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Electric Propulsion

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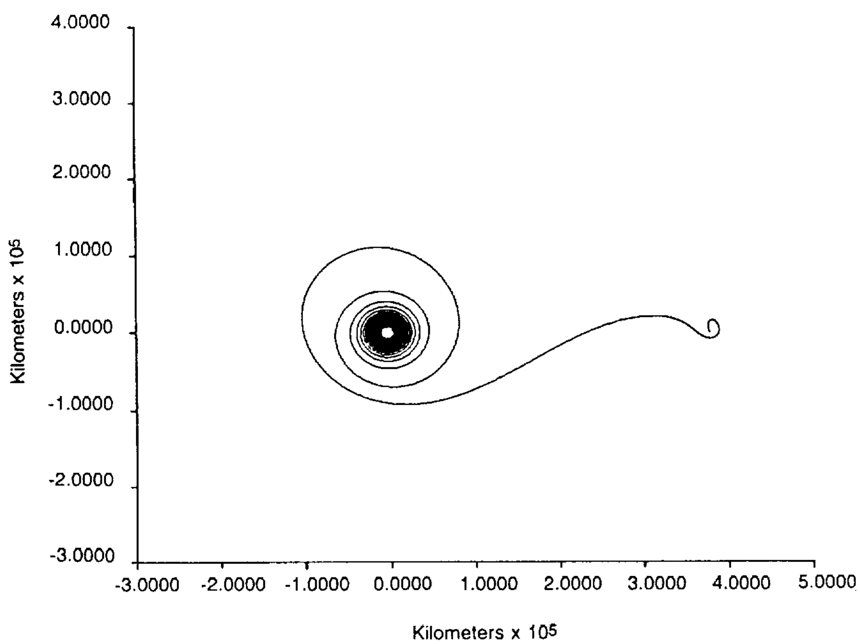
Electric propulsion (EP) is an attractive option for unmanned orbital transfer vehicles (OTVs). Vehicles with solar electric propulsion (SEP) and nuclear electric propulsion (NEP) could be used routinely to transport cargo between nodes in Earth, lunar, and Mars orbit. See figure 28. Electric propulsion systems are low-thrust, high-specific-impulse systems with fuel efficiencies 2 to 10 times the efficiencies of systems using chemical propellants. The payoff for this performance can be high, since a principal cost for a space transportation system is that of launching to low Earth orbit (LEO) the propellant required for operations between LEO and other nodes. See figures 29 and 30.



Distance with respect to the barycenter (that is, the center of mass of the Earth-Moon system)

Figure 28

Earth-to-Moon Trajectory for a Spacecraft Using Electric Propulsion

An electrically propelled spacecraft traveling from low Earth orbit (LEO) to lunar orbit would follow a spiral trajectory. This trajectory results from the fact that the low-thrust engines of such a vehicle work continuously. Such a smoothly changing trajectory contrasts with that of a chemical rocket, in which sharp changes in altitude or orbital plane reflect the intermittent firing of its high-thrust engines. (Compare figures 4 and 25 in this part of volume 2.)

Once the spacecraft with electric propulsion has achieved escape velocity, it coasts until it nears the Moon. Then its engines are restarted to slow the spacecraft, allowing it to be captured by the Moon's gravity and held in lunar orbit.

For missions between the Earth and the Moon, the gravitational pull of the Earth so overwhelms the low thrust provided by an electric propulsion device that trip times are much longer than those using conventional chemical rockets. For missions to the outer solar system, by contrast, the continuous acceleration provided by an electric propulsion thruster can yield shorter trip times than those afforded by chemical rockets.

Courtesy of Andrew J. Petro, Advanced Programs Office, Lyndon B. Johnson Space Center

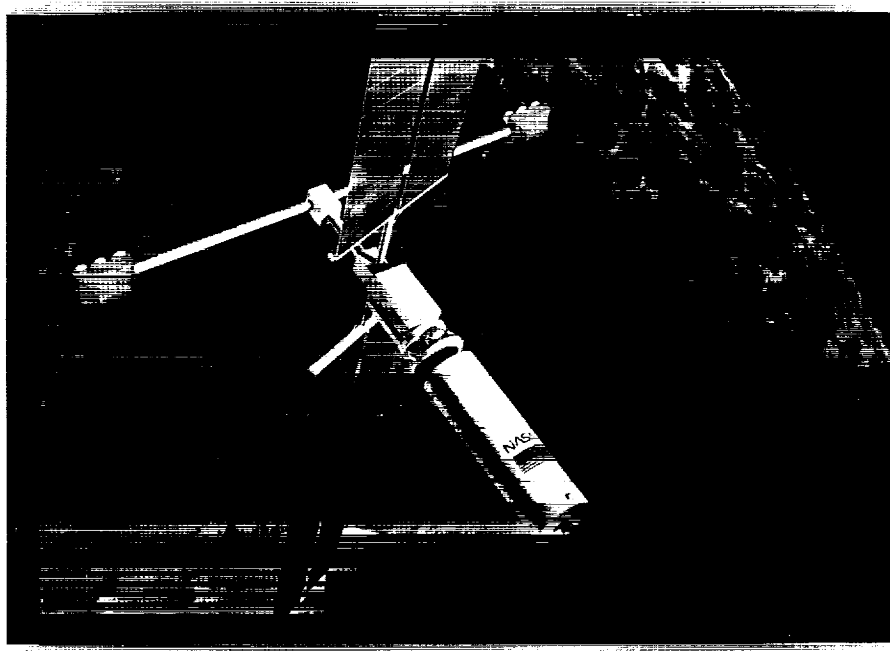


Figure 29

A Lunar Ferry Using Solar Electric Propulsion

At a power of 300 kW, in 5 years, two such lunar ferries could transfer 100 000 kg of habitat modules and power systems from low Earth orbit (LEO) to lunar orbit. The ferries and their payloads could be brought to LEO in only 12 launches of the Space Shuttle.

By contrast, transporting such a 100 000-kg payload from LEO to lunar orbit by conventional oxygen-hydrogen rockets would require about 600 000 kg of propellant, and bringing that 700 000-kg total to LEO would require 25-30 Shuttle launches.

Artist: Ken Hodges

Figure 30

An Advanced Nuclear Electric Propulsion System

In this application, an advanced version of the proposed SP-100 nuclear power plant supplies electricity to an electric thruster which is being used to propel a large unmanned payload to Neptune. A 2-MW generator could place a 2000-kg payload in orbit around Neptune with a trip time of about 5 years.

In this drawing, the nuclear reactor with its radioactive material is at the tip of the conical structure. Most of the cone consists of heat radiators to remove the excess heat of the reactor. The electricity is used to expel a charged gas at very high velocity and thus propel the vehicle in the opposite direction.

Artist: Thomas Reddie

The performance of the EP orbital transfer vehicle is strongly influenced by the power-to-mass ratio of the nuclear or solar electric power system that supplies electricity to the propulsion system because the power plant must be carried along with the payload. The power requirement for cargo OTVs will be high (1-5 MW_e) for useful payloads and trip times. Advances in space power technology will reduce mass and make possible systems producing higher power. These systems, coupled with electric propulsion, will provide faster trips and permit the use of this technology for manned as well as unmanned transportation.

Candidate Systems

Electric propulsion systems of various types have been proposed for space missions. Such systems can produce much higher exhaust velocities than can conventional rockets and thus are more efficient. In a conventional rocket system, a fuel is oxidized in an exothermic reaction; the exhaust velocity is limited by the temperature of the reaction and the molecular weights of the exhaust gases. In an electric propulsion system, an electrical current is used to ionize the propellant and to accelerate the ions to a much higher velocity. In the simple case of an ion thruster, ions are generated, accelerated across a voltage potential, and emitted through a nozzle. Because of the high velocity of the ions, such a device has a very high specific impulse (a measure of engine performance or efficiency; see p. 90).

With existing power systems, electric propulsion devices can produce only low thrust. However, emerging high-power systems will enable both ion engines that can produce higher thrust and other types of electric engines. Magnetoplasmadynamic (MPD) thrusters use power systems operating at 10-20 kV and at 12 000 amperes. The large current creates a magnetic field that can accelerate ions to 15-80 km/sec. An alternative system, called an arc jet, uses a high voltage arc, drawn between electrodes, to heat the propellant (hydrogen) to a high temperature.

Figure 31

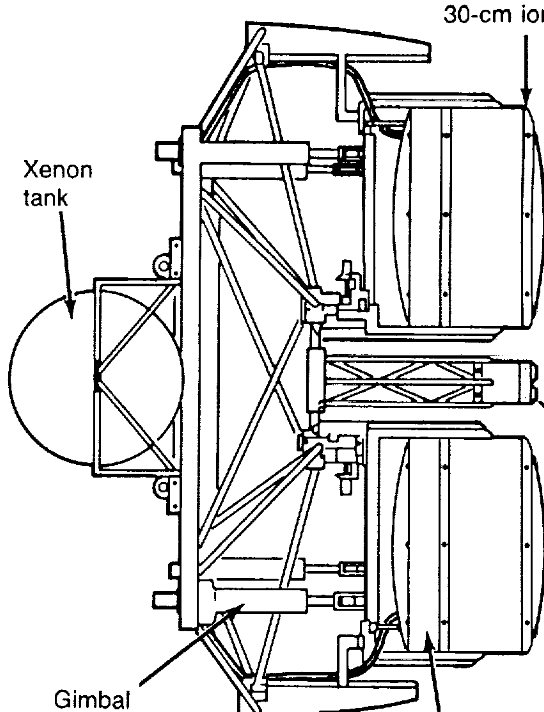
Ion Thruster

Because of its potential for providing very high exhaust velocity (10^5 meters per second) and high efficiency, ion propulsion is well suited to meet the high energy needs of planetary missions. Research is being directed toward improving the life and reliablity of the mercury ion thruster and toward developing ion thrusters that use inert gases.

Lewis Research Center (LeRC) successfully operated a 30-cm xenon thruster at approximately 20 kW, more than five times the thrust per unit area of its predecessor mercury thruster. LeRC is investigating the performance and lifetime of the 30-cm xenon thruster and designing and testing a 50-cm ion thruster with the potential to use 60 kW of power.

*The Jet Propulsion Laboratory (JPL) has designed and begun testing a two-engine xenon ion propulsion module. At a power input of 10 kW for the module, the maximum thrust and exhaust velocity are projected to be 0.4 N and 3.5×10^4 m/sec, for a total module efficiency of 67 percent.**

The principal focus of the U.S. electric propulsion technology program has been the J-series 30-cm mercury ion thruster. This technology is reasonably mature but not yet flight qualified. Mercury may not be an acceptable propellant for heavy OTV traffic operating from Earth orbit. Ion thrusters are currently being developed for argon and xenon (see fig. 31). Specific impulses between 2 000 and 10 000 seconds are possible, but a value less than 3 000 seconds is typically optimum for these missions.



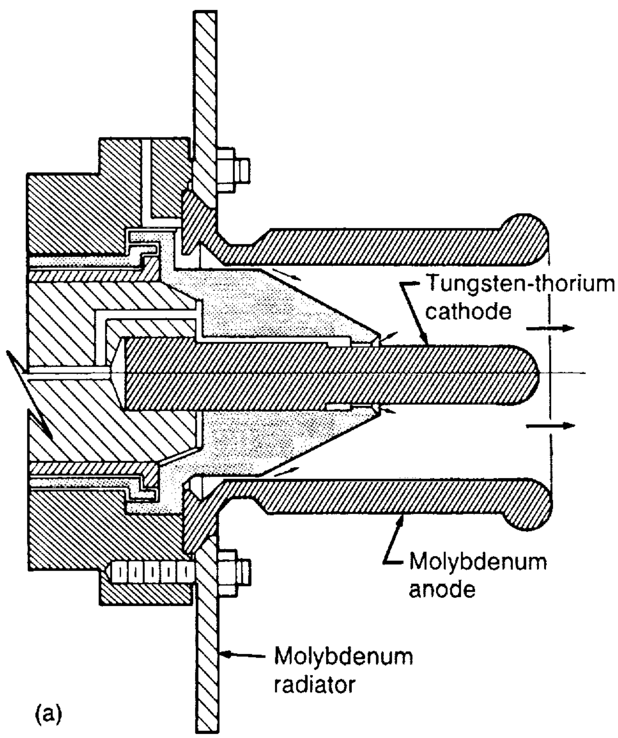
**Because jet power equals its kinetic energy (1/2 mv^2) over time (t) and mv/t is an expression of force, the output power of a jet engine is expressed as 1/2 its thrust (F) times its exhaust velocity (v) and*

$$\text{Efficiency } (\eta) = \frac{\text{output power}}{\text{input power}} =$$

$$\frac{1/2 \text{ thrust} \times \text{exhaust velocity}}{\text{input power}} =$$

$$\frac{0.4 \text{ N } (3.5 \times 10^4 \text{ m/sec})}{2 \times 10 \text{ kW}} = 0.7$$

Magnetoplasmadynamic thruster technology is also being developed in the United States and elsewhere, but it is significantly less mature than mercury ion or arc jet technology. MPD thrusters (see fig. 32) can operate with a wide range of propellants providing specific impulses of approximately 2 000 sec using argon and up to 10 000 sec using hydrogen. MPD thrusters operate in both pulsed and steady-state modes. A steady-state MPD thruster is a high-power device (approximately 1 MW_e) and is an attractive option for EP OTV applications.



(a)

Figure 32

Magnetoplasmadynamic Thruster

Studies show that multimegawatt nuclear-powered magnetoplasmadynamic (MPD) propulsion is well suited to orbit transfer and spacecraft maneuvering. MPD research, sponsored by NASA, the Air Force Office of Scientific Research (AFOSR), and the Air Force Rocket Propulsion Laboratory (AFRPL), is being conducted at JPL, Princeton University, and MIT.

In an MPD device, the current flowing from the cathode to the anode sets up a ring-shaped magnetic field, B_Θ.

This magnetic field pushes against the plasma in the arc. As propellant flows through the arc plasma, it is ionized and blown away by the magnetic field.

[In this explanation one can see how ion thrusters, MPD thrusters, and arc jets are related. Furthermore, one can perceive similarities in operating principles between the MPD device and an electromagnetic launcher (discussed in Snow's paper) and an electrodynamic tether (discussed in the immediately preceding paper by Cutler) and, for that matter, an ordinary electric motor. In all four of these cases, a force is created by the interaction of an electrical current and a magnetic field.]

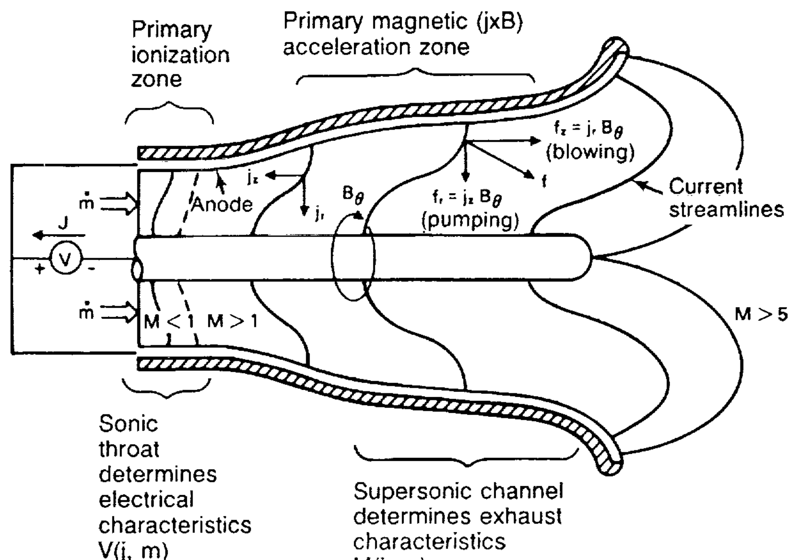
The objective of this work is to develop an improved understanding of the physics of the magnetic field set up by the arc and the acceleration process produced by that field. This understanding, it is hoped, will lead to thruster lifetimes of thousands of hours and to efficiencies above 50 percent. Measurements and analyses

(continued)

Figure 32 (concluded)

have shown that the cathode can efficiently operate at temperatures where metal evaporation from it does not limit thruster life. Experiments are being conducted to measure cathode life in the subscale 100-kW engine shown in this figure.

Diagram b taken from Edmund P. Coomes et al., 1986, Pegasus: A Multi-Megawatt Nuclear Electric Propulsion System, in vol. 2 of Manned Mars Missions Working Group Papers, pp. 769-786, NASA Report M002 (Huntsville, AL: Marshall Space Flight Center).



(b)

Extensive work was done on arc jet and resistojet technology in the 1960s, but this technology has received little attention in recent years. The arc jet (see fig. 33) is also a high-power device and provides a specific impulse between 900 and 2000 sec. The arc jet, like the MPD thruster, can operate with a wide variety of propellants.

Research conducted at the Jet Propulsion Laboratory since 1984 (see Aston 1986, Garrison 1986) has demonstrated the successful operation of (1) a 30-cm ion thruster at 5 kW and 3600 seconds with xenon propellant, (2) a steady-state MPD thruster at 60 kW with argon propellant, and (3) an arc jet for 573 hours at 30 kW with ammonia propellant. NASA's Lewis Research Center has recently initiated programs to develop the technology for 50-cm, 30-kW xenon ion thrusters and low-power arc jets. The Air Force is funding research in MPD thrusters at Princeton University and MIT and in high-power arc jets at Rocket Research Corporation.

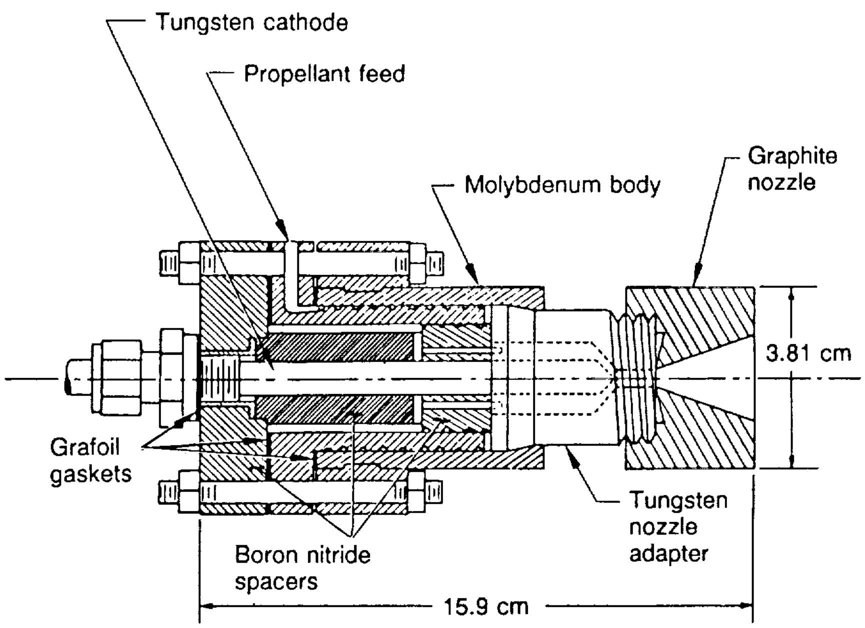


Figure 33

Arc Jet

A high-power arc jet with exhaust velocities between 8 x 10^3 and 2 x 10^4 meters per second is an attractive option for propelling an orbital transfer vehicle. Experimental and analytical work, sponsored by the Air Force Rocket Propulsion Laboratory (AFRPL) and conducted at JPL and at Rocket Research, is addressing the technology of this class of engine.

During 1985, two new arc jet test facilities were built. Tests at JPL of a 30-kW engine have provided new information about the effects of arc jet nozzle contour on engine performance. Tests at Rocket Research of an arc jet using ammonia as its propellant and operating at power levels in the 10-50 kW range have mapped the stability and measured the performance of such an engine.

Technology Needs

Because of the difficulty of developing larger ion thrusters, large numbers of ion thrusters are required for a multimegawatt OTV. Steady-state MPD thrusters and arc jets are likely to be better suited to the cargo OTV application. Of the two, the arc jet is the more mature technology.

The funding for each of the above EP technologies is nearly subcritical because there is no established mission requirement for the technology. Increased funding will be necessary to make this technology available for the scenarios under consideration.

Impact of Scenarios Utilizing Nonterrestrial Materials

Nonterrestrial material utilization has two potential impacts on EP technology needs. If a demand for large quantities of lunar materials is established, electric propulsion is a highly competitive option for transporting both the bulk materials needed to construct the bases and factories for such an operation and the raw materials and products output by it. Electrically propelled OTVs, such as the lunar ferry described in figure 29, can beneficially supplant chemically propelled vehicles when cargo traffic to and from the Moon reaches some level, perhaps 100 metric tons (100 000 kg) per year. The second impact concerns the ability of the transportation system to rely on nonterrestrial resources for resupply of consumables. All other aspects being equal, a system that can be resupplied from local resources is clearly preferred.

However, the most readily available lunar propellant, oxygen, is not well suited to EP operations. Significant technology advances are required to operate any of the EP devices with oxygen, the principal technology barriers being the development of techniques to prevent the rapid oxidation of high-temperature thruster components. On the other hand, if hydrogen could be obtained from lunar (or asteroidal) sources, it would significantly enhance the performance of the EP OTV as well as benefit the oxygen-hydrogen chemical propulsion vehicles needed for high-thrust surface-to-orbit operations.

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