

IN-SPACE PROPULSION PROGRAM OVERVIEW AND STATUS

Paul F. Wercinski

ISP Program Executive
Solar System Exploration Division
NASA Headquarters, Office of Space Science
Washington, D.C. 20546

Les Johnson

In Space Transportation Investment Area Manager
Advanced Space Transportation Program/TD15
NASA Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

Randy M. Baggett

Project Manager, Next Generation Ion
Advanced Space Transportation Program/TD15
NASA Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ABSTRACT

NASA's In-Space Propulsion (ISP) Program is designed to develop advanced propulsion technologies that can enable or greatly enhance near and mid-term NASA science missions by significantly reducing cost, mass, and/or travel times. These technologies include: Solar Electric Propulsion, Aerocapture, Solar Sails, Momentum Exchange Tethers, Plasma Sails and other technologies such as Advanced Chemical Propulsion. The ISP Program intends to develop cost-effective propulsion technologies that will provide a broad spectrum of mission possibilities, enabling NASA to send vehicles on longer, more useful voyages and in many cases to destinations that were previously unreachable using conventional means. The ISP approach to identifying and prioritizing these most promising technologies is to use mission and system analysis and subsequent peer review. The ISP program seeks to develop technologies under consideration to Technology Readiness Level (TRL) -6 for incorporation into mission planning within 3-5 years of initiation. The NASA TRL 6 represents a level where a technology is ready for system level demonstration in a relevant environment, usually a space environment. In addition, maximum use of open competition is encouraged to seek optimum solutions under ISP. Several NASA Research Announcements (NRA's) have been released asking industry, academia and other organizations to propose propulsion technologies designed to improve our ability to conduct scientific study of the outer planets and beyond. The ISP Program is managed by NASA Headquarters Office of Space Science and implemented by the Marshall Space Flight Center in Huntsville, Alabama.

INTRODUCTION

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, will require propulsion system efficiencies well over 1,000 sec. Chemical propulsion systems cannot meet this requirement.

The In-Space Propulsion Program was a NASA new start in Fiscal Year (FY) 2002. Significant effort was spent in the summer and early fall of 2001 preparing for FY02 implementation. Mission analysis and technology prioritization were completed in order to gain an initial understanding of the potential pay-off of each technology and their applicability to a wide range of NASA missions. This effort was called Integrated

In-Space Transportation Planning (IISTP). The IISTP sought to iterate and develop future NASA requirements for In-Space transportation and perform a prioritization of relevant propulsion technologies. An agency wide team was assembled with technical experts representing over 20 different propulsion technology elements. Propulsion technologies were assessed on their ability to meet a broad spectrum of mission needs including, reliability and safety, technology maturity, development costs and risk. The Propulsion function of interest was the transportation of a payload from the Earth's vicinity to a distant location, which also included insertion maneuvers at the destination, such as orbital insertion. The highest ranked propulsion technologies were those that had a broad range of mission applications and represented an enabling or significantly enhancing capability. The results of this IISTP effort served as the basis for selecting the ISP technology sub-areas for focused development efforts.

The ISP Program currently utilizes focused Technology Assessment Groups (TAGs), one for each major in-space propulsion technology, which play an integral role in helping NASA develop a technology maturation strategy. Several ISP technology TAGs were convened in early CY02 to begin to process of developing technology roadmaps, performing technology level assessments, and recommending technology maturation strategies. The TAGs are represented by experts in NASA, industry, and academia who come together in a forum to exchange information and offer technical insight to address the challenges of advancing the state-of-the-art of ISP technologies.

DISCUSSION

The ISP Program is currently developing and evaluating a suite of propulsion technologies. Below is a brief description of the technologies along with references where more detailed information may be obtained.

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 propellant¹. Ionized gas, such as xenon, is electrostatically accelerated to a speed of >30 km/sec and provides the "exhaust" for the propulsion system. 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.

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 (DS-1) mission.² The successful demonstration of electric propulsion for DS-1 enabled the DAWN mission, recently selected in the Discovery Program, to baseline electric propulsion. The ISP Program 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. Recently, NASA has begun development of NASA's Evolutionary Xenon Thruster (NEXT)³ which is designed to have the same current density as NSTAR but produce twice the thrust. Figure 1 shows the performance advantages of the NEXT for outer planet exploration missions.

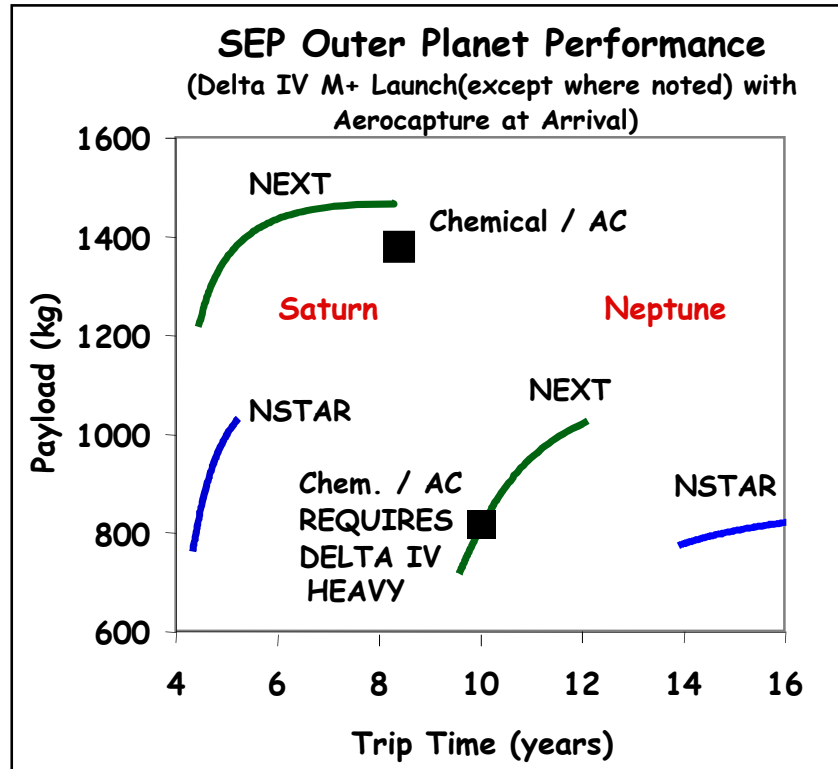


Figure 1. Solar Electric Propulsion Advantages for several Outer Planet destinations.

AEROCAPTURE

Aerocapture -- the use of a planet's atmosphere to slow down a spacecraft -- is part of a unique family of "aeroassist" technologies that will enable robust science missions to the most distant planets in our solar system. An aerocapture vehicle approaching a planet on a hyperbolic trajectory is "captured" into orbit as it passes through the atmosphere, without the use of on-board propulsion. This fuel-free method could reduce the typical mass of an interplanetary spacecraft by half, allowing for a smaller, cheaper vehicle -- one better equipped to conduct robust, long-term science at its destination. Aerocapture has been studied for over 40 years. Refs. 4 and 5 are some recent discussions on aerocapture.

To aerocapture, a spacecraft requires adequate drag to slow its speed and some protection from the heating environment. These two functions can be fulfilled in a variety of ways, including a traditional blunt, rigid aeroshell, such as that used during the Mars Pathfinder entry and descent in 1997; by a potentially lighter, inflatable aeroshell; or by a large, trailing "ballute," a combination parachute and balloon made of durable, thin material and stowed behind the vehicle for deployment.

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. Figure 2 shows the significant mass savings for aerocapture orbital missions.

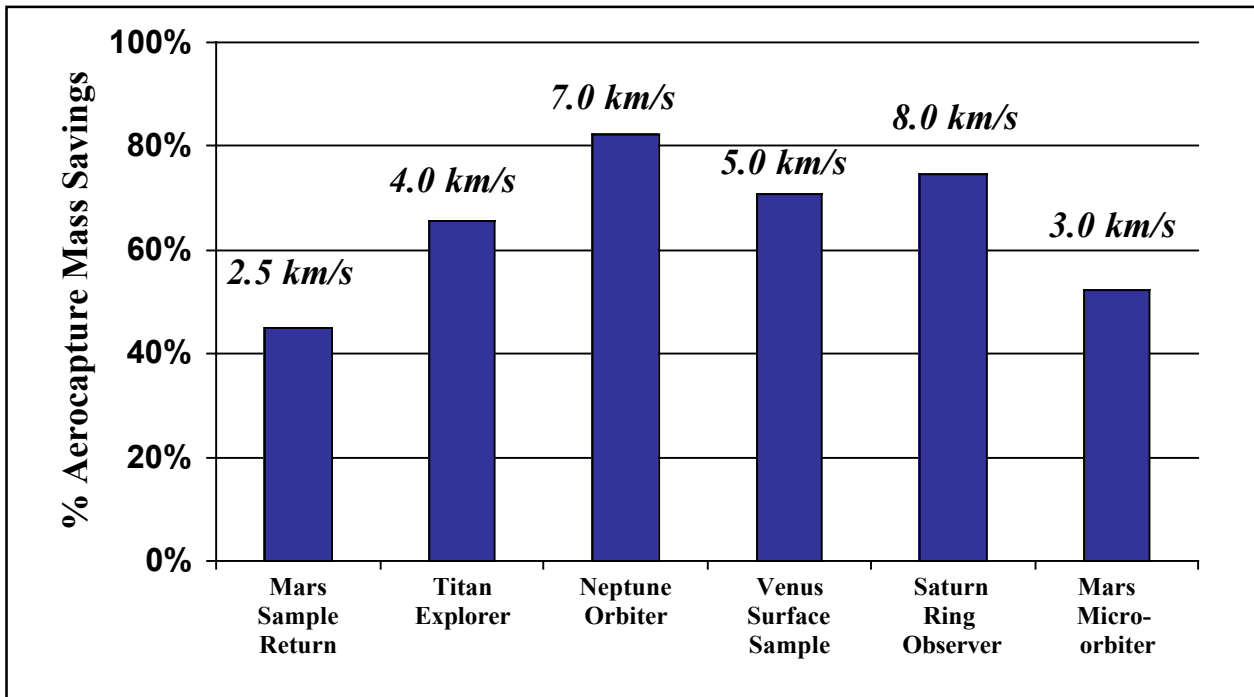


Figure 2. Aerocapture mass savings benefits for a variety of orbital missions. All values are compared to the mass of an all-propulsive capture. Equivalent Delta-V from aerocapture noted above each column.

SOLAR SAILS

The chief advantage of the solar sail is its unique capability to accomplish scientific endeavors in the inner solar system.^{6,7} NASA is now proposing several missions to study the “Sun-Earth Connection,” our planet’s relationship with its parent star and the turbulent space weather it creates. Because some missions would call for the craft to hover in space, rather than orbit Earth or the Sun, the vehicle would need a constant propulsion source to hold its position. Conventional chemical propulsion or even an electric propulsion system would require too much fuel to sustain such a mission.

A solar sail, however, could carry out such missions for an extended duration. It would be uniquely suited, for instance, to hover at the so-called “sub-L1 point.” The L1 point is a location in space where the gravitational forces of Earth and the Sun are in balance. A position in the Earth-Sun line closer than L1, hence sub-L1, would require a constant thrust force to maintain this non-Keplerian orbital motion. A spacecraft at the sub-L1 point could provide early warning of large-scale geomagnetic storms that might threaten satellites in Earth orbit or disrupt and damage communications systems and power grids on the planet. Figure 3 depicts a proposed GeoStorm mission for monitoring solar weather using solar sails as the primary propulsion system.

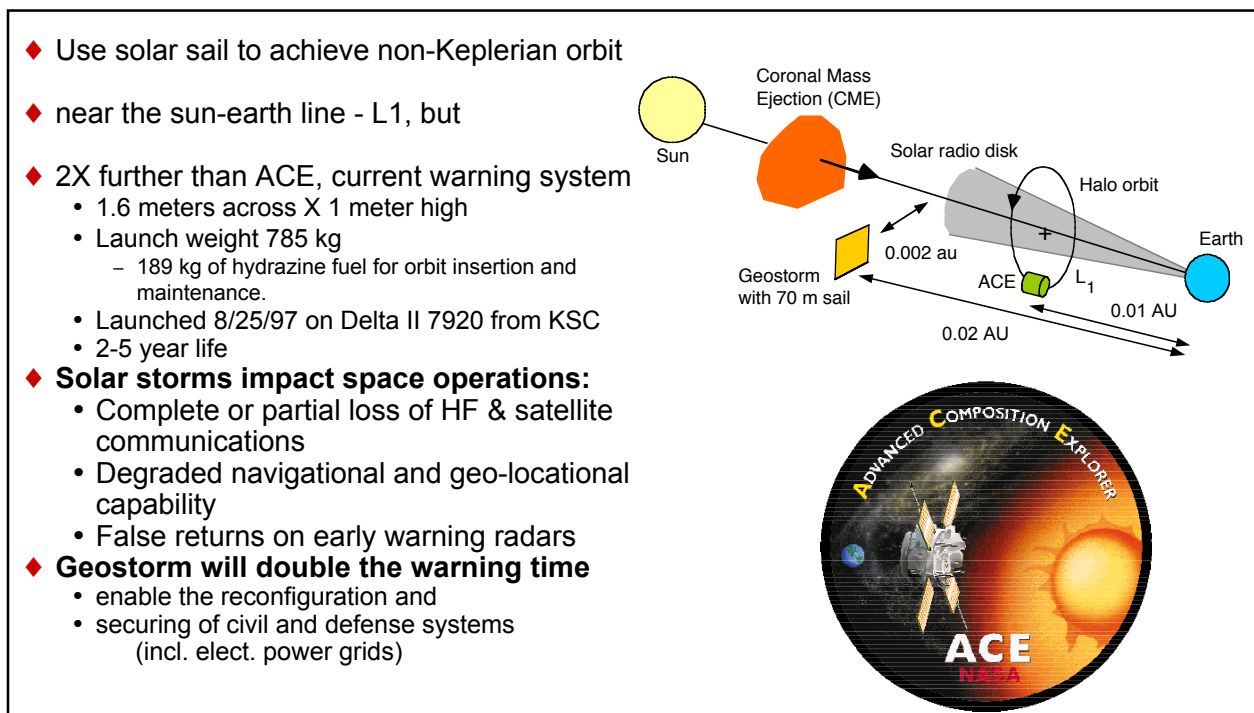


Figure 3. Solar Sail Propulsion Application for the GeoStorm Mission.

Sailing in space has only become a real possibility in the last few years, with the advent of strong, lightweight materials. The sail itself could vary in size -- depending on the thrust level needed -- from the length of the Space Shuttle to that of a football field. The sail would be thinner than cellophane, with a density of just 5-10 grams per square meter. NASA and its partners are now evaluating sail hardware and materials to understand how well they will survive the harsh environment of space.

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.^{8,9} 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 injected 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 hr. 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.

PLASMA SAILS

A novel new 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.^{10,11} 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 more than 1million km/hr.

Such an idea was first proposed by science fiction writer Carl Wiley in 1951, and advanced as a scientific possibility by physicist Richard Garwin later that decade. But it wasn't until the mid-1990s that practical research into harnessing plasma -- or the super-energized gas that would serve as the foundation of such a unique propulsion system -- were undertaken.

ADVANCED CHEMICAL PROPULSION

These technologies may provide new solutions for interplanetary travel. NASA is investigating promising new chemical fuels, including non-toxic monopropellants and advanced hydrocarbons, as well as new means of improving chemical fuel efficiency through development of lightweight components, cryogenic fluid management technologies and other improvements to fuel storage and delivery systems.

RECENT PROGRESS

ISP's final FY02 budget, received in November 2001, was \$19.6M. This was 40% less than originally planned. In order to accommodate this budget reduction, only the high priority technologies and systems analysis were funded for FY02. The high priority technologies are: solar electric propulsion, solar sails, aerocapture, and high-powered electric propulsion for near-term nuclear systems and power conversion technologies for nuclear electric power and propulsion systems.

Two NASA Research Announcements were used to select awards for the development for these high priority technologies. The ISP Program has a programmatic goal to compete, via the NRA process, 70% of its funding. The NRA solicitations lead to the selection of contractors that best met the evaluation criteria of intrinsic merit, relevance to the ISP goals, and cost realism. In addition, the Department of Energy was funded \$1M to assist in requirements definition for a Nuclear Electric Propulsion system and to evaluate nuclear reactor concepts.

The first NRA, for the Next Generation Ion Engine, was issued in November 2001 and proposals were received in January. The proposals were peer reviewed and selections were made in May 2002. Two awards are currently in negotiation for a total of \$25M over three years. The second NRA (ISP Cycle 1), which includes Aerocapture, Nuclear Electric Propulsion, and Solar Sails, was issued in January 2002.

ISP – NEXT GENERATION ION NRA

In June 2002, the ISP Program announced the selection of a team for the development of an advanced ion propulsion system along with a second team which was selected to develop advanced ion optics, which are critical components of ion engines. Details of this NRA solicitation can be found at http://research.hq.nasa.gov/code_s/nra/current/NRA-01-OSS-01-NGIT/index.html.

NASA's Glenn Research Center in Cleveland, Ohio, was selected to lead development of NASA's Evolutionary Xenon Thruster (NEXT) system, which will use xenon gas and electrical power to drive future spacecraft. Additionally, a team led by Boeing Electron Dynamic Devices, Inc. of Torrance, Calif., was selected to pursue development, fabrication and testing of carbon-based ion optics – one of the critical components of high-power ion thrusters that have traditionally limited thruster lifetime.

The NEXT activity consists of a Phase 1 (12 months) effort to design & fabricate initial versions of the 40-cm ion thrusters, propellant feed system, power processing unit (PPU), and integrate into a system breadboard for overall performance evaluation. At the end of Phase 1, NASA may elect to exercise the Phase 2 (30 months) option to complete hardware development and integrate components into a full-scale ground demonstrator to evaluate multi-thruster performance. The total NASA funding for Next Generation Ion technologies and system development activities is approximately \$23 million.

This new ion thruster development program builds on the success of the Deep Space 1 mission, a NASA probe launched in 1998 to validate advanced flight technologies. Deep Space 1 was powered by an ion thruster just 12 inches in diameter, which accelerated the spacecraft to a velocity of 7,900 mph over a 20-month period. The NEXT ion engine will be capable of carrying significantly more payload and have a longer lifetime than the Deep Space 1 ion engine.

ISP - CYCLE 1 NRA

In August 2002, the ISP Program announced the winners from its second solicitation. The awards cover four propulsion technology areas: Aerocapture, High-Power Electric Propulsion for Nuclear Systems, Power Conversion Technologies for Nuclear Electric Propulsion, and Solar Sails. Details of the NRA solicitation can be found at http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01-ISPT/index.html. Details of the 15 selected proposals can be found at http://research.hq.nasa.gov/code_s/nra/current/NRA-02-OSS-01-ISPT/winners.html.

Beginning in FY03, the propulsion technologies unique to nuclear power systems will be managed under NASA's Nuclear Systems Initiative (NSI), including the High-Power Electric Propulsion (EP) and Power Conversion (PC) technologies.

ISP - CYCLE 2 NRA

The ISP Program has recently announced another NRA solicitation as part of the NASA Research Announcement 02-OSS-02 which asks for proposals in six technology areas of in-space propulsion research: aerocapture; advanced chemical propulsion; kilowatt solar electric propulsion systems; space-based tether propulsion; plasma sail and solar sail technologies. Details of the NRA solicitation can be found at http://research.hq.nasa.gov/code_s/nra/current/nra-02-oss-01/appendA4_4.html. ISP will announce selections for Cycle 2 NRA in late Spring 2003.

SUMMARY

The coming generation of scientific exploration missions presents NASA with unique challenges. Chief among these: fast access throughout the solar system and the ability to rendezvous with, orbit and conduct *in situ* exploration of planets, satellites and small bodies. It is the mission of the In-Space Propulsion Program to develop propulsion technologies that will benefit future NASA science missions by significantly reducing travel times required for transit to distant bodies; to increase their capability by reducing the mass of the propulsion system; and to enable new destinations and new vantage points for science.

At the forefront of this effort is research now being conducted by NASA's In-Space Propulsion Program, managed by the Office of Space Science in Washington, D.C., and implemented for NASA by the Marshall Space Flight Center in Huntsville, Ala. The In-Space Propulsion program is also supported by Ames Research Center in Moffett Field, Calif.; Glenn Research Center in Cleveland, Ohio; the Jet Propulsion Laboratory in Pasadena, Calif.; Johnson Space Center in Houston, Texas; and Langley Research Center in Hampton, Va. NASA also partners with government, industry and academic organizations around the nation to pursue its in-space propulsion goals

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