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**NASA'S IN-SPACE PROPULSION TECHNOLOGY PROGRAM:
A STEP TOWARD INTERSTELLAR EXPLORATION**

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ABSTRACT

NASA's In-Space Propulsion Technology Program is investing in technologies that have the potential to revolutionize the robotic exploration of deep space. For robotic exploration and science missions, increased efficiencies of future propulsion systems are critical to reduce overall life-cycle costs and, in some cases, enable missions previously considered impossible. Continued reliance on conventional chemical propulsion alone will not enable the robust exploration of deep space. The maximum theoretical efficiencies have almost been reached and are insufficient to meet needs for many ambitious science missions currently being considered. By developing the capability to support mid-term robotic mission needs, the program is laying the technological foundation for travel to nearby interstellar space.

The In-Space Propulsion Technology Program's technology portfolio includes many advanced propulsion systems. From the next-generation ion propulsion systems operating in the 5–10 kW range, to solar sail propulsion, 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. Propellantless propulsion technologies include scientific innovations, such as solar sails, electrodynamic and momentum transfer tethers, and aerocapture. This paper will provide an overview of those propellantless and propellant-based advanced propulsion technologies that will most significantly advance our exploration of deep space.

Keywords: aerocapture, electric propulsion, solar sails, interstellar propulsion

INTRODUCTION

The NASA In-Space Propulsion Technology Program is in its fourth year and significant strides have occurred in the advancement of key transportation technologies that will enable or enhance future robotic science and deep-space exploration missions. At the program's inception, a set of technology investment priorities was established using a NASA-wide prioritization process¹ and, for the most part, has changed little, thus allowing a consistent framework in which to fund and manage technology development. Technologies in the portfolio include aerocapture, advanced chemical propulsion, solar electric propulsion (SEP), and solar sails.

1. AEROCAPTURE

Aerocapture uses a planet or moon's atmosphere to accomplish a quick, near-propellantless orbit capture—the placement of a space vehicle in its proper orbit. The atmosphere is used as a brake to slow down a spacecraft, transferring the energy associated with the vehicle's high speed into thermal energy. The aerocapture maneuver starts with a hyperbolic trajectory into the atmosphere of the celestial body. The atmosphere's density creates friction, slowing the craft and placing it into an elliptical orbit. Onboard thrusters are then used to circularize the orbit.

This nearly fuel-free method of decelerating a space vehicle could reduce the typical mass of an interplanetary spacecraft by more than half, allowing for a smaller and less expensive vehicle—one better equipped to conduct long-term science at its destination and to enable greater scientific return—and for faster trip times. Figure 1 illustrates the potential mission-level mass savings resulting from the use of aerocapture at multiple solar system destinations.²

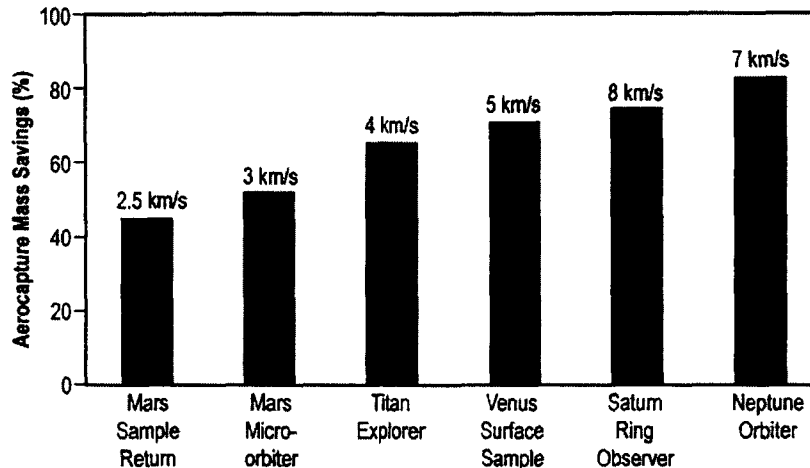


Fig. 1. Mass Savings Resulting from the use of Aerocapture

The requirement to slow down a spacecraft nonpropulsively can be achieved in two ways: (1) The craft can be enveloped by a structure with heat shielding applied to the external surfaces of a rigid aeroshell, and (2) the vehicle can deploy an aerocapture inflatable deceleration system as an inflatable ballute—a combination parachute and balloon made of thin, durable material.

1.1 Aerocapture Development Approach

Multiple technology concepts are under consideration or development for aerocapture:

(1) The blunt body, rigid aeroshell system encases a spacecraft in a protective shell. This shell provides an aerodynamic control surface and a means of protection from the high heating experienced during high-speed atmospheric flight. Once a space vehicle is captured into a planet's orbit, the aeroshell is jettisoned.³

(2) The slender body, rigid aeroshell configuration looks much like an elongated capsule with a hard shell surrounding the spacecraft. The design could provide increased volume in the interior of the spacecraft when compared to the blunt body design, allowing for improved packaging of larger crafts. Because of its slender body shape, the system also could provide increased tolerance for navigational and atmospheric uncertainties.

(3) The trailing ballute features an inflated toroidal volume that is much larger than the spacecraft it is towed behind—much like a parachute—to slow the vehicle down. The trailing ballute design allows for easy detachment and minimizes interference with the spacecraft's operation. The ballute itself is made of a lightweight, thin-film material.⁴

(4) The attached forebody ballute looks much like the rigid aeroshell or blunt body. It is often referred to as a hybrid system, with a rigid foreshell and an inflated, attached ballute extending from either the front or back of the spacecraft.⁵ The inflatable, attached ballute extends from a rigid nose cap and works much like a parachute, providing a large surface area to slow the spacecraft down to allow for an aerocapture maneuver to occur. As the spacecraft approaches a planet's atmosphere, the ballute is inflated and then jettisoned once the craft is captured into orbit.⁶

1.2 Aerocapture Technology Status

Aerocapture has never been flight tested. Relevant experience, however, exists from ablative entry capsules. Ablative entry technologies have been used throughout the history of the U.S. Space Program, including the Apollo return capsule and the Galileo Probe.

In the last year, several aerocapture thermal protection system (TPS) candidate materials—both ablative and nonablative—have undergone extensive arcjet testing. Advanced, lightweight structures have also been developed and are currently undergoing testing. Both heat flux and recession sensors are also being developed. Integration of these sensors into the TPS and preliminary testing have been completed.

Aerocapture is one of five candidate technologies for the New Millennium Program Space Test-9 (ST-9) mission. ST-9 would provide an opportunity to flight validate aerocapture computational modeling and design tools and would provide for an opportunity to flight validate an integrated aerocapture system for future mission applications.

2. SOLAR ELECTRIC PROPULSION

SEP uses solar array power to ionize and accelerate heavy propellants, such as xenon, as inputs to a low-thrust, fuel-efficient, ion propulsion system (IPS). The low thrust level of ion engines means that they have to run for a long time to accelerate the spacecraft to its desired velocity. Ion engines are the most fuel-efficient rockets used in space today—roughly 10 times more fuel efficient than conventional chemical rocket engines.

2.1 Solar Electric Propulsion Technical Approach

The electrostatic thrusters being developed rely on application of an electric field to accelerate the propellant directly. The propellant is initially ionized and then injected across a voltage potential established between an anode and cathode. The resulting force on the charged propellant ions accelerates them to high exhaust velocities. This type of device can achieve very high specific impulse (3,000 to 12,000 s and above) and is ideal for missions in which propellant mass must be minimized. These devices are generally limited to very low thrusts, but can achieve extremely high vehicle velocities due to their efficient propellant utilization. Ion propulsion and Hall thrusters fall in this category. The emphasis of the In-Space Propulsion Technology Program is on ion thrusters, though advancements in Hall and pulsed inductive thrusters are also part of the technology portfolio.

2.2 Solar Electric Propulsion Status

Ion engines have been demonstrated in space and are the primary propulsion system for NASA's Dawn mission. The first use of an IPS for primary propulsion was on the Deep Space-1 (DS-1) mission in 1998.⁶ Dawn is scheduled to launch in 2006.

The NASA solar electric propulsion technology application readiness (NSTAR) ion engine on DS-1, jointly developed by NASA's Glenn Research Center (GRC), Boeing, and NASA's Jet Propulsion Laboratory (JPL), was designed to operate for 1 yr at its maximum power level of 2.5 kW. Over this time, NSTAR used ≈ 83 kg of xenon propellant. Several long-duration tests were performed to make sure the ion engine for DS-1 would last long enough to perform the mission. Beginning in the fall of 1998, the DS-1 flight spare engine was placed in a long-duration test at JPL with the objective of demonstrating that the engine could be run for 150% of its design life. At the end of the JPL extended life test (ELT) in June 2003, the NSTAR flight spare engine had operated for more than 30,352 h and processed more than 235.1 kg of xenon. This is by far the longest any rocket engine has ever been operated and corresponds to 283% of its original design life.⁷

The In-Space Propulsion Program is currently extending ion propulsion technology with the development of NASA's Evolutionary Xenon Thruster (NEXT). NEXT will demonstrate system-level performance at power levels of ≈ 7 kW. GRC operated the 40-cm NEXT thruster for more than 2000 h and identified several design improvements for the prototype thruster. The NSTAR ELT results and hardware evaluation significantly improved the NEXT thruster design and ultimately its lifetime.

3. SOLAR SAIL PROPULSION

Solar sail propulsion uses sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, reflective material. The continuous photonic pressure provides propellantless thrust to hover indefinitely at points in space or conduct orbital maneuver plane changes much more efficiently than conventional chemical propulsion. Eventually, it might propel a space vehicle to tremendous speeds—theoretically, much faster than any present-day propulsion system. Because the Sun supplies the necessary propulsive energy, solar sails also require no onboard propellant, thus reducing payload mass.

First-generation sails will vary in size from 100 to 200 m, depending on mission destination, and typically would be three-axis stabilized. The sails would be compacted and stowed for launch. Once deployed, ultra-lightweight trusses would support the sails. Solar sails are composed of flat, smooth material covered with a

reflective coating and supported by lightweight structures attached to a central hub. Near-term sails likely will use aluminized Mylar® or CP-1. Both are proven materials previously flown in space. More robust sails might use a meshwork of interlocking carbon fibers.⁸

3.1 Solar Sail Propulsion Technical Approach

There are four classes of solar sails, defined by their operating environments. A solar sail could fly in low-Earth orbit, but it would need to be robust enough to withstand gravity and environmental loads greater than the other classes. Missions to the outer solar system and beyond require further innovations in architectures and materials to achieve those orbits within a reasonable trip time. While an interstellar probe is a notable potential future mission application for sails, it is a far-term vision. The most near-term applications are for heliocentric missions in the Earth's neighborhood; e.g., the Earth-Sun librations point. This class is the current focus of NASA's investments. It will lead to the next generation of solar sails that will enable a close approach to the Sun (<0.25 AU) where the thermal and radiation environment will be more stressing.

NASA is concentrating its development effort on the three-axis stabilized, square sails. This sail looks much like a kite. Four booms extend from a central hub that houses the four triangular sail quadrants during launch.

3.2 Solar Sail Propulsion Status

Two teams have been selected by NASA to lead hardware development activities that will culminate in ground demonstrations of key solar sail technology systems. L'Garde Inc., Tustin, CA, is developing a solar sail system that employs booms that are flexible at ambient temperatures but "rigidize" at low temperatures. Their concept uses articulated vanes located at the corners of the square to control the solar sail attitude and thrust direction. Able Engineering Company, Goleta, CA, is developing a coilable longeron that deploys in space much the way a spring-loaded screw is rotated to remove it from an object.⁹

The key metric to assess the progress and mission applicability of a particular solar sail technology is its areal density. The areal density of today's solar sails and those required to implement some potential science missions in the mid to far term are shown in Figure 2.

Both hardware vendors fabricated and tested 10-m subscale solar sails in the spring of 2004. This year they will conduct 20-m subscale solar sail deployments at the Plum Brook facility at GRC near Sandusky, OH. Solar sails are one of the candidate technologies for the New Millennium Program ST-9 mission.

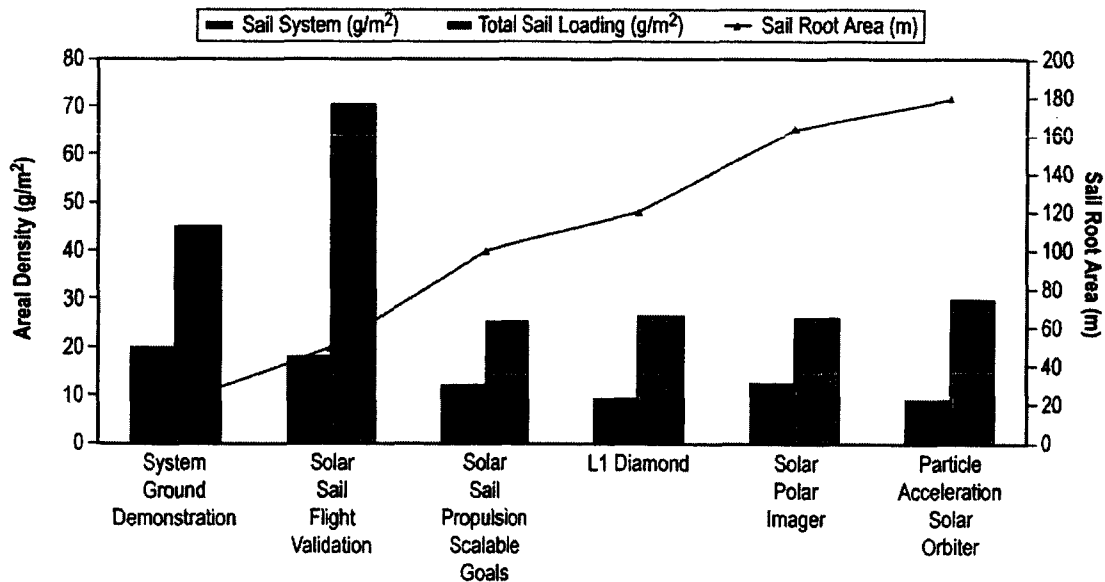


Fig. 2. Solar Sail Propulsion Metrics

4. CONCLUSIONS

Progress is being made toward the delivery of high-priority, first- and second-generation in-space propulsion technologies for potential deep-space science applications within the next 2 to 3 years. The next-generation electric (ion) propulsion system is moving toward an integrated ground demonstration in FY 2007. The first-generation rigid aeroshell aerocapture system is comparably headed toward ground validation in the same timeframe. Solar sail technology, while impossible to completely validate to Technology Readiness Level-6 on the ground, will be matured sufficiently for flight validation as early as FY 2007/2008.

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