The Grand Challenge: A New Plasma Thruster

by Samuel A. Cohen and Michael A. Paluszek

Visionary leaders at NASA have set "Grand Challenge" goals for America's space program. Among the ambitious candidate missions are comprehensive explorations of the solar system and manned ventures to remote planets. For these types of missions to be practicable, rocket engines are required to have larger exhaust velocities, greater efficiencies and more reliability than those currently available. A novel plasma thruster design offers great promise for providing these revolutionary advances in propulsion technology.

Advanced electric propulsion systems, both ion and plasma thrusters, have been developed over recent years because of their high propellant exhaust velocity, U_e. The presently available high-U_e systems, however, produce too low a thrust for many of the Grand Challenge missions. Here, we describe technical features that make a new plasma thruster design a revolutionary step beyond the existing systems and able to provide a propulsion method scaleable to more demanding Grand Challenge missions.

The primary innovative technical features are the wave-heating mode, thrust-generation mechanism and the technique for decoupling the exhaust plume from the engine. These are predicted to result in more than an order-of-magnitude increase in thrust, while also significantly extending specific impulse, $I_{sp} = U_e /g$ (where g is the gravitational acceleration, 9.8 m^2/s), thruster life and reliability.

Electromagnetic waves heat a fully ionized gas that is confined by a super-conducting magnetic coil and expelled through a magnetic nozzle. The novel nozzle in this design is a constriction in the plasma flow channel set by shaping (tapering) the magnetic field rather than a material surface. Magnetic fields strongly inhibit charged particle motion perpendicular to them while allowing easy flow parallel to the field lines. This reduces plasma contact with nearby materials, considerably extending their lifetime. Plasma expanding through the magnetic nozzle is accelerated to supersonic speed by a strong electric field that develops in the nozzle. In the expansion process, plasma cooling occurs; if sufficiently rapid, the plasma will recombine into a supersonic stream of neutral gas. Neutral particles are free of the magnetic force. Proper shaping of the magnetic nozzle subsequent to the recombination zone will generate a small angle exhaust plume, increasing thrust efficiency. This propulsion concept can lead to high-thrust, high-specific-impulse propulsion systems that could grow in capability over a 40-year period. A fusion power reactor could be incorporated as the direct-drive power source, if scientists are able to produce a working fusion reactor.

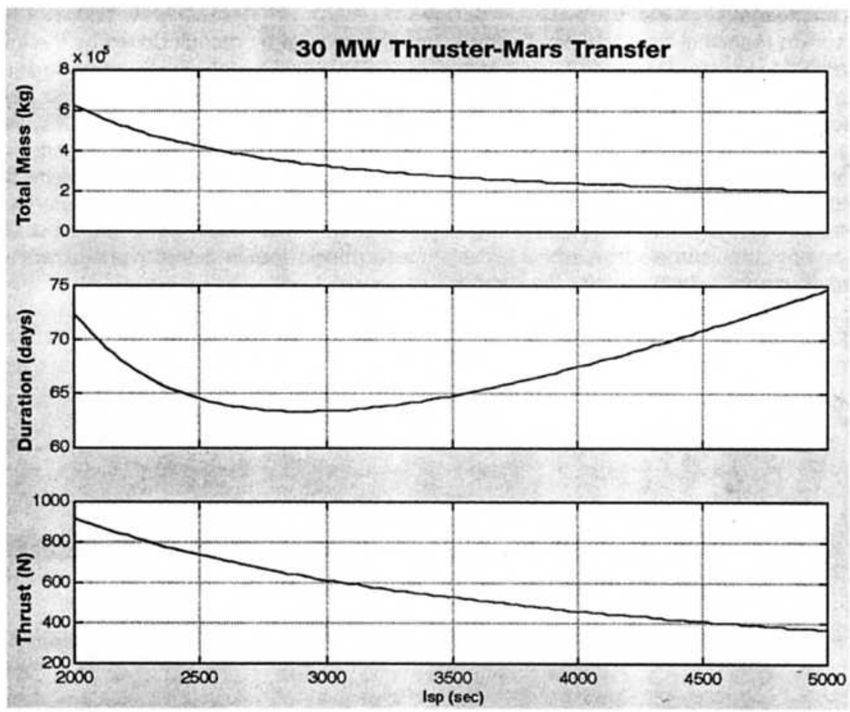

Figure 1. Manned Mars mission. The top plot shows total vehicle mass including the 100,000-kilogram payload. The second plot shows the maneuver duration and the bottom plot shows the thrust generated by the thruster. The minimum mission duration is obtained with a specific impulse near 3,000 seconds.

Before describing these technical features in more detail, we give a comparison of the parameters of this novel thruster with existing electric propulsion methods.

In terms of thrust and power capability, the closest competitor to the WHT is the Magnetoplasmadynamic (MPD) thruster. In MPD thrusters, strong currents flow between electrodes in the plasma. The most promising fuel for MPD thrusters is lithium. However, lithium presents a contamination problem to the rest of the spacecraft. Even though lithium is the best of all fuels in this regard, plasma contact with the electrodes causes them to degrade, limiting the thruster lifetime and mission duration. Hall thrusters, now used on satellites, have somewhat less severe electrode degradation but produce lower thrust. These two configurations use magnetic fields to increase the plasma density. Their magnetic fields are oriented perpendicular to the plasma exhaust; electrical currents are driven along the magnetic field, between electrodes, to heat and accelerate the plasma. This is a surface power input method, a major difference from the WHT and one reason why these thrusters are difficult to scale to the higher powers needed for certain Grand Challenge missions.

In the WHT, plasma flow and thrust are generated by the plasma pressure gradient parallel to the magnetic field. There are no electrodes in contact with plasma to degrade. The magnetic field forms an insulating barrier between the plasma and the surrounding material surfaces. (The "thermal insulation" provided by this magnetic field shape exceeds that of Styrofoam.) The WHT can potentially produce higher thrust/specific impulse products than the other systems on the graph, to a large degree, because of the high densities achievable with the confinement properties of the specific magnetic field configuration of the method, a wave-heated magnetic mirror configuration.

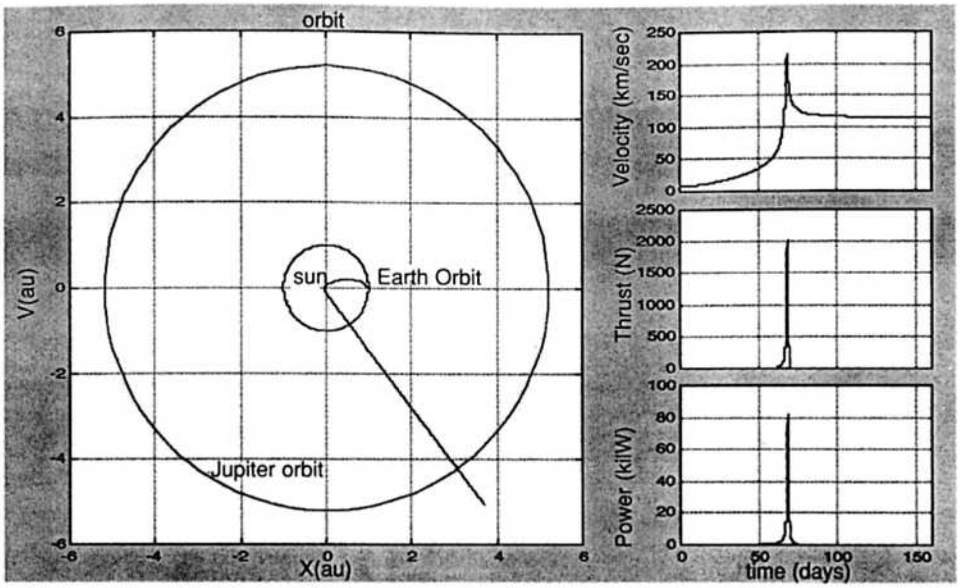

Figure 2. *Interstellar mission. The plot on the left shows the trajectory, starting with insertion into the elliptical transfer orbit. The top right plot shows the spacecraft velocity, which peaks at perigee where the delta-V is performed. The thrust and power magnitudes are also shown. Due to the close pass to the sun, the flux per unit area of solar collector is much higher than near the Earth.*

Maximizing Thrust

Many wave-heated plasma systems have operated with similar magnetic geometry to that in the WHT. None has employed a feature essential for space propulsion applications: a method for decoupling the plasma exhaust from the magnetic field. Without this feature, plasma expelled from the rear of the spacecraft will follow magnetic field lines back to the nose of the spacecraft, counterbalancing the thrust. In this specific WHT design, the decoupling is achieved by causing plasma cooling and recombination — ions combining with electrons to produce neutral atoms — in the expansion zone of the magnetic nozzle. Other decoupling methods may be possible, such as asymmetric magnetic nozzles, but analyses of these predict lower efficiencies in converting input energy into thrust.

The main advantages of the WHT are: higher power capability, because of volumetric heating; higher plasma density, because of better plasma confinement produced by the magnetic geometry; and ability to use a magnetic nozzle for plasma cooling and recombination, because of the linear magnetic-field geometry.

An important consideration for Grand Challenge missions is the power available to the thruster. Large thrust and high specific impulse require high power. Power levels up to 20 kW will be available on near-term commercial satellites. Power levels up to hundreds of kilowatts may be feasible using multijunction and concentrator solar photovoltaic technology or solar dynamic systems using heat engines. If the power source is solar, then large solar collector areas, and possibly high pointing accuracy and tight figure control of the solar collectors, are required.

Megawatt power levels could be supplied for extended periods by an external fission or fusion reactor. Both make consideration of radiation and environmental effects essential. In an internal fusion-powered option, the application of high-power RF would ionize the mixture in the WHT chamber, form a reversed-field configuration (FRC) there and heat the fuel to fusion temperatures.

The FRC is an intrinsically high-beta plasma, favorable to the use of advanced (neutronless) fuels. (Beta, b, is the ratio of plasma thermal energy to magnetic field energy.) Recent research has shown more potential for p-11B fusion than earlier predicted. In an optimal FRC fusion reactor, a mixture of boron and hydrogen is injected into the FRC. Fusion creates energetic helium, which further heats the fuel, sustaining the burn. Plasma crosses the FRC's closed flux surface, flows along the open magnetic field lines to the nozzle and exits there, providing thrust. The FRC requires a solenoid-shaped magnetic field, the same geometry needed by the wave thruster and the magnetic nozzle. These factors make the FRC the most attractive fusion reactor from an engineering perspective.

Many of the components are common to both the nearer (non-fusion) and longer-term (fusion) propulsion systems. As a consequence, development of the wave-heated plasma thruster will create technology that will be directly applicable to future fusion propulsion systems.

This novel thruster differs from earlier wave-heated thermal thrusters in that it employs a confined, fully ionized warm plasma, a strong axial magnetic field and a magnetic nozzle with large expansion. Wave heating in this field geometry is a volumetric method; that is, waves launched from antennas at the plasma's edge propagate deep within the plasma before their energy is absorbed. This reduces the power loads on and losses to the surrounding structures.

Five different frequency ranges are candidates for wave heating: electron cyclotron (EC), lower hybrid (LH), helicon, ion cyclotron (IC) and rotating magnetic field (RMF). Although a thruster must produce high-velocity ions, apparently favoring the IC method, acceleration in the proposed thruster design is caused by the nozzle's electric field. This converts electron thermal energy into directed ion momentum. Thus, there is no clear reason yet for selecting one candidate from the others. Indeed, the optimal choice may

TABLE 1. Candidate RF and mwave modes for heating plasmas for thruster applications

Mode	**EC**	**LH**	**Helicon**	**RMF**	**IC**
Approximate frequency (GHz)	2.5-10	0.5-2.5	0.1-0.5	0.3-100	0.03-10
Temperatures achieved (eV)	20	5	3	20	5
Densities achieved (cm-3)	5 x 1012	1 x 1014	1 x 1014	1 x 1014	1 x 1013
Ionization fraction (%)	50	90	50	10	10

change with each mission's specific requirements.

The magnetic field required by each is similar, between 1 and 5 kG. The low end is set by the plasma b requirements. The upper end may be more practical by easing antenna design. The nozzle magnetic field strength is about 10 times higher than that needed by the heating method. Even 50 kG field strengths are readily achievable by present-day superconductor technology. High-temperature superconductors would improve the attractiveness of the engines by reducing the cooling requirements. (see table 1)

The LH system has achieved more than 90% ionization, primarily because of the high density and controlled startup procedures. This is desirable for improved fuel utilization efficiency. (The RMF has yet to achieve a high ionization fraction because of the low magnetic fields used and the high fill pressures necessary with the traditional plasma formation procedures.) With improved operational techniques, all the candidate frequencies are likely to produce full ionization at high power. The main question is whether they can also produce the proper electron temperatures within the plasma — temperatures that produce high thrust without compromising the recombination properties of the nozzle.

The achieved parameters shown in Table 1 were at relatively low power, typically 0.5-3 kW. The only exception was RMF, which needed higher power because of the enhanced losses and high fill pressure. Extending the database for each heating mode to higher power is needed and one of the technical objectives to be addressed by research and development efforts. Scalability, i.e., achievable plasma parameters versus nozzle radius, is another subject that must be addressed by R&D.

The overall energy efficiency of this method will depend on the product of the usual factors: the efficiency for converting power from the spacecraft power source to the wave power supply; the coupling of the wave power to the plasma; the power lost to the thruster structures by radiation and plasma conduction; and the frozen-in power loss. The choice of propellant is particularly important for determining the frozen-in losses.

The axial magnetic field used by these wave-heating methods allows both ions and electrons to be exhausted along B. As noted, the nozzle generates the thrust by converting random electron thermal motion into directed ion motion in the nozzle's electric field. Strong electric fields have been found in many mirror machines, such as studied in the fusion program. Potential drops of kilovolts were obtained, very good for ion acceleration. As we shall soon see, this was too large to allow recombination. Contrary to Mae West's statement, too much of a good thing was too much.

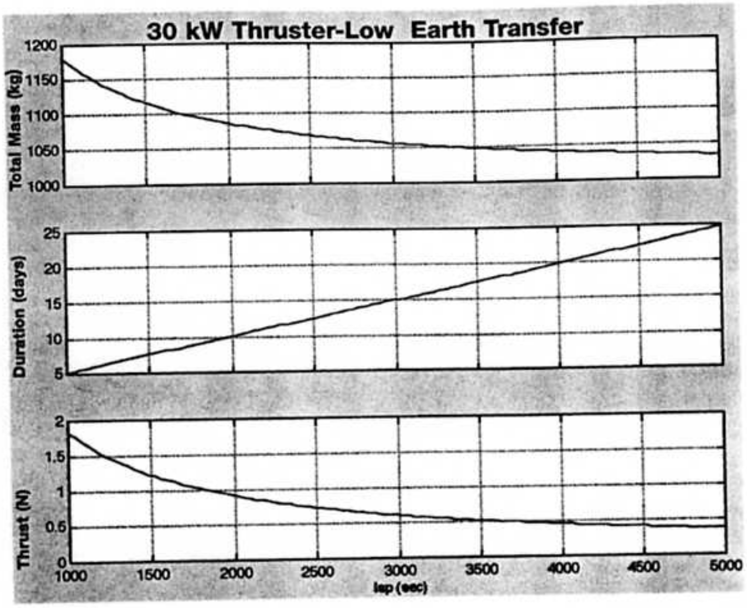

Figure 3. *Low Earth orbit transfer. The top plot shows total vehicle mass including the 1000-kilogram payload. The second plot shows the maneuver duration and the bottom plot shows the thrust generated by the thruster. This shows the relationship between fuel mass, thrust and duration for a fixed power level as a function of specific impulse. Essentially, fuel consumption can be traded against mission duration.*

In 1995, a steep electric field of approximately the proper strength, ~10 eV/cm, was discovered in a linear plasma device in our Princeton University laboratory. This was accomplished by collision cooling of the plasma electrons, rather than by magnetic expansion cooling. The remarkable observation associated with this modest electric field was rapid plasma recombination to neutral gas, something not attained in the hotter fusion magnetic mirror experiments.

This brings us to the major conceptual leap provided by the magnetic nozzle. The question arose, how can the plasma exhaust be decoupled from the strong magnetic field? In an axially symmetric magnetic nozzle, the plasma is constrained to follow the field lines, even for high plasma dielectric constant, 8pmnc2/B2. (This is in contrast to the flow of a plasma slab across a magnetic field with simple, one-dimensional curvature.) A resolution to this vexing problem is to cause sufficient plasma cooling in the nozzle expansion that recombination transforms the plasma exhaust into a supersonic stream of neutral gas. Figure 4 shows that cooling to temperatures below ~ 1 eV (11,600 K) is necessary to get rapid recombination.

Expansion from a nozzle results in cooling and acceleration. There is a direct relation between the cooling and the Mach number achieved by a nozzle. Calculations show that the recombination rate coefficient increases with Mach number approximately proportional to M3 for g=5/3 and proportional to M5 for g=2, where g is the usual ratio of specific heats. By examining the calculated Mach number as a function of magnetic field expansion we predict that nearly complete recombination can be generated by a magnetic expansion of 50 for g=2 or 1000 for g=5/3 (g is expected to be between 5/3 and 2 for a magnetized monatomic plasma of initial density 1×10^{14} cm^{-3}).

How did the Princeton experiment show extensive recombination? The plasma appeared as different as night from day. Recombining plasmas are characterized by emission of intense light with a special spectral signature. Warm plasma, viewed through a window of the linear apparatus, flows from left to right. As the plasma cools from 50,000 K to 10,000 K, its brightness dramatically increases. Detailed analysis of the spectrum showed this could be quantitatively explained by three-body recombination.

A critical aspect of the thruster design is the selection of the fuel. At Te < 1 eV, helium has the most rapid three-body recombination rate of all the singly charged monatomic ions. However, its high ionization potential unfavorably increases the frozen-in losses. Other inert gases like xenon are much better in that regard, but have relatively low second-ionization potentials. The optimal fuel will depend on the overall plasma temperature and plasma confinement time. R&D are essential for selecting the optimal electron temperature, hence wave-heating method and plasma shape.

Propulsion designs

Two candidate WHT operating points are described to illustrate the potential of this engine. The first, at 30 kW power, is for a reusable transfer orbit vehicle for low Earth orbit operations. The second, at 30 MW power, is for interplanetary and trans-lunar operations. The 30 kW mission is an orbit transfer mission from a 400-kilometer orbit to a 2000-kilometer orbit, including a return mission with the full payload. The low Earth mission is shown in Figure 3. A thruster with this power level could also be used as a drag makeup thruster on the International Space Station. It would be difficult to perform the drag makeup mission or the reusable upper stage with other electric thrusters due to their relatively short lifetimes.

Two missions are shown for the 30 MW thruster. One is a manned Mars mission. (Figure 1) The second is a near-sun flyby for an interstellar mission. (Figure 2) The Mars mission assumes a 100,000-kilogram payload, including the propulsion system. The minimum one-way travel time is about two months, which is a reasonable amount from an operational cost and radiation dose standpoint. The power for this mission would need to come from a nuclear reactor, which could be the internal fusion reactor described above. The spacecraft for the interstellar mission is inserted into an elliptical heliocentric orbit with its perigee close to the sun. The idea is to perform all of the delta-V near perigee to get an additional boost due to the sun's gravity well and to take advantage of the high solar flux at that distance. The plots show a numerical simulation of the mission in which the propulsion system produces a 40 km/second delta-V. The final velocity is in excess of 100 km per second and it passes the orbit of Jupiter 160 days after injection into the elliptical Earth/sun transfer orbit. The specific impulse is held constant at 2500 seconds and the thrust is allowed to vary up to the limit of the available power. This trajectory is by no means optimal, nor does it account for thruster limitations.

Numerous advanced electric propulsion concepts have been developed over recent years because of higher propellant exhaust velocity, m*, compared to chemical systems. The wave-heating method, thrust-generation mechanism, decoupling of plasma from magnetic fields and scalability make the WHT system a significant advance over existing electric thruster concepts. Wave-heated plasma propulsion is a revolutionary concept that could be used in the short term to produce a high-thrust, high specific-impulse electric thruster and could incorporate a fusion propulsion, if a practical one is ultimately developed. It is in an early stage of development. Considerable effort will be required before a prototype is ready for flight.

Samuel A. Cohen received a Ph.D. in physics from MIT in 1973. He has been at the Princeton University Plasma Physics Laboratory ever since, now serving as a lecturer with rank of professor in the Astrophysical Sciences Department and director of the Program in Plasma Science and Technology in the School of Engineering and Applied Science.

Mr. Michael Paluszek is the founder of Princeton Satellite Systems, Inc. He received his S.B. degree from MIT in Electrical Engineering in 1976 and his E.A.A. and S.M. degrees from MIT in Aeronautics and Astronautics in 1979. In 1986 he joined GE Astro Space, where he led the design of the attitude control systems for GPS IIR, Inmarsat 3, GGS Polar Platform and the Mars Observer Delta-V mode. His current research includes collaborative work with the Princeton Plasma Physics Laboratory on advanced plasma thrusters and the development of artificial intelligence techniques for embedded systems.