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Propulsion technologies for exploration of the solar system and beyond (plenary)

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NASA's Advanced Space Transportation Program (ASTP) is investing in technologies to achieve a factor of 10 reduction in the cost of Earth orbital transportation and a factor of 2 reduction in propulsion system mass and travel time for planetary missions within the next 15 years. Since more than 70% of projected launches over the next 10 years will require propulsion systems capable of attaining destinations beyond low-Earth orbit, investment in in-space technologies will benefit a large percentage of future missions. The ASTP technology portfolio includes many advanced propulsion systems. From the next-generation ion propulsion system operating in the 5–10 kW range to fission-powered multikilowatt systems, substantial advances in spacecraft propulsion performance are anticipated. Some of the most promising technologies for achieving these goals use the environment of space itself for energy and propulsion and are generically called "propellantless," because they do not require onboard fuel to achieve thrust. An overview of state-of-the-art space propulsion technologies, such as solar and plasma sails, electrodynamic and momentum transfer tethers, and aeroassist and aerocapture, are described. Results of recent Earth-based technology demonstrations and space tests for many of these new propulsion technologies are discussed. [DOI: 10.1063/1.1431426]

I. THE LIMITS OF CHEMICAL PROPULSION

A vigorous and robust space science and exploration program will require a new generation of propulsion systems. Chemical propulsion, which relies on making chemical bonds to release energy and produce rocket exhaust, has been the workhorse of space exploration since its beginning. However, we have reached its performance limits and those limits are now hindering our continued exploration of space. The efficiency with which a chemical rocket uses its fuel to produce thrust, specific impulse (I_{sp}), is limited to several hundred seconds or less. In order to attain the high speeds required to reach outer planetary bodies, much less rendezvous with them, propulsion system efficiencies well over 1000 s will be required. Chemical propulsion systems cannot meet this requirement.

II. ELECTRIC PROPULSION

An electric propulsion system uses electrical energy to energize the propellant to much higher exhaust velocities (V_e) than those available from chemical reactions. Ion propulsion is an electric propulsion technology that uses ionized gas as propellant. Ionized xenon gas is electrostatically accelerated to a speed of ≈30 km/s and provides the "exhaust" for the propulsion system. Ion propulsion is being used by commercial telecommunication satellites and has been demonstrated as a primary spacecraft propulsion system by the NSTAR demonstration on the Deep Space 1 mission.

Electric propulsion thrusters can be divided into three broad categories: (1) electrothermal thrusters use electric energy to simply heat the propellant, (2) electrostatic thrusters use charge potential differences to accelerate propellant ions, and (3) electromagnetic thrusters use electromagnetic forces ($\mathbf{J}\times\mathbf{B}$) to accelerate a propellant plasma.

NASA is pursuing technologies to increase the performance of electrostatic thrusters by going to higher power levels and by increasing the I_{sp} on a system level. Figure 1 illustrates the mission benefit of using electric propulsion to increase the payload mass fraction.

III. FISSION PROPULSION

A fission reactor in space can be used for propulsion in two ways. The energy created by the fission reaction can be used to heat a propellant to extremely high temperatures, thus increasing its exhaust velocity and I_{sp}. Alternatively, fission energy can be converted to electricity and used to power an electric propulsion system. The first space fission system is likely to use the latter approach for propelling a series of robotic spacecraft to the outer planets and beyond. Figure 2 shows the relative benefits of nuclear propulsion for human and robotic exploration missions of interest to NASA.

A nuclear electric propulsion system for a Kuiper Belt exploration mission might use a 100–200 kW$_e$ nuclear reactor, launched "cold"—where only zero power testing has been conducted. The reactor would be activated at a positive C3 (beyond Earth escape) to power a krypton-fueled ion propulsion system. The propulsion system would carry a science payload on an indirect trajectory (heliocentric spiral trajec-

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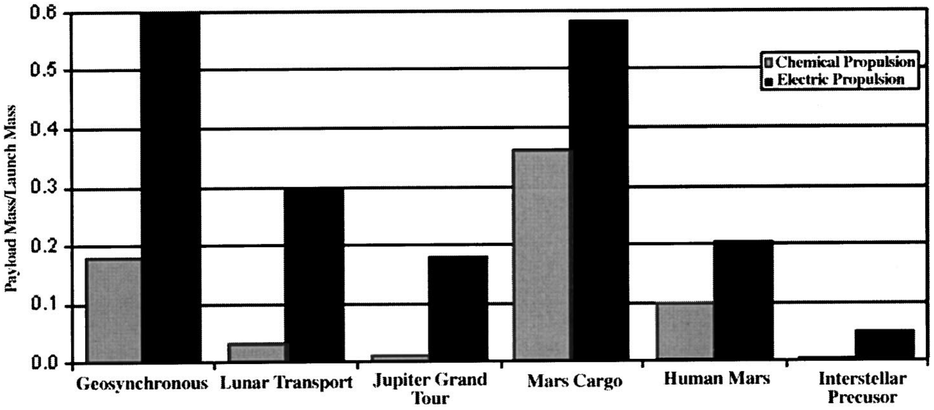

FIG. 1. Electric propulsion systems provide up to ten times the payload capacity of chemical rockets to the same destination.

tory) building up to a final velocity of ≈25 AU/year after a 10 year run time. After engine burnout, the science payload would be deployed.

The first step toward using advanced fission propulsion systems is development of a safe, affordable fission system that can enhance or enable near-term missions of interest. To this objective, NASA is defining a safe, affordable fission engine (SAFE) test series, designed to demonstrate a 300 kW flight configuration system using non-nuclear testing. The SAFE-30 test series is a full-core test capable of producing 30 kW using resistance heating to simulate the heat of fission. The 30 kW core consists of 48 stainless-steel tubes and 12 stainless-steel/sodium heat pipes welded together longitudinally to formulate a core similar to that of a fission flight system. Heat is removed from the core via the 12 heat pipes, closely simulating the operation of an actual system.

IV. PROPELLANTLESS PROPULSION

Conventional space propulsion relies on the transfer of momentum from propellant to spacecraft, with the momentum of the system remaining unchanged. For example, a large-mass spacecraft using chemical propulsion will experience a small velocity change through the exhaust of a small mass having a large velocity. A rocket, therefore, exchanges momentum with the propellant, striving to reduce propellant consumption by increasing the exhaust velocity of the propellant. A rocket can expel hydrogen, water vapor, antimatter annihilation products, etc.; the principle is still the same.

A "propellantless" propulsion system simply uses a different form of momentum exchange to produce thrust, usually through interaction with the natural space environment. Solar sails, plasma sails, aerocapture, and tethers are examples of propellantless propulsion technologies being investigated.

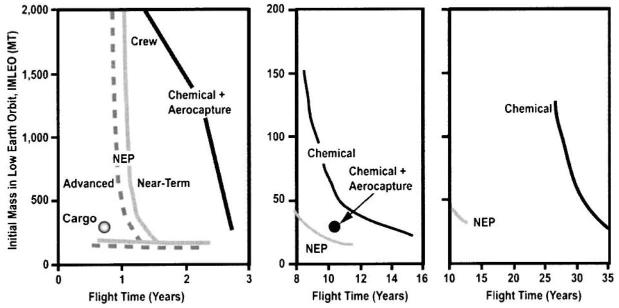

FIG. 2. Nuclear electric propulsion enables a new class of space missions.

V. SOLAR SAILS

A solar sail is a propulsion concept which makes use of a flat surface of very thin reflective material supported by a lightweight deployable structure. Solar sails accelerate under the pressure from solar radiation (essentially a momentum transfer from reflected solar photons) thus requiring no propellant. Since a solar sail uses no propellant, it has an effectively infinite I_{sp}; however, the thrust-to-weight ratio is very low, typically between 10^{-4} to 10^{-5} for the 9 $\mathrm{N/km}^{1,2}$ solar pressure at Earth's distance from the Sun.

In the near term, deployable sails will be fabricated from materials such as Dupont Mylar® or Kapton® coated with ≈500 Å of aluminum. The thinnest available Kapton films are 7.6 μ in thickness and have an areal density of ≈11 g/m.^{2} Sails thinner than this, made from conventional materials, have the potential to rip or tear in the deployment process. Recent breakthroughs in composite materials and carbon-fiber structures may make sails of areal density $<1\mathrm{g/m}^2$ a possibility. The reduced sail mass achieved this way may allow much greater acceleration, greater payload carrying capability, and reduced trip time.

VI. PLASMA SAILS

An approach to spacecraft propulsion using a virtual sail composed of low-energy plasma might harness the energy of the solar wind to propel a spacecraft anywhere in the solar system and beyond. Such plasma sails will affect their momentum transfer with the plentiful solar wind streaming from the Sun. Plasma sails use a plasma chamber attached to a spacecraft as the primary propulsion system. Solar cells and solenoid coils would power the creation of a dense magnetized plasma, or ionized gas, that would inflate an electromagnetic field up to 19 km in radius around the spacecraft. In the future, fission power could be used. The field would interact with and be dragged by the solar wind. Creating this virtual sail will be analogous to raising a giant physical sail and harnessing the solar wind, which moves at speeds >1 M km/h. Tests of the plasma sail concept are ongoing at Mar-

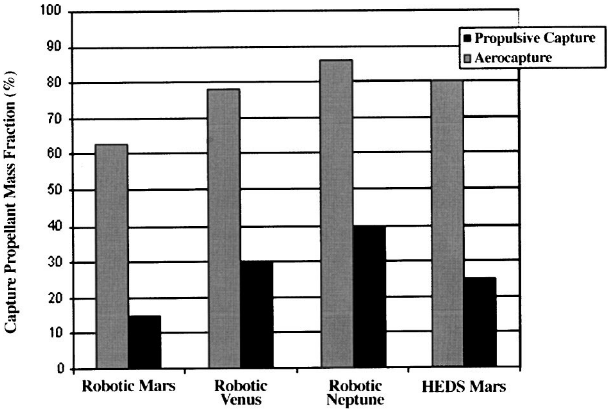

FIG. 3. Aerocapture dramatically reduces the propulsive requirements for planetary capture maneuvers.

shall Space Flight Center and the University of Washington. Thrust measurements, using a Hall thruster to simulate the solar wind, are planned in 2002–2003.

VII. AEROCAPTURE

Aerocapture relies on the exchange of momentum with a planetary atmosphere to achieve thrust, in this case, a decelerating thrust leading to orbit capture. Aerocapture has not yet been demonstrated, though it is very similar to the flight-proven technique of aerobraking, with the distinction that aerocapture is employed to reduce the velocity of a spacecraft flying by a planet so as to place the spacecraft into orbit about the planet. This technique is very attractive for planetary orbiters since it permits spacecraft to be launched from Earth at high speed, providing a short trip time, and then reducing the speed by aerodynamic drag at the target planet. Without aerocapture, a large propulsion system would be needed on the spacecraft to perform the same reduction of velocity, thus reducing the amount of delivered payload, increasing the size of the launch vehicle (to carry the additional fuel required for planetary capture) or simply making the mission impossible due to the tremendous propulsion requirements. Figure 3 shows the propulsion system mass savings that are possible with an aerocapture system.

The aerocapture maneuver begins with a shallow approach angle to the planet, followed by a descent to relatively dense layers of the atmosphere. Once most of the needed deceleration is reached, the vehicle maneuvers to exit the atmosphere. To account for the inaccuracies of the atmospheric entering conditions and for the atmospheric uncertainties, the vehicle needs to have guidance and control as well as maneuvering capabilities. Given the communication time delay resulting from the mission distances from Earth, the entire operation requires the vehicle to operate autonomously while in the planet's atmosphere.

VIII. ELECTRODYNAMIC TETHERS

A predominantly uninsulated (bare wire) conducting tether, terminated at one end by a plasma contactor, can be used as an electromagnetic thruster. A propulsive force of $F=IL\times B$ is generated on a spacecraft/tether system when a current, I, from an onboard power supply is fed into a tether of length L against the electromagnetic force induced in it by the geomagnetic field, B. This concept will work near any planet with a magnetosphere (Earth, Jupiter, etc.) by exchanging momentum with that planets' rotational angular momentum. This was demonstrated in Earth orbit by the Tethered Satellite System Reflight mission; the orbiter experienced a 0.4 N electrodynamic drag thrust during tether operation. No instrumentation was flown to actually measure this thrust; it is derived from the physics of the electrodynamic interaction.

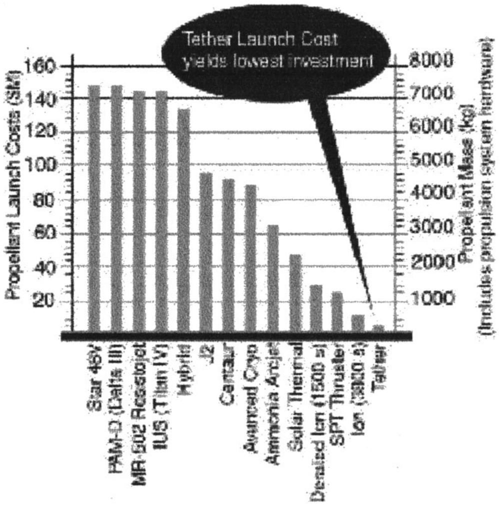

FIG. 4. An orbit transfer vehicle propelled by an electrodynamic tether would be highly reusable and require no resupply.

An electrodynamic tether upper stage could be used as an orbital tug to move payloads within low-earth-orbit (LEO) after insertion (Fig. 4). The tug would rendezvous with the payload and launch vehicle, dock/grapple the payload, and maneuver it to a new orbital altitude or inclination within LEO without the use of boost propellant. The tug could then lower its orbit to rendezvous with the next payload and repeat the process. Such a system could conceivably perform several orbital maneuvering assignments without resupply, making it a low, recurring-cost space asset. The same system can be used to change the orbital inclination of a payload as well.

IX. MOMENTUM-EXCHANGE ELECTRODYNAMIC REBOOST TETHERS

An Earth-orbiting, spinning tether system can be used to boost payloads into higher orbits with a Hohmann-type transfer. A tether system would be anchored to a relatively large mass in LEO, awaiting rendezvous with a payload delivered to orbit. The uplifted payload would meet with the tether facility which then begins a slow spin-up using electrodynamic tethers (for propellantless operation) or another low thrust, high I_{sp} thruster. At the proper moment and tether system orientation, the payload is released into a transfer orbit, potentially to geostationary transfer orbit (GTO) or lunar transfer orbit.

Following spin-up of the tether and satellite system, the payload is released at the local vertical. The satellite is in-

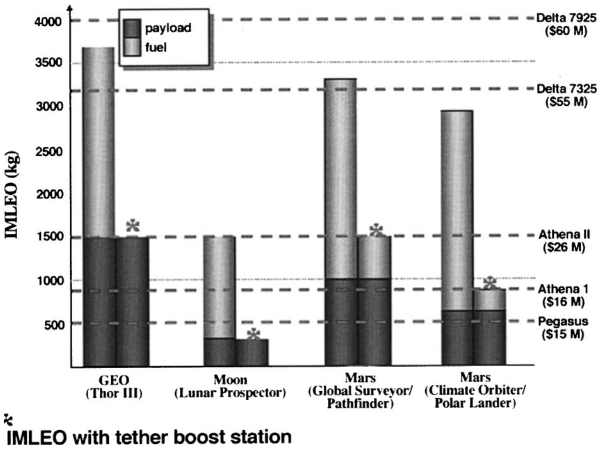

FIG. 5. A MXER tether system could reduce launch vehicle size and cost for a variety of planetary exploration missions.

jected into a higher orbit with perigee at the release location; the orbital tether platform is injected into a lower orbit with apogee at the release location. Momentum is transferred to the satellite from the orbiting tether boost station. The satellite then enters a GTO trajectory and accomplishes the transfer in as little as 5 h. The platform then reboosts to its operational altitude. The system thus achieves transfer times comparable to a chemical upper stage with the efficiencies of electric propulsion. This type of system could be used to reduce launch vehicle requirements or to increase injected payload mass for any interplanetary mission. Figure 5 shows the launch vehicle benefits derived from using a momentum exchange tether boost system.

X. SUMMARY

A sustained investment in new in-space propulsion technologies will change the way scientists seek to explore our solar system. Early implementation of advanced electric propulsion systems will increase the mass fraction of many planned missions. Fielding nuclear electric propulsion systems will enable new classes of missions and allow prolonged on-site investigations. Revolutionary propellantless propulsion systems will dramatically reduce trip times and provide new vantage points for scientific exploration of our solar system and beyond.

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