

A Harvesting Planetary Orbiter to Enable Deep Space Missions to the Jovian Planets

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Abstract. To create a more efficient propulsion system for in-space transportation the NEP and NTP systems are now being developed to facilitate the human exploration of Mars. They are, however, unlikely to meet the challenge of deep space without significant advances in efficiency and the ability to use in-situ resources. The concept outlined in this paper is the development of a planetary orbiter spacecraft that can operate on virtually any gas, and is designed in such a way that it can also harvest the planetary atmospheres to obtain the fuel required for the return transit. It is based on experimental results employing a robust plasma creation and sustainment methodology referred to as a Rotating Magnetic Field (RMF) generated Field Reversed Configuration (FRC). In the experiments a Hydrogenic gas was partially ionized and accelerated out of a magnetized cascaded arc source with directed velocities of 35 km/s that is characteristic of the conditions that would confront a Harvesting Planetary Orbiter (HarPO) in the atmospheres of the Jovian planets. The transverse RMF fully ionized the gas, and in the process generated large azimuthal currents which produced an FRC that confined and heated the ions. The stationary, axial guide magnetic field confined the plasma within the chamber wall and conducted the plasma exhaust to form an on-axis plasma jet. In the spacecraft implementation, this system would efficiently process the incoming atmosphere into the necessary thrust and Isp for drag makeup. Based on the ion temperature measurements in the experiments, only a fraction of the gas ingested during the orbital transit would be required as the projected Isp is 12 ksec. The plasma chamber radius, which is the same as the spacecraft intake aperture, need be no larger than that employed in past RMF FRC experiments (0.4m). Given that the HarPO is electrodeless and magnetically insulated, it quite capable of long-term operation on the lighter elements, so that the array of HarPO's could also be employed as the main thrusters for the transits to and from the outer planets. The analysis and design of a prototype HarPO has been completed based on the drag, power processing, energy and fuel storage requirements that would be encountered in the Jovian atmospheres. The results from this analysis, as well as the architectures for a Neptune and Jupiter mission will be described.

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1. INTRODUCTION

Deep space exploration and development has been stymied due to the enormous energy demands of rapid transit over such vast distances. Past missions have been carried out by relatively small spacecraft, launched on the few occasions when rare planetary alignments provided for the gravitational boosting necessary to perform the trip on a somewhat reasonable timescale. To create a more efficient propulsion system for in-space transportation one must look to the NEP and NTP systems that are now being developed, and which show tremendous potential to facilitate the human exploration of Mars. They are, however, unlikely to meet the challenge of deep space without significant advances in efficiency and the ability to use in-situ resources. NTP is limited in Isp even though it could make use of the hydrogenic fuels of the outer planets. NEP can achieve the high Isp necessary for these missions but has been primarily developed to utilize Electric Propulsion (EP) thrusters that require the use of heavy noble gases to obtain reasonable efficiencies and electrode lifetimes.

The ultimate goal of this effort is the development of a planetary orbiter spacecraft that can operate on the gases found in virtually every planetary atmosphere, and is designed in such a way that it can also harvest the planetary atmospheres to obtain the fuel required for the return transit. As the Harvesting Planetary Orbiter (HarPO) can operate at much higher powers, this device can also function as the main EP engines for the transits to and from the target planet. This would enable the much higher power NEP missions desired for surface exploration and development of the Jovian moons. Such missions were seriously considered in the recent past by both NASA and ESA for NEP-powered missions such as the Jupiter Icy Moons Orbiter (JIMO)^{1,2}. Among other issues, the mission was deemed too expensive due to the multiple-launch and the in-orbit assembly architecture. The one-way trip required 12,000 kg of Xenon and as many as 20 high power Ion and Hall thrusters. With the ability to obtain essentially unlimited amounts of fuel in situ, the exploration of the Jupiter's Moons, as well as those of Saturn and the

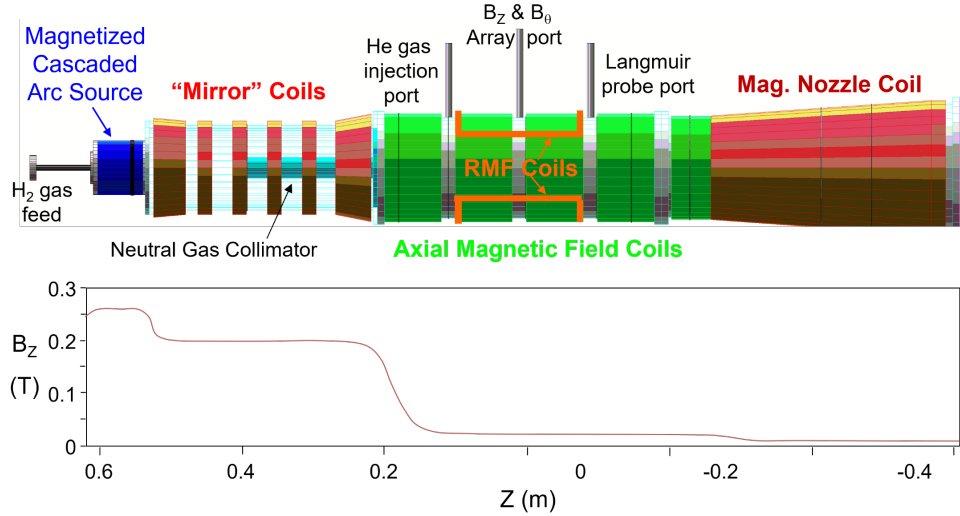


Figure 1. The Startup Experiment-High Flux (STX-HF) that demonstrated the essential physics to be employed in HarPO.

outer planets could be explored by “planet hopping” as part of the same mission with a “sample and return” as well.

2. KEY EXPERIMENTAL RESULTS

Essential to the groundbreaking in-space propulsion technology being described here was the demonstration of critical performance criteria in experiments performed at MSNW. These experiments employed a robust plasma creation and sustainment methodology referred to as a Rotating Magnetic Field (RMF) generated Field Reversed Configuration (FRC)³⁻⁵. Most importantly, the tests were executed in a manner pertinent to the very environment that would be encountered in planetary atmospheres, and in particular, the gas giants. The methodology was actually developed as a startup process for a nuclear fusion concept that employs light gases similar to the Jovian planetary atmospheres, namely Deuterium (²H) and Helion (³He) as the nuclear fuel. In the experiments, a Hydrogenic gas was partially ionized and accelerated out of a Magnetized Cascaded Arc Source with directed velocities of 35 km/s that is characteristic of the conditions that would confront a Harvesting Planetary Orbiter (HarPO) in the atmospheres of the Jovian planets. The experimental layout is depicted in Fig. 1.

The transverse RMF fully ionized the gas, and in the process generated large azimuthal currents which produced an FRC that confined and heated the ions⁷. A plot of the measured plasma temperatures during the equilibrium phase on STX is shown in Fig. 2. The plasma density was determined from both Langmuir probes and infrared laser interferometry. It should be noted that the overall slow decrease in temperatures observed is due to the drop in RMF input power as the energy source was an electrolytic capacitor bank. To obtain a direct measure of the ion temperature, a small jet of Helium gas was introduced into the plasma from a side port (see Fig.1). After sufficient time to reach equilibrium with the Hydrogen, the

observed temperature from Doppler broadening measurements of a He II line confirmed the ion temperature inferred from radial pressure balance with the external magnetic field shown in Fig. 2. The ion heating is a consequence of the RMF induced flows to establish and maintain the field-reversed magnetic field profile. The electron temperature is more or less clamped at ~ 10 eV by energy losses to the continuous process of ionization of the incoming neutral flow.

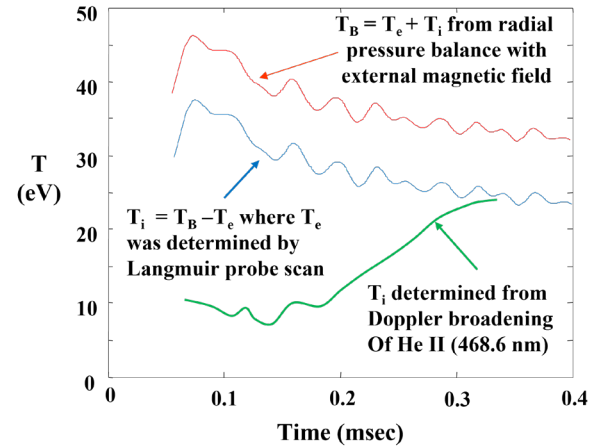


Figure 2. Electron and ion temperature measurements with Helium injection on the STX experiments.

The stationary axial guide magnetic field confined the plasma within the chamber wall and conducted away the lost plasma at the end of the FRC forming an on-axis plasma jet, and thereby converted plasma thermal energy to directional energy. A singular and particularly advantageous effect of the RMF electric fields is that it produces a radially inward flow of the plasma which dramatically reduced the plasma loss rate from the FRC. The transit time of the highly directed neutral flow through the FRC formation region observed with no RMF was only ~ 5 μsec. The transverse RMF immediately entrained electrons to flow azimuthally and with the inwardly

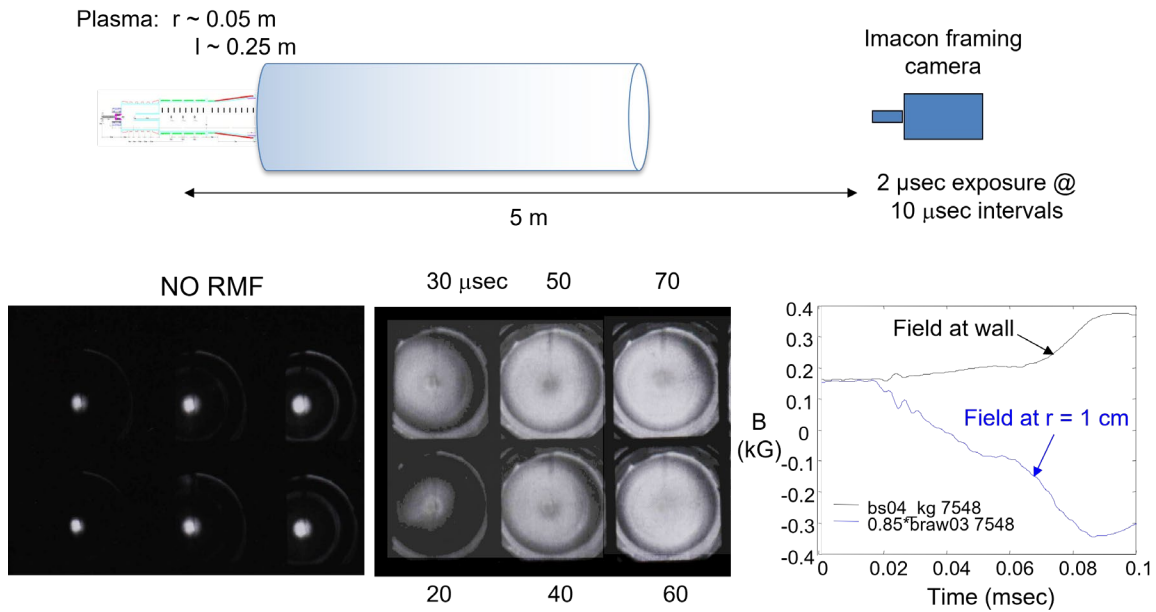


Figure 3. End-on filtered (510-600 nm) plasma emission. Filter eliminates H α and H β line radiation. In “No RMF” case: emission is brighter primarily due to Hydrogen molecular band radiation which is greatly diminished by dissociation with the RMF.

directed flow, rapidly built up the density and size of the FRC, but now with a plasma confinement time an order of magnitude larger.

The entire process can be observed from the end-on filtered plasma emission captured by a fast-framing camera. The images and setup can be found in Fig. 3. The camera is positioned far enough away from the FRC that there is very little parallax. It is clear that the FRC is isolated from any contact with the formation chamber wall with the exhaust eventually intercepting the large chamber walls nearer the

camera. The hard vacuum maintained in this chamber ($\sim 10^{-9}$ Torr) assures that a spacelike environment is maintained throughout the experimental run. The large mirror ratio axially across the formation chamber assures that the plasma flows only in the downstream direction. All of the advantageous features observed in the experiments make for a uniquely efficient and revolutionary electric propulsion system, and the initial design of the HarPO spacecraft (see Fig. 4) was made to assure that they would be maintained in a scaled-up version.

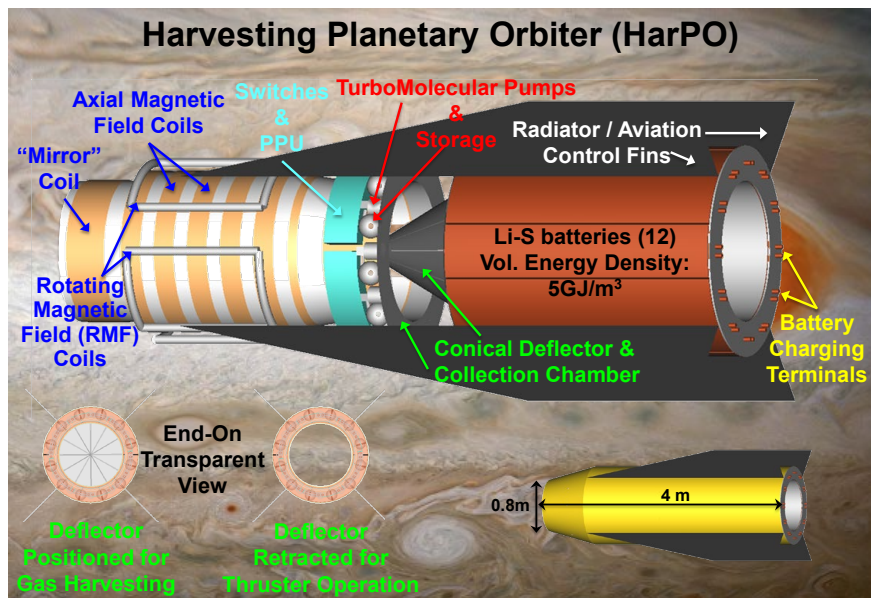


Figure 4. Initial Harvesting Planetary Orbiter (HarPO) design for exploration and fuel harvesting at the Jovian gas giants. Internal segmented conical deflector redirects incoming flow to an array of pumps. Deflector is retracted to convert HarPO into a high-power electromagnetic thruster with only the incoming flow as propellant.

It should be noted that the HarPO concept has actually several aspects that hold promise for an electric propulsion system that would have critical advantages over traditional systems utilizing Xenon. For one, the RMF FRC based thruster is a fully electromagnetic and electrodeless propulsion technology. RMF FRCs have been successfully formed and maintained at powers ranging from 1 kW to 10 MW. Due to the electrodeless nature of the thruster, FRC plasmas have been produced in a myriad of gases from Hydrogen through Xenon⁶. The RMF-formed FRC technology has been demonstrated to be very lightweight as it is essentially comprised of nothing more than a hollow-tube dielectric chamber surrounded by a set of cylindrical coils capable of generating a few hundred Gauss axial field with a pair of saddle shaped antenna coils arranged radially on top (see Fig. 4). The circuitry required is a steady, low voltage supply for the axial coils. The RMF is created by a sinusoidal current oscillation for each antenna driven 90 degrees out of phase. This is accomplished by a capacitor connected to the RMF antenna and IGBT switch to drive the L-C circuit. The specific mass for the preliminary flight design is anticipated to be less than 1 kg/kW for thruster and PPU combined. And finally, there is the magnetic isolation of the FRC plasma from the thruster walls and spacecraft during operation while also providing efficient thermal conversion of the plasma exhaust provides much higher efficiencies and specific power. It is these attributes, combined with the low-drag, maximal intake design that provides for the dual role as a propellant harvester.

The initial spacecraft design is based on the key elements of STX, but on a scale and in a manner that would allow for both the operation of the HarPO as a high-power thruster, as well as a fuel harvester, and is illustrated in Fig. 4. The location and size for the various components required for this dual operation of the HarPO spacecraft are also indicated.

The HarPO system needs to efficiently process the incoming atmosphere into the necessary thrust and Isp for drag makeup. With an ion temperature similar to that observed in the STX experiments, only a fraction of the gas ingested during the orbital transit would be required as the projected Isp operating on a Hydrogen propellant is 12 ksec. The plasma chamber radius, which is the same as the spacecraft intake aperture, need be no larger than that employed in past RMF FRC experiments (0.4 m)⁵. Several 2D Magneto-Hydrodynamic (MHD) calculations for both STX and the larger RMF FRC experiments have been performed that reproduced the experimental results. This same code was used for numerical simulation of the HarPO thruster system. The results from these calculations are shown in Fig. 5. It can be seen that as plasma is lost from the FRC, it flows down the magnetic gradient along the separatrix onto the open field near the axis and in the process forms a highly directed plasma jet far from the HarPO walls thereby maximizing both thrust and Isp.

It should be noted that this is a 2D MHD fluid calculation. The effect of the magnetic mirror reflection of the plasma ions and electrons moving in the upstream direction cannot

be resolved as this effect is due to the individual particle behavior in velocity space. Also, the influence of a relatively strong directional neutral particle flow was also not part of the calculation. These two important effects will be incorporated in future analytical efforts in optimizing the HarPO both as a thruster and as a harvester with the addition of a kinetic particle tracker which can capture the effects of both the ambient magnetic and electric fields on the individual particle motion.

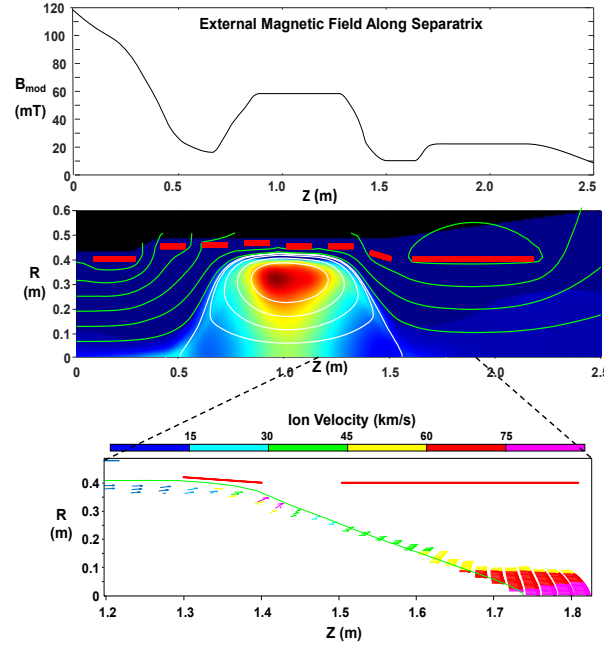


Figure 5. (Top) Magnetic field magnitude experienced by particle lost across the FRC plasma separatrix. (Middle) Magnetic field lines and plasma density contours for HarPO RMF FRC equilibrium. Hydrogen plasma density scale is in units of 10^{19} m^{-3} . (Bottom) Velocity vectors of plasma near the separatrix. The vector length reflects local plasma density.

3. PRELIMINARY ANALYSIS

The preliminary analysis and design of a prototype HarPO has been completed based on the drag, power processing, energy and fuel-storage requirements that would be encountered in the Jovian atmospheres. At this point the operational scenario would be as follows. The basic mode of transportation to/from the planetary systems will employ a NEP reactor along the lines of that proposed for the JIMO mission. It is believed that the HarPO, as indicated in the MHD analysis, should be capable of operating on Hydrogenic fuel at a steady power of 300-400 kW. This is made possible by the negligible plasma radiative (fully stripped ions) and conduction losses (thruster walls magnetically isolated from plasma). A significantly larger reactor power is thus envisioned (0.5 to 2 MWe), allowing for several HarPOs to be mounted to the main spacecraft. At arrival, the HarPOs

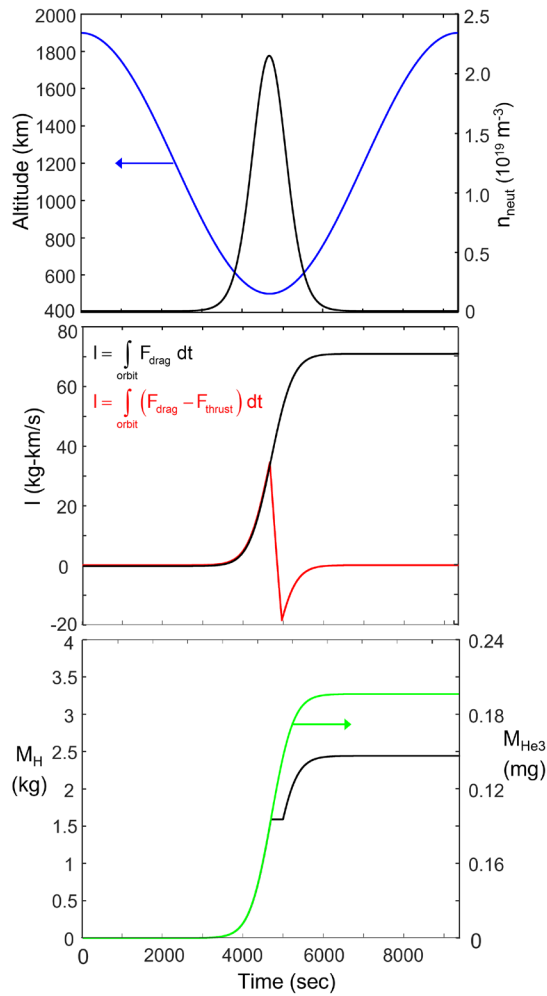


Figure 6. Key Parameters during HarPO elliptical orbit at Neptune.

would be sequentially launched on an elliptical orbit around the planetary body such that the apogee (and main spacecraft orbit) is at an altitude for negligible drag, and the perigee of the HarPO is at the proper altitude for optimal propellant harvesting (see Fig. 6). During most of the orbit the HarPO is in the harvesting configuration where a segmented conical deflector is engaged to direct the flow into the annular collection plenum where it is pumped and stored (see Fig. 4). For drag make-up, the deflector is retracted so that all of the atmospheric flow into the maw of the HarPO can be utilized as propellant. There is enough energy in the HarPO battery array to power the HarPO for drag makeup for the entire orbit. On return to apogee, it docks to the NEP spaceship, unloads the propellant, and recharges its batteries for the next orbital run. An example of the propellant collection and impulse required for drag makeup for an orbit at Neptune can be found in Fig. 6. While the thruster is in operation there is no propellant collection, but it is also clear that from Fig. 6 that little propellant is lost to that end.

Starting with this preliminary analysis, there are a series of studies yet to be performed to address the significant unknowns in terms of the physics, required technologies, and mission architecture in order to have confidence that the

HarPO concepts is viable. These studies will now be discussed in turn.

Physics of the neutral flow dynamics and capture efficiency—It should be possible to make reasonably accurate assessment of the capture physics using DSMC calculations and the COMSOL Multiphysics® software with the molecular flow module. A preliminary DSMC calculation similar to what would be encountered by a HarPO in the Jovian atmospheres, i.e., the interaction of a high Knudsen number, supersonic neutral flow into a conical deflector such as that to be employed on HarPO (see Fig. 4) was carried out. The result is shown in Fig. 7. It is observed that virtually all particles diffuse out radially into the pump-out chamber region. The drag coefficient was calculated to be 2.05 indicating nearly complete flow stagnation, which is the desired result. Future calculations will quantify the collection efficiency as well as examine a range of capture geometries to optimize harvesting.

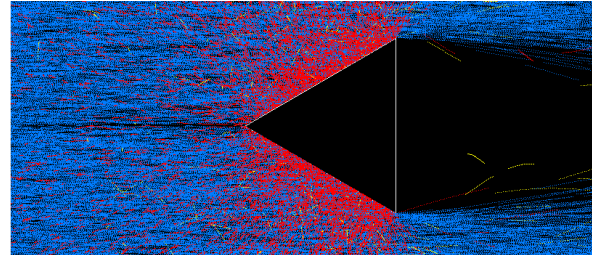


Figure 7. DSMC calculation for supersonic ($M = 10$) molecular flow onto a conical surface with a diffusive reflection. Red tracers represent particles that have struck the surface; yellow – particles suffering secondary collisions, and blue – initial free streaming particles.

Determination of the optimal configuration and scale for HarPO—There are several parameters one would like to optimize such as jet power, Isp, thrust and propulsion efficiency both during the drag makeup maneuvers as well as during transit to planetary bodies. It is particularly important to examine these key metrics as a function of both propellant species and electrical power input. The basic propulsion physics of the device has been experimentally demonstrated in STX with a reasonable accounting of the physics from the 2D MHD and analytic scaling analysis. A more sophisticated model needs to be developed for quantifying the thruster physics in the context of a full implementation in space. This can be accomplished by further resistive 2D MHD calculations that will be enhanced with particle trajectories to capture the interaction with the upstream mirror field as well as flow behavior in the nozzle jet. This can be performed using commercial software such as the COMSOL Plasma and Particle Tracing Modules®. Parametric studies can then be performed to illuminate the operational space for the HarPO spacecraft. It should be pointed out that operation on Hydrogen combined with other gases (e.g., O_2 , N_2), allows for multimode operation of the main spacecraft as these gases could be utilized for chemical-based propulsion during the high thrust, lower Isp initial phases of the mission. They

could also be used during the orbital maneuvers required for sortie missions to the various planetary moons.

Thermal analysis of the HarPO modes of operation—This needs to be performed for HarPO in both harvesting and interplanetary propulsion modes. Again, commercial software can be used for this analysis. It is believed that the COMSOL Heat Transfer Module® can make accurate assessment of the system heat flow. This is a high priority as it impacts spacecraft cooling design requirements and thus mass.

Determine HarPO spacecraft mass budget. Based on the results from these studies, it should be possible to determine an optimized spacecraft design, and based on this design an initial mass budget for all the main spacecraft systems can then be made. With the physics of the device vetted and numerically modelled, it should also be possible to make reasonably accurate assessment of the key mission parameters such as dry and wet mass, payload, trip time, etc. After completing these evaluations, the next major task of incorporating them into a new mission architecture can then be undertaken. Some preliminary work in that regard has been done and will now be discussed.

4. MISSION STUDIES

The representative mission to best evaluate the impact of HarPO is to revisit the NEP powered Jupiter Icy Moons Orbiter (JIMO) mission as a starting point where it is anticipated that the mission architecture, as well as mission objectives will be significantly enhanced with HarPO. With the optimized HarPO operation and spacecraft design, the Copernicus 5.0 orbital software can be employed to study various mission scenarios. Due to the new thruster

capabilities and vast propellant resources, the ability to extend the JIMO mission to include other planets can also be explored.

Additionally, once the main spacecraft is established at the target planet, sortie missions to the various moons will be examined. There is some confidence that the trip times for the Jovian mission can be considerably reduced. As can be seen in Fig. 8, the original JIMO transit would have taken over 5 years. Figure 8 shows the ΔV requirements for a faster mission to Jupiter as calculated by Copernicus. It can be seen that not only does ΔV increase with reduced trip time, but that the ΔV required to orbit the target planet is as large, if not even greater than that required for the transfer orbit. It is believed that a direct mission employing HarPO as a multimode thruster, and inserted into an appropriately high velocity Jovian orbit at arrival can accomplish the transit in significantly less time. The fast transit described in Fig. 8 also assumed that in addition to a HarPO propelled spacecraft, a suitable plasma-based aerobraking system can also be employed in the Jovian atmosphere such as the one developed in a previous NIAC grant at MSNW⁸⁻⁹, and a paper submitted to this conference will be presented detailing the concept.

Example mission employing HarPO—To get a sense of the amount of propellant that must be harvested by the HarPO for a typical Jovian planetary mission, it is useful to make a “back of the envelope” calculation for a specific interplanetary transit. A good representative case would be a sample return mission from Jupiter for a spacecraft similar to the NEP powered JIMO spacecraft. The dry mass for this spacecraft was to be roughly 24,000 kg. As the reactor module made up only 25% of this mass, and a large fraction of the remainder was comprised of the spacecraft module itself, the possible differences in nuclear power requirements and thruster masses between the JIMO and a HarPO mission

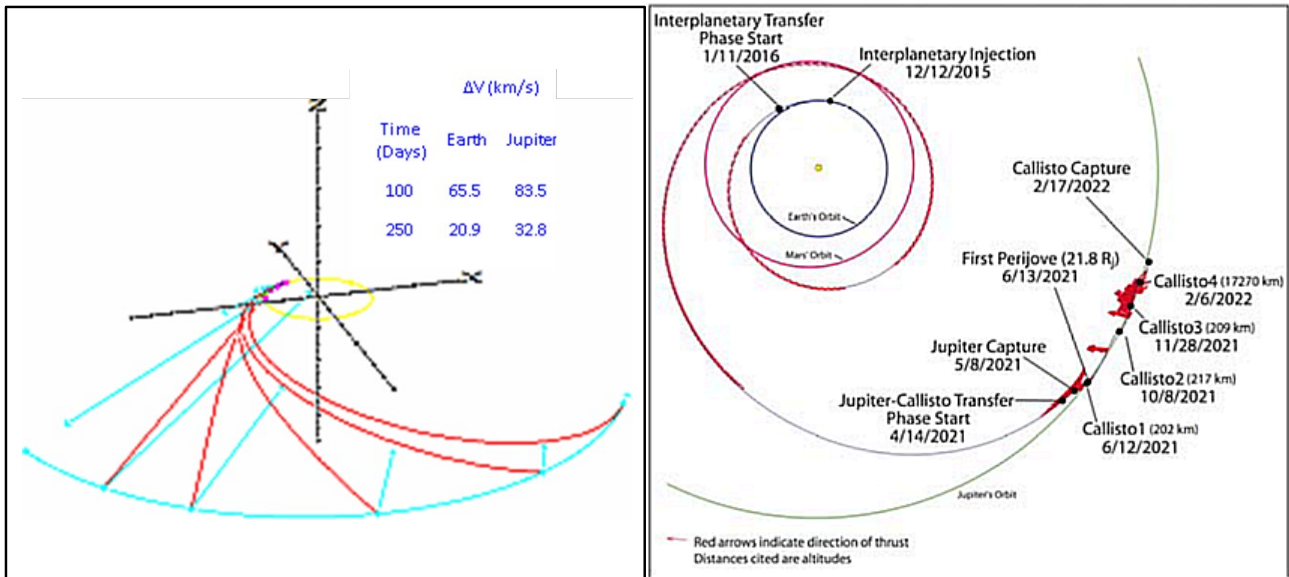


Figure 8. (Left) Copernicus calculation of impulsive orbital transfer from Earth (yellow) to Jupiter (cyan). Shown are the ΔV requirements for transfer and insertion orbits. (Right) JIMO Reference Mission Interplanetary Trajectory and Jupiter Arrival (from Ref. 1). This trajectory is a direct path with no planetary gravity assists

Table I. Candidate planetary and atmospheric data for a HarPO-based mission

Planet	Radius (10 ⁶ m)	Mass (10 ²⁴ kg)	Orbital Vel. (m/s)	Orbital Period (hr.)	Altitude where $\rho \sim 10^{-9}$ kg/m ³ (km)	Principal Gases (%)
Earth	6.38	5.97	7,900	1.4	170	N2 [78] O2 [21] Ar [1]
Mars	3.4	0.642	3,549	1.7	135	CO2 [95] N2 [3] Ar [1]
Venus	6.05	4.87	7,327	1.4	135	CO2 [96] N2 [3]
Jupiter	71.5	1898	42,078	3.0	550	H2 [90] He [10]
Saturn	60.3	568	25,066	4.2	950	H2 [96] He [3]
Uranus	20.6	86.8	16,764	2.1	800	H2 [83] He [15] CH4 [2.5]
Neptune	24.8	102	16,563	2.6	810	H2 [80] He [19] CH4 [1]
Titan	2.57	0.134	1,865	2.4	900	N2 [96] CH4 [3.5] H2 [0.5]

should not be that significant a factor in this zero-order analysis.

For simplicity, it will be assumed that a Hohmann transfer orbit will be employed on the return, and that aerobraking in the Earth's atmosphere will be employed at Earth. The ΔV budget for the Hohmann transfer for a Jupiter-Earth mission is 6.3 km/sec with a transit time of 2.7 Earth years. It will be assumed that the HarPO spacecraft thrusters will operate on hydrogen achieving the same ion thermal temperatures as found in the subscale experiments at MSNW (~40 eV) which produced an RMS exhaust velocity of 107 km/sec. The transfer will thus require a propellant mass at departure from Jupiter equal to 6 % of the spacecraft dry mass, or 1,440 kg of Hydrogen.

As was discussed earlier for HarPO harvesting in the Neptune atmosphere (see Fig. 6), a similar analysis was performed for a HarPO operating in the Jovian atmosphere. Due to the higher orbital velocity at Jupiter, more propellant was consumed in drag makeup so that roughly a net of 1 kg of Hydrogen was obtained on each HarPO orbit. The time to complete one orbit at Jupiter is 3.0 hours. A conservative 50% duty cycle for HarPO orbiting will be assumed with depositing propellant and battery recharging making up the remainder. The propellant collection rate would be 1 kg/hr for the array of 6 HarPO thrusters. The time to refuel for the return transit mission would thus be 60 days. Given the 985-day return transit time, this is a very reasonable collection period, and would likely be increased to provide more exploratory time at Jupiter as well as to fuel a shorter return trip time.

Other possible planetary missions for HarPO on non-Hydrogenic propellants—It should be recalled that the HarPO is propelled by a plasma jet that is produced by the RMF FRC thereby providing for a contactless and electrodeless, electromagnetic thruster (see Fig. 5). Operation on other gases is not only feasible, but has been readily accomplished in the laboratory at MSNW as well as at other facilities¹⁰. At MSNW, the device has operated successfully on all the principal gases found in all the planetary and lunar atmospheres listed below in Table I.

The major effect of employing gases such as CO₂ or N₂, as opposed to Hydrogen, is a decrease in efficiency as the radiative losses increase somewhat at the optimal plasma number-densities $\sim 1\text{--}5 \times 10^{19} \text{ m}^{-3}$ that are typical of RMF FRC operation. The Isp is also reduced by the square root of the mass ratio for the plasma ion temperatures realized operating in these medium-mass gases as they were similar to that found on STX in Hydrogen. The Isp reduction can thus be as much as a factor of 4 for oxygen. However, the need for the high Isp in the gas giants is driven by the high spacecraft orbital speeds required. The Isp for HarPO operating on the medium mass gases found in the inner planets should ideally be in the range of 3-5 ksec, and this is what it is calculated it would be. HarPO thruster operation on planetary gases would therefore be satisfactory for all the inner planets in their respective atmospheres. Thus, missions to the inner planets are very much within the operational space of the HarPO. Mission scenarios for sample and return missions to Mars and Venus should also be explored.

Next steps for HarPO spacecraft development—Once all the relevant physics is better understood, the required technologies delineated, and the mission architecture fleshed out, it would be appropriate at that point to determine the next steps for advancement of the concept. This will surely involve the design and construction of a prototype HarPO at power and scale with a testing program for validation of performance. These tasks will no doubt involve collaboration with a large aerospace company and/or a NASA center. In the near term, an effort to determine the current TRL for the various HarPO components, and an outline what could be done to evolve the lowest of these to higher TRL should be made.

5. SUMMARY

A successful development of HarPO could radically change in-space transportation in several ways. With the ability to refuel at virtually all planetary destinations, it would reduce the time and cost of cargo missions, sample and return missions, and possibly all the way to manned missions. It would enable deep space missions to all the Jovian planets. With essentially unlimited amounts of fuel, the exploration of

the Jupiter's Moons, and by "planet hopping", those of Saturn through Neptune could be further explored on the same mission. Importantly, the ability to fuel a return to Earth opens up the possibility of a much greater trove of both small and large specimens from the many moons that populate these planets, not least of which is the return of the very valuable spacecraft and scientific hardware deployed for the mission. The reuse of these assets would substantially reduce the cost of further missions to both the inner and outer planets.

The emphasis of this paper has been on the gas giants. As indicated earlier, the HarPO spacecraft can readily be used on missions to several of the inner planetary objects found in Table I. In particular, the use of the HarPO on a Mars sample and return and manned missions could be quite valuable. For these missions, it may not be necessary to use nuclear power. For all the inner planets solar electric power is a feasible and an obviously less technologically demanding option. With the tremendous strides in battery energy density and solar panel power efficiency, a solar powered HarPO spacecraft could operate much in the same way as was considered for NEP and take advantage of the atmospheres of Mars and Venus to refuel for large-scale sample return as well as reusable cargo missions in the near future. It should not go unmentioned that an Earth deployment of a HarPO with the requisite solar power station in high orbit could also uniquely serve several valuable missions in LEO. Primary among them would be Active Debris Removal (ADR) as well as relocation, recovery, and repair of viable space assets. A preliminary understanding of how to accomplish this task, as well as the significant impact a refueling spacecraft would be to achieving significant ADR was obtained in a previous NIAC study at MSNW¹¹. In this regard, HarPO represents a substantial improvement from the original concept in terms of experimental validation, functionality, feasibility, and cost.

The ability to selectively harvest ^3He should also not be undervalued. Even though the ratio $^3\text{He}/\text{H}_2 \sim 0.5\text{-}1 \times 10^{-4}$ in the Jovian atmospheres, the fusion energy yield from that small fraction would still be over 300 times that of the chemical combustion of all the H_2 ! Establishing a viable source of ^3He would greatly improve the chances of a fusion-based propulsion system¹²⁻¹⁵ that would in turn considerably enhance the reach of mankind throughout our solar system.

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BIOGRAPHY



John Slough received his B.A and PhD in Astrophysics from Columbia University. He has spent over 30 years working in the field of experimental physics. He founded MSNW in 1991, a small business with a long history in the research and development of advanced space propulsion and plasma physics technologies. He was the principal investigator on several large fusion related projects funded by the Dept. of Energy. Experiments performed by Dr. Slough led to advances in the formation and confinement of FRCs as a fusion concept as well as a better understanding of the relevant physics. Recently, he founded a spin-off company, Helion Energy, to develop a commercial fusion reactor which has received both DOE and venture capital funding. Dr. Slough was also on the faculty in the Astronautics and Aeronautics Dept. at the University of Washington for many years.