Plasma Propulsion in Space

FEATURE

by Eric J. Lerner

Electromagnetic plasma thrusters enter space propulsion's mainstream

Since the beginning of spaceflight, chemical rockets have propelled spacecraft and controlled their positions in orbit. Equally as long, engineers have known that the much higher exhaust velocities that are possible with electric propulsion systems are needed to make spaceflight less expensive and some deep-space missions even feasible. But until the past few years, electric propulsion systems have been relegated to the margins, especially in the U.S. and European space programs.

Now, that situation is changing dramatically as electric propulsion systems enter the mainstream of spaceflight. Within a year, several such systems will be launched into space as either station-keeping thrusters on earth-orbiting satellites or propulsion units for probes to the moon and beyond. Increasingly powerful thrusters are being developed, with electromagnetic plasma designs muscling aside earlier electrothermal and electrostatic thrusters. The National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) are planning ambitious missions during the next decade that will use electric propulsion as the main drive once a craft achieves Earth orbit (Figure 1).

Electrothermal to electromagnetic

The key limitation of chemical rockets, which electric propulsion can overcome, is that their exhaust velocity is relatively low, around 2 km/s and never more than 3.5 km/s. Because achieving Earth orbit requires a velocity change (ΔV) of 8 km/s, a rocket must carry far more propellant than payload. In fact, the ratio of propellant to payload rises exponentially as the ratio of ΔV to exhaust

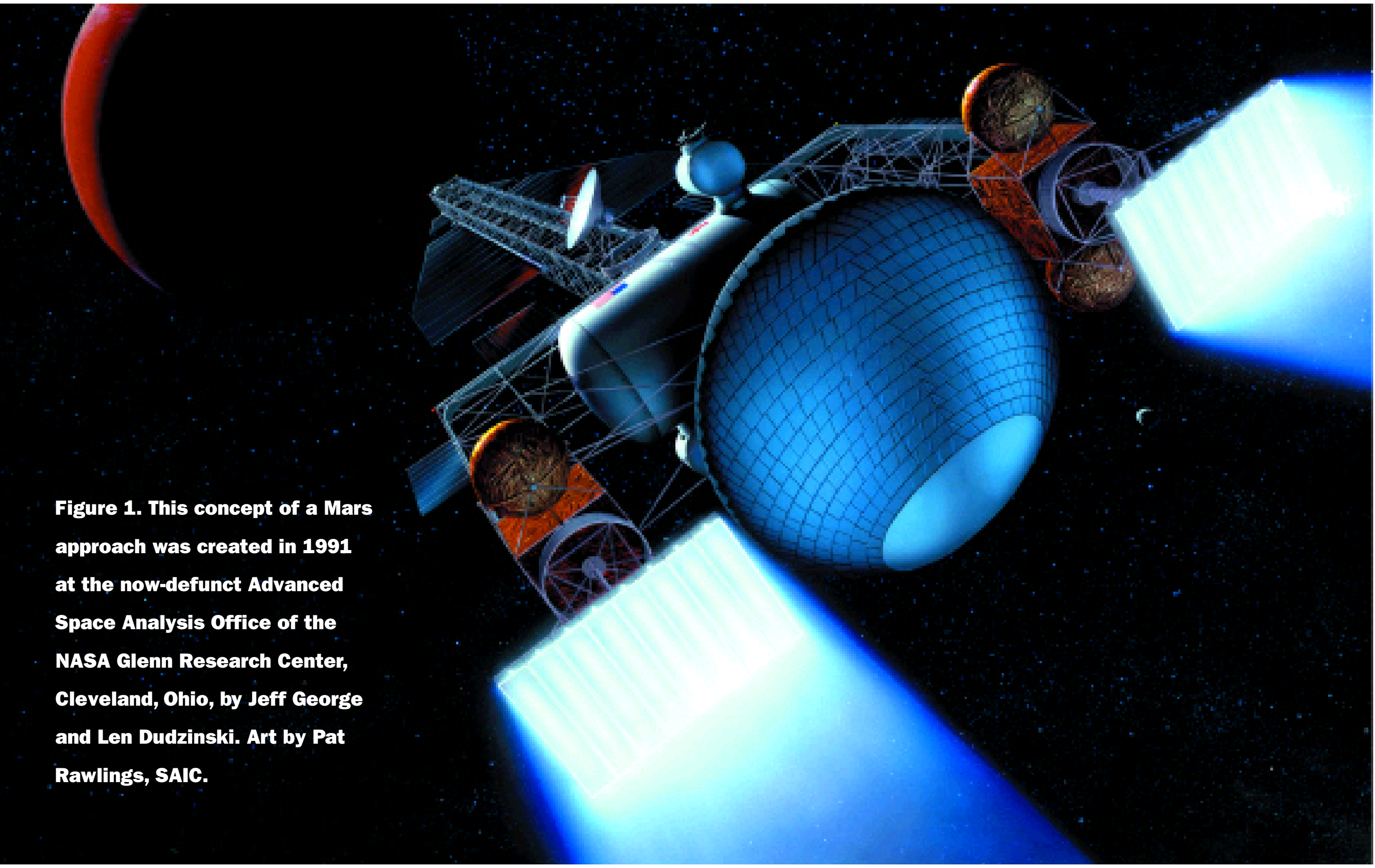
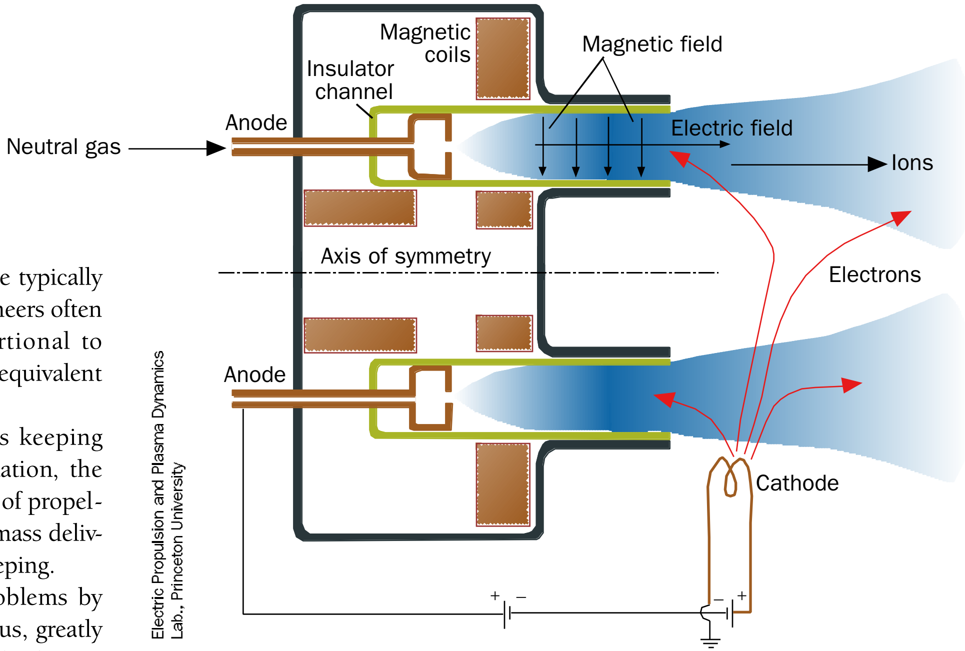


Figure 1. This concept of a Mars approach was created in 1991 at the now-defunct Advanced Space Analysis Office of the NASA Glenn Research Center, Cleveland, Ohio, by Jeff George and Len Dudzinski. Art by Pat Rawlings, SAIC.



Electric Propulsion and Plasma Dynamics Lab., Princeton University

Figure 2. Schematic of a Hall thruster with an extended insulator channel, showing the external cathode, internal anode, radial magnetic field, and typical particle trajectories.

velocity increases, and so orbiting payloads are typically only 1% of total lift-off mass. (Propulsion engineers often refer to specific impulse, which is proportional to exhaust velocity. A specific impulse of 100 s is equivalent to an exhaust velocity of 1 km/s.)

Even for low-velocity operations, such as keeping communication satellites from drifting off station, the lower the exhaust velocity, the larger the mass of propellant needed. So a large fraction of a satellite's mass delivered to orbit must be propellant for station-keeping.

Electric propulsion can alleviate these problems by providing far higher exhaust velocities and, thus, greatly reducing the required propellant mass. But early electric-propulsion devices had their own limitations.

The first electric propulsion thrusters were electrothermal, in which the propellant was heated by contact with a heated coil or by passing an arc through ionized propellant. Resistojets, which use resistance-heated coils, started to enter widespread commercial use in the early 1980s, providing the small thrusts needed to keep satellites on station.

Resistojets could not sustain temperatures above 3,000 K, however, so exhaust velocities could not exceed 10 km/s, even with the lightest propellant, hydrogen.

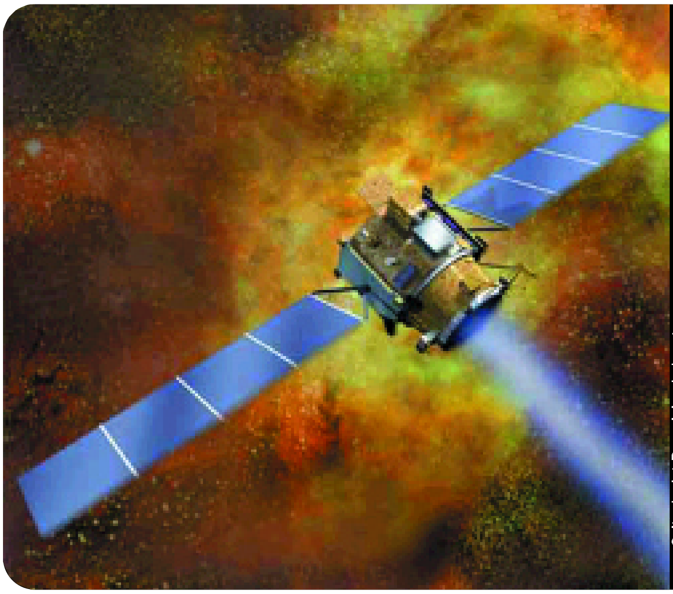
By the early 1990s, resistojets were superseded by arc jets, in which direct currents of tens or hundreds of amperes passed though the propellant, heating it to tens of thousands of kelvins at the axis. The natural tendency of currents in plasma to pinch together through interaction with their own magnetic fields keeps these higher temperatures away from the walls of the device and allows exhaust velocities of more than 10 km/s. But the electrodes are still exposed to very high temperatures, so the power of the devices must remain low or their lifetime becomes short.

To achieve both high exhaust velocities and longer lifetimes, designers and manufacturers in the mid-1990s started to emphasize electrostatic propulsion, also known as ion propulsion. In electrostatic units, a downstream grid accelerates ions from a source. After the ions are accelerated, a stream of electrons is injected to neutralize the exhaust and prevent a buildup of charge on the spacecraft that would counteract the accelerating field. This design—which entered station-keeping duty in 1994 and was first used on a NASA space probe in 1998 (see *The Industrial Physicist*, June 1998, pp. 24–26)—provides exhaust velocities of 100 km/s. In addition, beam divergence is small (20°), efficiency high (65%), and lifetime long (20,000 h). Because the beam of ions is positively charged during acceleration and builds up a charge that combats the accelerating force, there are serious limits to how much thrust can be developed per unit area of nozzle—a few newtons per square meter at best.

Hall-effect thrusters

The way around space-charge limitation is through electromagnetic thrusters, also called plasma thrusters, which accelerate a neutral plasma by the interaction of magnetic fields and currents. By far, the most developed members of this propulsion family are the Hall-effect thrusters, which were invented in the United States in the 1960s but then abandoned by the West. The Soviet space program perfected them, however, and beginning in 1972, the Soviets orbited about 100 of the thrusters for satellite control and propulsion. Only in the past year or so have Hall thrusters been re-adopted by the European and U.S. space communities.

In a Hall thruster, magnetic coils generate a radial field perpendicular to an electric field along the axis (Figure 2). The Hall effect traps the electrons in the plasma, forcing them to move in a circle around the axis. [When a conductor carries an electric current (current density J_x) perpendicular to a magnetic field (field strength B_z), a voltage gradient (E_y) develops perpendicular to both the current and the magnetic field.] But the much heavier ions, which are almost unaffected by the magnetic field, are accelerated down the axis by the electric field. The electrons gradually drift in the opposite direction to complete the circuit, but—slowed by the magnetic



Caltech, Jet Propulsion Laboratory

THE LITTLE ENGINE THAT COULD

An ion-propulsion engine driving Deep Space 1 has operated for more than 4,800 h since its launch on Oct. 24, 1998, surpassing the previous record for an engine operating in space by some 1,000 h. The craft, a NASA test-bed for advanced technology, is the first space vehicle to use an ion engine as its primary propulsion system. The highly efficient engine uses only about 100 g of xenon a day as propellant. Deep Space 1 completed its primary mission of assessing the ion engine and 11 other systems in September 1999, about two months after a flyby that took it within 26 km of the asteroid 9969 Braille. The craft, now more than 333 million kilometers from Earth, is in the midst of an eight-month burn intended to propel it toward a rendezvous with Comet Borrelly in September 2001. NASA extended the mission to target Borrelly in the hope that the craft will make new comet discoveries. If Deep Space 1 completes its full mission shortly thereafter, its ion-propulsion engine will have logged more than 14,000 h of operation.

field—they do not move fast enough to short out the field. In other words, the magnetic field diverts the electrons just enough to produce the right amount of resistance to keep the current from shorting.

Because the plasma remains neutral, much higher thrust densities (thrust per unit area) can be achieved than with electrostatic ion propulsion, a big advantage for both station-keeping and deep-space missions. The first Western mission likely to use Hall thrusters beyond Earth orbit will be the SMART-1 probe, which ESA plans to send into lunar orbit in late 2001. After launch into Earth orbit by a chemically powered Ariane-5 booster, SMART-1 will spend six months cruising to the moon for a six-month lunar-orbiting mission. The French firm SNECMA developed the tiny 10-cm-diameter thruster in collaboration with the Russian space program. It provides a much smaller thrust than a chemical rocket—leading to a much longer transit time to the moon—but uses far less propellant, allowing a larger payload. As in many electric propulsion devices, xenon is the propellant for SMART-1.

Although no Hall thrusters have yet flown on NASA missions, two companies are actively pursuing their development. Primex Aerospace Co. (Redmond, WA) is developing devices closely modeled on the Soviet and Russian varieties, termed stationary plasma thrusters (SPTs). These use an insulating channel to stretch out the region in which ions are accelerated. So far, the prototypes that have been built and tested have generated up to 0.4 N of thrust with 6 kW of input power.

"Right now, we are working to optimize the thrust by changing the exact shape of the magnetic field and increasing the lifetime of the thrusters," explains Roger M. Myers, director of systems and technology development at Primex. In addition, researchers are trying to reduce the large, 45° plume divergence of the Hall thrusters. Such large plumes can pose problems in locating thrusters on some spacecraft.

Primex's competition is International Space Technology, Inc. (ISTI), a joint venture of Loral Corp. (Palo Alto, CA) and the Russian designer and manufacturer of all Hall thrusters flown to date. ISTI has requalified to Western standards the Russian SPT-100, a device that delivers 93 mN of thrust at an input power of 1,350 W and a specific impulse of 1,500 s. It will be flown on commercial spacecraft built by Loral and two French prime contractors starting next year. A higher-power, higher-efficiency unit is being developed with co-funding from the U.S. Air Force.

MPD for high thrust

For deep-space missions, those beyond the influence of Earth's gravity, higher thrust is required, and more powerful types of electric propulsion may be needed. One of the most promising systems uses the fully electromagnetic magnetoplasmadynamic (MPD) thruster, in which the accelerating force is applied directly to the neutral plasma. In an MPD thruster, a continuous arc flows radially outward from a central cathode to a coaxial anode. The interaction of the radial current with the azimuthal, circular magnetic field that it produces generates a Lorentz force that accelerates the plasma down the barrel of the electrodes and focuses it behind the end of the cathode (Figure 3).

Exhaust velocities of 40 km/s or more are obtained in this manner. More important, MPD thrusters have a very high thrust density, in theory as much as 100,000 N/m^2. Laboratory models of the thruster have yet to perform this well, but they have nonetheless achieved impressive results. At NASA's Jet Propulsion Laboratory (JPL), a 200-kW MPD device only 11 cm in radius generated 12.5 N, or 400 N/m^2, more than 10 times the thrust density achieved by Hall thrusters.

With high power flowing though a small area, one of the key challenges that MPD must overcome is cathode erosion at high temperatures. "The best way we've found to reduce cathode erosion is to use lithium as the propellant, flowing it out through the cathode," explains Edgar Choueiri, director of the Electric Propulsion and

Plasma Dynamics Laboratory at Princeton University, which is developing MPD thrusters for JPL. Liquid lithium at 1,000 °C flows into the cathode, where heat generated by the current vaporizes it. The lithium vapor then exits through holes in the cathode, is ionized, and becomes the propellant.

This design has allowed MPD thrusters to function without appreciable erosion for 500 h, which would be enough time for a 200-kW thruster to accelerate a 1-ton spacecraft to 22 km/s. MPD thrusters convert only about 15% of their input energy into waste heat, which must be radiated away from the spacecraft. This is a big advantage in space, where radiators can add significant mass to spacecraft.

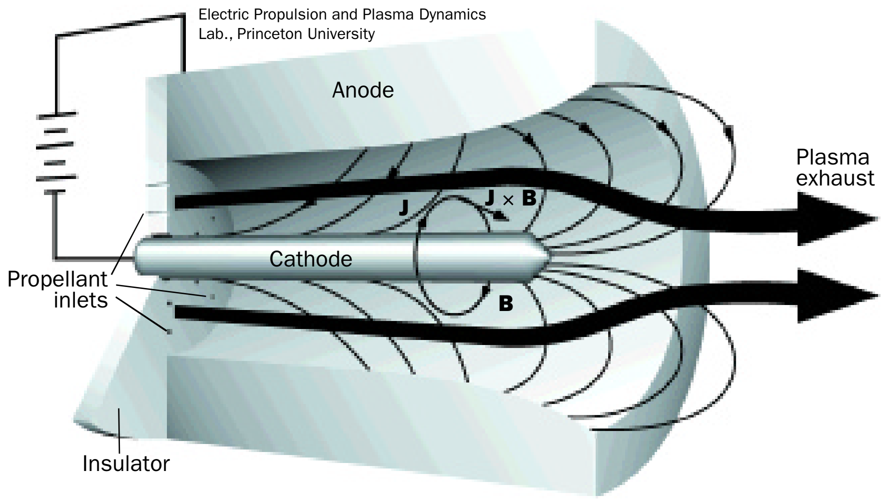


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Figure 3. Schematic of a magnetoplasmadynamic thruster. The interaction of the current density vector, J, with the self-induced magnetic field, B, produces a body force density, J × B, that accelerates the plasma to high exhaust velocities, producing thrust.

MPD thrusters have not yet been used in any spacecraft, but they are under study for several ambitious missions. One serious sticking point is that any thruster that consumes more than about 100 kW of power will almost certainly need a nuclear-power source because this demand is too much for solar panels to supply. With present technology, that source would be a fission reactor, and major safety concerns must be met before large fission reactors could be launched into space.

What next?

NASA is funding the investigation of even higher-performance and more technologically challenging plasma-propulsion systems. One such concept is the variable specific impulse magnetic rocket (VASIMR), which is under development at NASA's Advanced Space Propulsion Laboratory (Houston, TX). Although VASIMR is not a fusion reactor, it derives from a controlled-fusion concept, the magnetic mirror. Magnetic-mirror machines contain plasma by plugging the ends of a cylindrical chamber with strong magnetic fields.

In VASIMR, one of the ends is made deliberately leaky, so that plasma streams out at 70 km/s, generating thrust. By strengthening or weakening the magnets at the aft end, the leakage can consist of more mass at lower velocities and, thus, more thrust, or less mass at higher velocities, to produce less thrust. This design would allow the engine to generate high thrust when it is needed to escape a planet's gravitational field, and low thrust to conserve propellant on interplanetary cruises. Energy is supplied to the plasma by radio-frequency power, which would be supplied by a fission reactor. Although VASIMIR has been under development for 20 years, efforts have accelerated since 1997. Serious technical problems remain, such as how to efficiently detach the plasma from the magnetic field that contains it.

The only real alternative to fission reactors as an energy source for high-performance plasma propulsion is fusion, and NASA has several projects investigating the possibility of fusion-based space propulsion. One idea is a device called the plasma focus, which is similar to an MPD thruster, except that the electrodes are reversed, with the cathode being the outside electrode. A plasma focus operates in a pulsed mode, using a burst of electricity from a capacitor bank that generates a sheet of current that runs down the barrel of the coaxial electrodes. The current pinches together at the end of the electrode, producing highly compressed knots of plasma, or plasmoids, less than 1 mm across. These plasmoids are heated to high temperature by their internal currents, generating fusion reactions. Their decay generates a highly focused ion beam that shoots away from the device at velocities of up to 10,000 km/s. In theory, such ion beams could be used for ultrahigh specific-impulse propulsion, powered by the fusion energy generated by the focus itself. However, experimental work on this idea remains on a small scale.

Whether such advanced concepts will ever fly is an open question. But it is certain that plasma propulsion will play an increasingly central role in space propulsion for both Earth-orbit and deep-space missions.

For further reading

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