, fuel, and supplies in the two year wait for Mars to again be in optimum position for flight. Once the two year wait is over, the crew will leave Earth orbit for a 101 day trip. Upon entering Mars orbit, the crew will dock with the supply module, and descend to the Martian surface. Thirty days later the crew will be back in their speedboat en route to Earth (Fig. 4b).

Abort capability plays an important role in the feasibility of a mission scenario. During the Apollo program and currently in the Shuttle program, abort possibilities were and are inherent in mission design. Interplanetary missions should live up to and out-do the capabilities of these programs. Were the ship's life support systems to malfunction, or a crew member to become sick, or one or more of the modules of the rocket cluster to fail, the ship must have the capability to return to Earth, or at least arrive at the supply module orbiting Mars. For 90 day trips, if an abort condition occurred 15 to 20 days after leaving Earth orbit, a 75 day abort to Earth is possible with a full-up propulsion system. In the case of partial propellant loss, a 180 day abort is possible, although the amount of propellant and velocity away from Earth at abort time will determine the best abort trajectory.

After the first mission, the habitat that would remain in the Martian surface and the power plants left in orbit could be used by future missions. If a longer stay is desired, the crew would have to "winter down" on the Martian surface for two years. If a two year mission is planned, 90 day trips with 14.49°/0 inbound payload mass fraction are possible. Moreover, while still making the Mars-Earth trip in 90 days, the crew would have an 18.12% payload mass fraction upon return, allowing for a sample return equal to 3.63% of the mass of the ship.

Conclusion

The Magnetically Vectored Variable I_{SP} Plasma Rocket provides optimum thrust/I_{SP} modulation for fast interplanetary missions. Much theoretical and experimental work remains to be done to understand the optimum operating parameters and the behavior of plasma in an asymmetric tandem mirror. Although initial numerical simulations have been made,[10] the nozzle section and the processes which separate the plasma from the diverging magnetic field must be further studied. ASPL is devoted to developing this technology and experimentally demonstrating its feasibility in space borne missions in the coming years. The laboratory is undergoing major upgrades in the coming months and should be breaking new ground in power and data acquisition in 1997. Ongoing projects include a study into the trajectory for a Pluto flyby mission, continuing out into the heliosphere to study deep space to a the thousand astronomical unit (TAU) mark.

Mars, although the probable first planet in our human exploration of the solar system, will not be the last. Technologies must evolve and our commitment toward exploring the Solar system must solidify. Humans will need to master the art of living and working in space. To get there, we must continue to develop better and innovative propulsion systems. This is the goal of ASPL.

References

[1] Chang Díaz, F. R., "The Hybrid Plume Plasma Rocket," NASA Johnson Space Center Internal Report, January 1982.

[2] Balwin, D.E. and Logan, B.G., "TMX Major Project Proposal," Lawrence Livermore National Laboratory Report 11-Prop-148, 1977.

[3] Yang, T. F., Peng, S. and Chang Díaz, F.R. *AIAA/ASME/SAE/ASEE Int. Joint Propulsion Conference, paper AIAA-91-2338*, Sacramento, California, 1991.

[4] Peng, S., "ICRF Wave Propagation and Plasma Coupling Efficiency in a Linear Magnetic Mirror," Ph.D. Thesis, MIT, 1991.

[5] Irving, J.H. and Blum, E.K., "Comparative Performance of Ballistic and Low-Thrust Vehicles for Flights to Mars," *Vistas in Astronautics*, Vol II, Pergamon Press, New York, 1959.

[6] Stuhlinger, E., *Ion Propulsion for space Flight*, McGraw-Hill, 1964.

[7] Melbourne, W. G., "Interplanetary Missions with Low Thrust Propulsion of Advanced Propulsion Vehicles," Jet Propulsion Laboratory Internal Report 32-68, Pasadena, California, March, 1961.

[8] Chang Díaz, F. R., Yang, T.F., Kruger, W.A., Peng, S., Urban, J., Yao, X. and Griffin, D. *DGRL/AIAA/JSASS Int. Electric Propulsion Conference, paper DGLRA-88-126*, Garmisch-Partenkirchen, W. Germany, 1988.

[9] Chang Díaz, F.R., Hsu, M.M., Braden, E., Johnson, I. and Yang, T.F., "Rapid Mars Transits with Exhaust-Modulated Plasma Propulsion," NASA Technical Paper 3539, March 1995

[10] Krueger, W.A, "Plasma and Neutral Jet Interactions in the Exhaust of a Magnetic Confinement System," Ph.D. Thesis, MIT, June 1990.