NASA's In-Space Propulsion Technology Project Overview, Near-term Products and Mission Applicability
August, 2008

Executive Summary: The In-Space Propulsion Technology (ISPT) Project, funded by NASA's Science Mission Directorate (SMD), is continuing to invest in propulsion technologies that will enable or enhance NASA robotic science missions. This overview provides development status, near-term mission benefits, applicability, and availability of in-space propulsion technologies in the areas of aerocapture, electric propulsion, advanced chemical thrusters, and systems analysis tools. Aerocapture investments improved (1) guidance, navigation, and control models of blunt-body rigid aeroshells, 2) atmospheric models for Earth, Titan, Mars and Venus, and 3) models for aerothermal effects. Investments in electric propulsion technologies focused on completing NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, a 0.6-7 kW throttle-able gridded ion system. The project is also concluding its High Voltage Hall Accelerator (HiVHAC) mid-term product specifically designed for a low-cost electric propulsion option. The primary chemical propulsion investment is on the high-temperature Advanced Material Bipropellant Rocket (AMBR) engine providing higher performance for lower cost. The project is also delivering products to assist technology infusion and quantify mission applicability and benefits through mission analysis and tools. In-space propulsion technologies are applicable, and potentially enabling for flagship destinations currently under evaluation, as well as having broad applicability to future Discovery and New Frontiers mission solicitations.[1]

1. ISPT PROJECT INFORMATION

The objective of the ISPT project is to develop in-space propulsion technologies that can enable and/or benefit near and mid-term NASA science missions by significantly reducing cost, mass, and/or travel times. The premise of the ISPT project is that the development of new enabling propulsion technologies cannot be reasonable achieved within the cost or schedule constraints of mission development timelines, specifically the requirement of achieving TRL 6 prior to PDR. ISPT develops primary in-space propulsion technologies; Earth departure, entry, descent and landing (EDL) and attitude/reaction control systems are not currently in the project scope. Given that the ISPT objective is to develop products that realize near-term and mid-term benefits, ISPT primarily focuses on technologies in the mid technology readiness level (TRL) range (TRL 3 - 6+ range) which have a reasonable chance of reaching maturity in 4-6 years provided adequate development resources.

The project strongly emphasizes developing propulsion products that NASA missions need and will fly. Any NASA, other US government, or commercial entity that needs in-space propulsion technology is considered a potential ISPT customer. However, the primary ISPT customer and the customer which determines ISPT investment priorities is the NASA Science Mission Directorate (SMD) and in particular the Planetary Science Division within SMD.

The ISPT project office at NASA Glenn Research Center (GRC) manages the ISPT project for SMD and implements the program through task agreements with NASA centers, contracts with industry, and via grants with academic institutions. The ISPT project office currently resides in the Advanced Flight Projects Office of the Space Flight Systems Directorate at NASA GRC. Implementing NASA centers include Ames Research Center (ARC), Glenn Research Center, Goddard Space Flight Center (GSFC), Johnson Space Center (JSC), Langley Research Center (LaRC), Marshall Space Flight Center (MSFC) and the Jet Propulsion Laboratory (JPL). There are also numerous industry sources of ISPT products. In fact, it is an ISPT objective that all ISPT products be ultimately manufactured by industry and made equally available to all potential users for missions and proposals. This may prove difficult as NASA science missions do not necessarily occur with sufficient frequency to support the continuity of industrial sources.

The ISPT project manages the development efforts through six technology areas. These include Advanced Chemical, Aerocapture, Electric Propulsion, Emerging Technologies, Solar Sails, and Systems/Mission Analysis. According to the most recent NASA SMD roadmaps, particularly the Solar System Exploration Roadmap [1], the highest priority propulsion technologies are Electric Propulsion and Aerocapture. This, therefore, is reflected in ISPT priorities as well and in the number of tasks and the level of investment in these areas.

1.1 In-Space Propulsion Technology Investments

The In-Space Propulsion Technology Project is continuing to invest in propulsion technologies. The program's objective is to develop in-space propulsion technologies that can enable or benefit near and mid-term NASA space science missions by significantly reducing risk, cost, mass and travel times of NASA robotic science missions. SMD missions seek to answer important science questions about our planet, the Solar System and beyond. ISPT technologies will help deliver spacecraft to the destinations of interest. This paper provides a brief overview of the ISPT project

with development status, near-term mission benefits, applicability, and availability of in-space propulsion technologies in the areas of aerocapture, electric propulsion, and advanced chemical thrusters.

Selected under a competitive solicitation for a Flagship electric propulsion (EP) system, investments in EP technologies focused on completing NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system. It is a 0.6-7-kW throttle-able gridded ion system suitable for future Discovery, New Frontiers, and flagship missions. The ISPT project also continued the developments in other electric propulsion products such as the HiVHAC Hall thruster. This thruster specifically designed to be a low cost, highly reliable thruster ideally suited for cost-capped missions like NASA Discovery missions, the development of a lightweight reliable flow control module, and thruster life modeling activities.

Advanced chemical propulsion investments include the demonstration of active-mixture-ratio-control lightweight tank technology manufacturing and non-destructive evaluation techniques. The primary investment is in the development of the Advanced Material Bi-propellant Rocket (AMBR). The advanced chemical propulsion technologies has an opportunity for rapid-technology infusion with minimal risk and broad mission applicability.

Aerocapture investments resulted in better models for: 1) guidance, navigation, and control (GN&C) of blunt body rigid aeroshells, 2) atmosphere models for Earth, Titan, Mars and Venus, and 3) models for aerothermal effects. In addition to enhancing the technology readiness level (TRL) of rigid aeroshells, improvements were made in understanding and applying inflatable aerocapture concepts. Aerocapture technology was a contender for flight validation on NASA's New Millennium ST9 mission.

ISPT currently does not invest funds in solar sails and emerging propulsion technologies, but the technologies made considerable progress in prior years. The solar sail technology area completed a thorough ground development and test program for two sail and deployment concepts. A solar sail was also a candidate for a potential flight on NASA's ST9 New Millennium mission.

The systems analysis technology area performed numerous mission and system studies to guide technology investments and quantify the return on investment. Recent focus of the systems analysis area was on tools to assist technology infusion including the low-thrust trajectory tool (LTTT) suite and the aerocapture quicklook tool.

Due to funding constraints, ISPT project focus is on completing all four of its highest priority products to TRL 6 by the end of FY10. The ISPT project will complete the following four critical technology development tasks to support future SMD missions:

1) Complete NEXT ion propulsion system validation to TRL6 in FY08 and continue NEXT thruster life validation to achieve 450 kg xenon throughput by FY10. Maintain support through Phase A of next Discovery, and New Frontier AO cycles to ensure transition to flight.
2) Complete aerocapture technology ground validation required for Titan mission by the end of FY09.
3) Complete high temperature chemical rocket technology validation (Advanced Material Bi-propellant Rocket - AMBR) to TRL 6 by FY09.
4) Complete development of the HiVHAC Hall thruster to TRL 6 by the end of FY10.

1.2 Emphasis on Science Community Input

The ISPT project always emphasized technology development with mission pull. Initially, the project goal was to develop technologies for Flagship missions that led to the priorities of aerocapture and electric propulsion. These technologies are well suited for enabling significant science return for the outer planetary moons under investigation. The ISPT technologies were quantified to allow greater science return with reduced travel times.

Specifically, the Solar System Exploration Roadmap describes Transportation technologies as a highest priority (new developments are required for all or most roadmap missions). That "Aerocapture technologies could enable two proposed Flagship missions, and solar electric propulsion could be strongly enhancing for most missions. These technologies provide rapid access, or increased mass, to the outer Solar System."[1] The ISPT project products are tied closely to the science roadmaps, advanced planning and integration office (APIO) strategic roadmap, the SMD's science plan, and the decadal surveys. Excerpts from the science community are listed below. [1-4]

1.2.1 Electric Propulsion

Solar Electric Propulsion (SEP) enables missions requiring large in–space velocity changes over time, approaching and exceeding 10 km/sec. SEP has applications to rendezvous and sample return missions to small bodies and fast trajectories towards the outer planets. This is particularly relevant to the Titan Explorer mission and the Neptune–Triton Explorer mission.

This technology offers major performance gains, only moderate development risk, and has significant impact on the capabilities of new missions. Current plans include completion of the NASA Evolutionary Xenon Thruster (NEXT) 40-cm engine. Its target is New Frontier and small Flagship missions, under NASA's In–Space Propulsion Program, and development of a standard SEP subsystem architecture to provide lower cost systems for Discovery and New Frontiers class missions.

Other agencies are also using the technology for lunar and deep space missions. The European Space Agency's SMART–1 mission used SEP to travel to the Moon in September 2003. The Japanese spacecraft Hayabusa also used the technology in an attempt to acquire and return a soil sample from an asteroid in 2006.

SEP technology is now widely accepted for commercial space, with over 100 ion and Hall thrusters flying on communications satellites. Adaptation of commercial SEP technologies, such as the Boeing's Xenon Ion Propulsion System (XIPS) technology, may significantly lower the cost of these systems. This allows wider utilization on cost–capped Discovery/New Frontiers missions. Fully exploiting the low–thrust SEP technology requires new trajectory design methods to cope with continuous thrusting, rather than executing a few large thrust maneuvers at optimal points in the trajectory.

Significant improvements in the efficiency and performance of SEP are underway. The resulting systems may provide substantial benefits to this Roadmap's planned missions to small bodies and the inner planets. When coupled with aerocapture (rapid aerodynamic braking within a planetary atmosphere), SEP enables rapid and cost–effective delivery of orbital payloads to the outer Solar System. "*SEP technologies should be fully integrated with missions planning aerocapture*." [1]

1.2.2 Aerocapture

Aerocapture represents a major advance over aerobraking techniques. Aerocapture enables rapid access to orbital missions at the outer planets and is enabling for two of the potential flagship missions in this Roadmap — Titan Explorer and Neptune–Triton Explorer. For targets in the outer Solar System, aerocapture technology would enable a substantial reduction in the trip time. It allows a larger delivered payload mass, enabling these missions to be implemented with the current generation of heavy lift launch vehicles.

The Titan Explorer would be the first use of this technology in a Flagship mission. Because of the deep atmosphere, large–scale height, and modest entry velocities, Titan is an attractive target for the use of aerocapture. For a potential Neptune–Triton Explorer (NTE) mission, aerocapture enables transit from Earth to Neptune in less than ten years. Because of the much higher entry velocity and a narrow entry corridor, Neptune is a more challenging target for aerocapture than Titan is.

"Aerocapture technologies and flight validation are a high priority to solar system exploration."[1]

"Aerocapture is a key enabling technology for the outer solar system, particularly at Titan, and some gas giant planets"[3]

2. ELECTRIC PROPULSION TECHNOLOGIES

Electric propulsion is both an enabling and enhancing technology for reaching a wide range of targets. The high specific impulse, or efficiency of electric propulsion system, allows direct trajectories to multiple targets that are chemically infeasible. The technology allows for rendezvous missions in lieu of fly-bys, and as planned in Dawn can enable multi-destination missions.

Investments within ISPT on electric propulsion primarily focused on the development of NEXT. NEXT provides lower level funding on a low-cost and long-life Hall Effect thruster and a very light-weight, reliable, and highly compact propellant management system.

2.1 Development Status and Availability

The GRC-led NEXT project was competitively selected to develop a nominal 40-cm gridded ion electric propulsion system.[5] The objectives of this development were to improve upon the state-of-art NSTAR system flown on Deep Space-1 to enable flagship class missions by achieving:

- lower specific mass,
- higher I_{sp} (4050s),
- greater throughput (current estimates exceed 700 kg of xenon),
- greater power handling capability (6.9 kW), thrust (240 mN), and throttle range (12:1).

The ion propulsion system components developed under the NEXT task include the ion thruster, the power-processing unit (PPU), the feed system, and a gimbal mechanism.

The NEXT project is developing prototype-model (PM) fidelity thrusters through Aerojet Corporation. In addition to the technical goals, the project also has the goal of transitioning thruster-manufacturing capability with predictable yields to an industrial source. Recent accomplishments include a prototype-model NEXT thruster that passed qualification level environmental testing. Refer to Figure 1. As of May 1, 2008 the thruster achieved over 314-kg xenon throughput and 15,400 h of full power operation. The NEXT wear test demonstrated the largest total impulse ever achieved by a gridded ion thruster. It far exceeds the 75-kg throughput experienced by DS-1 mission and 235 kg of the NSTAR extended life test (ELT).

In addition to the thruster, the system also includes a power-processing unit (PPU). The PPU contains all the electronics to convert spacecraft power to the voltages and currents necessary to operate the thruster. Six different power supplies are required to start and run the thruster with voltages reaching 1800 V DC and total power processing at 7 kW. L3 Communications designed and fabricated the NEXT EM PPU. After completing acceptance tests, the PPU was incorporated into the single-string integrated test.

Environmental testing follows including EMI/EMC testing to characterize the capability and emissions of the unit.
A xenon feed system is also being developed. It is comprised of a single high-pressure assembly (HPA) with multiple low-pressure assemblies (LPA). The HPA regulates xenon flow from tank pressure to a controlled input pressure to the LPAs. Each LPA provides precise xenon flow control to the thruster main plenum, discharge cathode, or neutralizer cathode. The entire system is the propellant management system (PMS). PMS development is complete and the system passed all performance and environmental objectives. The system is single fault tolerant, 50 percent lighter than the SOA system, and can regulate xenon flow to the various components to better than three percent accuracy.

An engineering-model (EM) fidelity gimbal mechanism was also developed that can articulate the thruster approximately 18 degrees in pitch and yaw. The NEXT project successfully demonstrated performance of the EM gimbal. The gimbal sub-system incorporates a design that significantly improves specific mass over SOA. The gimbal was mated with the thruster, and was successfully vibration tested first with a mass simulator and then with the NEXT PM thruster.

The project also completed development of the DCIU simulator. This allows communication and control of all system components during testing. A flight DCIU is the interface between the ion propulsion system and the spacecraft. Life models, system level tests, such as a multi-thruster plume interaction test, and various other supporting tests and activities are also a part of recent NEXT system developments. JPL, Aerojet and L3 Communications provided major support for the project.

The integrated NEXT system will be tested in relevant space conditions as a complete string. This brings the system to a TRL level of 6 and makes it a candidate for all upcoming mission opportunities. The demonstration of life by test already demonstrated sufficient throughput for many science destinations of interest. The test plan is to continue into the coming years validating greater total impulse capability until achieving the targeted throughput of 450 kg. For additional information on the NEXT system, please see the NEXT Ion Propulsion System Information Summary in the New Frontiers program library.

ISPT also invested in the HiVHAC thruster.[7] HiVHAC is the first NASA electric propulsion thruster specifically designed as a low-cost electric propulsion option. It targets Discovery and New Frontiers missions and smaller mission classes. The HiVHAC thruster does not provide as high a maximum specific impulse as NEXT, but the higher thrust-to-power and lower power requirements are well suited for the demands of Discovery class missions. Significant advancements in the HiVHAC thruster include a very large throttle range allowing for very low power operation. It results in the potential for smaller solar arrays at significant cost savings, and a very long-life capability to allow for greater total impulse with fewer thrusters. Again, it allows for lower complexity systems with significant cost benefits.

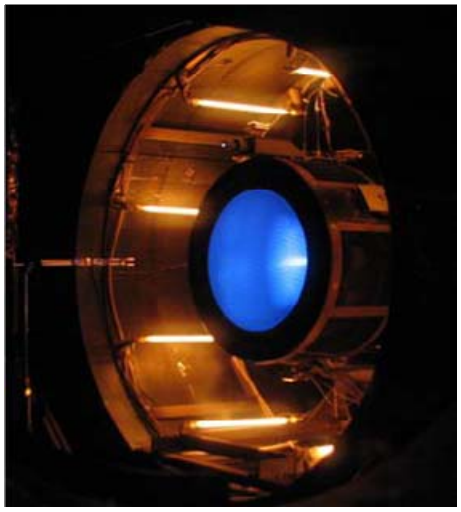


Figure 1. NEXT thermal vacuum testing at JPL.

A laboratory model HiVHAC thruster is currently in wear testing and successfully achieved over 4100 h and approximately 88 kg of xenon throughput as of December 1, 2007. After sufficiently validating the thruster life, an engineering model thruster is planned for manufacture and testing in FY08. Given sufficient funding, the system could reach TRL 6 by 2010, but current plans only include development of the thruster.

The ISPT office is also continuing its investment in a lightweight Advanced Xenon Feed System (AXFS) with increased reliability. VACCO Industries is developing the AXFS and delivered the Flow Control Module (FCM) in June of 2007. The FCM regulates the flow to the cathodes and main xenon flow. VACCO delivered two FCMs with one completing environmental testing to TRL 6. The continued effort is for the development of a Pressure Control Module (PCM) and system controller with plans to demonstrate them in an integrated hot-fire test. The integrated system is to have significantly increased reliability with both parallel and series redundancy against performance accuracy and mission loss. The integrated system should have both a mass and volume reduction of approximately 80 percent and 90 percent respectively over the NEXT feed system. The flow control module already met TRL 6 requirements and can be used in combination with a mechanical pressure regulator. Integrated system testing with the PCM is expected in of 2008. Variations of the PCM for use with closed loop control further reduces mass and cost of the flight unit feed system with potential control accuracies of <1 percent.

2.2 Mission Benefits

In the original solicitation NEXT was selected as an electric propulsion system for flagship missions. To that end, NEXT is the most capable electric propulsion system developed. A single NEXT thruster

- uses seven kilowatts of power,
- has an estimated propellant throughput capability of over 700 kg,
- has a lifetime of over 35,000 h of full power operation,
- has a total impulse capability of approximately 30 million N-s, or about three times that of the SOA DAWN thrusters.

This performance leads to significant benefits for a wide range of potential mission applications.

The NEXT thruster has clear mission advantages for very challenging missions. For example, the Dawn Discovery Mission only operates one NSTAR thruster at a time, but requires a second thruster for throughput capability. For the same mission, the NEXT thruster could deliver more mass, equivalent to doubling the science package, by performing the complete mission with only a single thruster. Reducing the number of thrusters significantly reduces propulsion system complexity and spacecraft integration challenges.

The missions that are most enabled through the use of the NEXT thruster are those requiring significant post-launch ΔV, such as sample returns, highly inclined, or deep-space body rendezvous missions. The comet sample return mission was studied for several destinations because of its high priority within the New Frontiers mission category. In many cases, chemical propulsion was considered infeasible due to launch vehicle limitations. Specifically for Temple 1 in references [8-9], the NSTAR thruster was able to complete the mission, but required very large solar arrays and four or five thrusters to delivery the required payload. NEXT was able to deliver 10 percent more total mass and required half the number of thrusters.

NEXT can not only deliver larger payloads, but can reduce trip times and significantly increase launch window flexibility. Chemical options exist for several missions of interest, however; the large payload requirements of flagship missions often require multiple gravity assists which both increases trip time and decreases the launch opportunities. In the recent Enceladus flagship mission study, the NEXT SEP option was able to deliver comparable payloads as the chemical alternative using a single Earth gravity assist. The chemical option for Enceladus required a Venus-Venus-Earth-Earth gravity-assist. This adds thermal requirements and increased the trip time by 57 months, from 7.5 to 12.25 years.

The ISPT project is also addressing the need for low-cost electric propulsion options. Studies [10] indicate that a low-power Hall thruster is not only cost enabling, but is performance enhancing as well. Initial studies compared the HiVHAC thruster to SOA systems for Near-Earth Object (NEO) sample returns, comet rendezvous, and the Dawn science mission. The HiVHAC thruster is expected to have both a greater throughput capability and a significantly lower recurring cost than the SOA NSTAR thruster.

For the NEO mission evaluated, the HiVHAC thruster system was able to deliver over 30 percent more mass than the NSTAR system. In addition, the performance increase accompanied a recurring cost savings of approximately 25 percent over the SOA NSTAR system. The Dawn mission was also evaluated, and the expected HIVHAC Hall thruster would be able to deliver approximately 14 percent more mass at a substantially lower cost than SOA, or the solar array can be decreased to provide equivalent performance at even greater mission cost savings.[10]

Overall, the ISPT portfolio of the NEXT system, HiVHAC thruster, and subsystem improvements offer electric propulsion solutions for scientific missions previously unattainable. The systems are compatible with spacecraft designs that can inherently provide power for additional science instruments and faster data transfer rates. Scientists can now open their options to highly inclined regions of space, sample return or multi-orbiter missions, or even deep-space rendezvous missions with significantly more science and reduced trip times.

3. CHEMICAL PROPULSION TECHNOLOGIES

The ISPT approach to the development of chemical propulsion technologies is evolutionary and synergistic with component development technologies. The component area of investment focuses on items that provide performance benefit with minimal risk to technology infusion. Current technology investments include the high temperature bi-propellant thruster, AMBR, and tasks to improve mixture ratio control, and reliable lightweight tanks.

3.1 Development Status and Availability

The primary investment within the advanced chemical propulsion technology area is the AMBR engine. The AMBR engine is a high temperature thruster addressing the cost and manufacturability challenges with iridium coated rhenium chambers. It expands the operating environment to higher temperatures with the goal of achieving a six-second increase in I_{sp} for NTO/N2H4 and ten seconds for NTO/MMH. This effort was awarded via a competitive process to Aerojet Corporation in FY2006. The current program includes manufacture and hot-fire tests of two engines demonstrating increased performance and validating new manufacturing techniques. For additional information on the AMBR engine, please see the AMBR Information Summary in the New Frontiers program library.

Mixture Ratio (MR) control is a concept to either reduce the residuals propellants carried or allow for additional extended mission operation otherwise lost due to an imbalance in the

oxidizer-to-fuel ratio experienced during operation. Small investments were made to characterize balance flow meters, validate MR control to maximize precision, and determine the potential benefits of MR control. A hot-fire test of the required system hardware is expected in the fall of 2008.

Small investments were also made to evaluate manufacturing and non-destructive evaluation (NDE) techniques for thin liner composite overwrap pressure vessels (COPV). The task involves evaluating liner bonding-and-welding techniques and the ability to detect manufacturing flaws in process. The product is intended to meet manufacturing recommendations and standards to minimize risk and increase yields for COPVs. The program works directly with members of NASA's COPV working group, who will implement the standard processes in future COPV efforts.

3.2 Mission Benefits

As stated previously, the mission benefits in the area of advanced chemical propulsion are synergistic, and the cumulative effects have tremendous potential. The infusion of the individual subsystems separately provides reduced risk, or combined provides considerable payload mass benefits.

The AMBR engine development [11] significantly benefits missions with large propulsion maneuvers through the reduction of wet mass. In addition, the expectation for the AMBR engine is to have a 30 percent reduction in cost with an increase in performance. The mission mass benefits are dependent on the mission-required ΔV, but are easily about the size of scientific instrument packages flown on previous missions. Figure 2 shows potential payload increases due to the increased specific power for multiple missions. For a mission like Cassini, having a higher thrust engine reducing complexity, reduces the number of thrusters. The system would also deliver additional mass, over 50 kg; which equates to a potential increase in scientific payload by 100 percent.

The use of MR control, studied extensively, stems from the propulsion system margin that must be carried due to MR

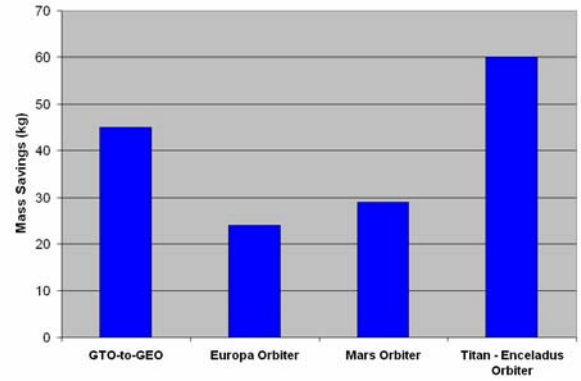


Figure 2. Mass benefits from the AMBR engine.

uncertainty. It is common for spacecraft with bi-propellant propulsion systems to reach end-of-life with residual oxidizer or fuel. Controlling the mixture ratio allows for either reduced residuals at launch, decreased mission risk by increasing propellant margin, or increase mission durations. Because the savings are directly proportional to the amount of propellant consumed, benefits are more significant on missions requiring large ΔV maneuvers. This is typically those missions already using bi-propellant systems.

The use of lightweight tanks has a direct savings by reducing the propulsion system dry mass. Mass benefits can be approximately 2.5 percent of the propellant mass, or net tank mass savings of 50 percent over SOA titanium tanks.

4. AEROCAPTURE TECHNOLOGIES

Aerocapture is the process of entering the atmosphere of a target body to reduce the chemical propulsion requirements of orbit capture. Aerocapture is similar to aerobraking, which relies on multiply passes higher in the atmosphere to reduce orbital energy. Aerocapture, illustrated in Figure 3, maximizes the benefit from the atmosphere by capturing in a single pass. Keys to successful aerocapture are lightweight thermal protection systems, accurate atmospheric models,

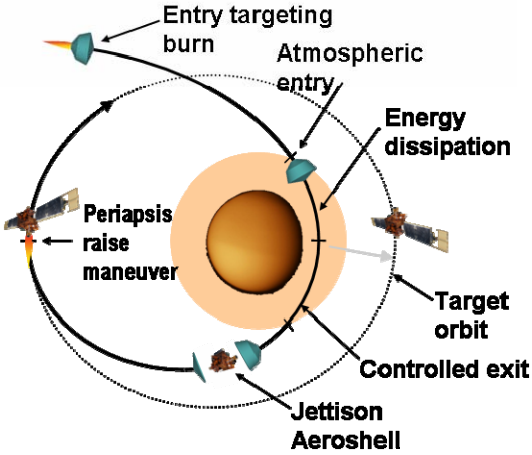


Figure 3. Illustration of the aerocapture maneuver.

and sufficient guidance during the maneuver.

Efforts in aerocapture related technologies include development of families of low and medium density (14-36 lbs/ft^3) thermal protection systems (TPS) and the related sensors, development of a carbon-carbon rib-stiffened rigid aeroshell, and higher temperature honeycomb structures and adhesives. Development also occurred at a low level on inflatable decelerators via concept definition and initial design and testing of several inflatable decelerator concepts. Finally, progress is being made through improvement of models for atmospheres, aerothermal effects, and algorithms and testing of a guidance, navigation and control (GN&C) system.

4.1 Development Status and Availability

The majority of investment in aerocapture technology occurred in furthering the TRL of the rigid aeroshell systems. A family of low-density TPS materials carrying the identifier "SRAM" was developed under a competitively awarded contract with Advanced Research Associates (ARA). These have a density range between 14 lb/ft^3 and 24 lb/ft^3 with the variable performance achieved by adjusting the ratios of constituent elements. These are applicable for heating rates up to 150 W/cm^2 and 500 W/cm^2 respectively. They could eventually be used on missions with destinations to small bodies such as Titan and Mars. The SRAM family of ablators was tested in both arcjet and solar tower facilities at the coupon level; 1 ft and 2 ft square flat panels, and recently on a 1 m blunt body aeroshell structure; shown in Figure 4. Another ARA family of low- to medium- density TPS systems (PhenCarb) is phenolic based, ranges in density between 20 and 32 lb/ft^3, and is applicable for heating rates between 200 and 1,100 W/cm^2.

In support of the rigid TPS system, ISPT funded testing of higher temperature adhesives and development of higher temperature structures effectively increasing the allowable bond-line temperature from 250˚C to 325˚ or 400˚C depending on the adhesive. Sensors that measure recession with accuracy of hundredths of millimeters were developed and currently planned for use on the Mars Science Laboratory (MSL) mission. Instrumenting entry systems to gather flight data is of primary importance to better understanding the environments and resulting vehicle requirements for future missions.

Figure 4. One meter ablative aeroshell with ARA's PhenCarb 20 TPS material.

Models that predict the entry thermal environments that will see the TPS system were developed and enhanced. In some cases, previous heating estimates were overly conservative because of the lack of resources available to produce validation data or to develop more complicated analysis methods. Coupled models updated with the most current Cassini data reveal, for example, that aerocapture at Titan will load the TPS system at less than 20 W/cm^2 verses prior predictions of 150-200 W/cm^2. Through multiple years of concentrated effort, researchers funded by ISPT made modeling improvements that will benefit all future entry missions. ISPT also updated the atmospheric models for all primary aerocapture destinations except Earth.

ISPT developed a rigorous plan as part of the ST9 New Millennium Proposal to take the ablative aerocapture system to a TRL 6 by FY09. Though the ST9 flight opportunity was cancelled, ISPT will still follow the ground development program thereby preparing the technology for a flight demo or first mission infusion. A 2.65-m diameter high-temperature aeroshell, with ARA's SRAM TPS, is being built as a manufacturing demonstration, to be completed by early 2010.

Another advancement, enabled by ISPT funding, is the development of a Carbon-Carbon aeroshell that was rib stiffened, reducing the need for an additional structure system. This, coupled with low-density insulation on the aft side of the shell, results in a 30 percent mass density improvement over the same size Genesis-like aeroshell. This product was mechanically tested to levels that are representative of expected environments. In fact, all testing was completed to the levels of system testing that were historically required of these types of systems before flight. This effort was competitively awarded and completed in early 2007 by Lockheed Martin.

Inflatable decelerator concepts promise an additional mass savings even beyond what is expected from rigid aeroshell systems. This prompted ISPT to consider several competing concepts and begin understanding and addressing the technical challenges with these types of systems. Ball Aerospace-led and Lockheed Martin-led teams developed first order fluid-structure models to begin understanding the requirements for thin film materials and adhesives. Preliminary testing was conducted in concept preparation for trailing toroidal, clamped afterbody, and inflatable forebody decelerators. Many of the team members funded by ISPT are continuing their inflatable decelerator efforts under NASA's Aeronautics Research Mission Directorate (ARMD).

Future plans are to complete the ground development of the ablative aeroshell system. This includes continuing to improve aerothermal models, atmospheric models and real-time testing a GN&C algorithm with flight software and hardware in the loop. Completion of the GN&C work is expected to be in FY09.

Additional information on ISPT developments in this technology area is in references [11-16].

4.2 Mission Benefits

The use of aerocapture was studied extensively, most notably for use at Titan, Neptune, Venus and Mars. Figure 5 shows the anticipated increases in delivered mass. The largest mass benefit from aerocapture was observed for Neptune, low Jupiter orbits, followed by Titan, Uranus, Venus, and then only marginal gains for Mars (the mass

benefit is directly correlated to the amount of velocity change required for each mission). Detailed mission assessment results are in references [17-19].

Even though the mission mass benefits to Mars are only expected to be about 5-15 percent, these benefits can be enabling. A multi-center team from ARC, JPL, JSC, LaRC, and MSFC conducted detailed mission and cost analyses for various Mars opportunities. An opposition-class sample return mission can be enabled in less than two years using aerocapture. Aerocapture is significantly enhancing for conjunction-class sample-return missions, and in general for large Mars orbiters. In addition, no new technology gaps were identified that would delay aerocapture implementation on such a mission.

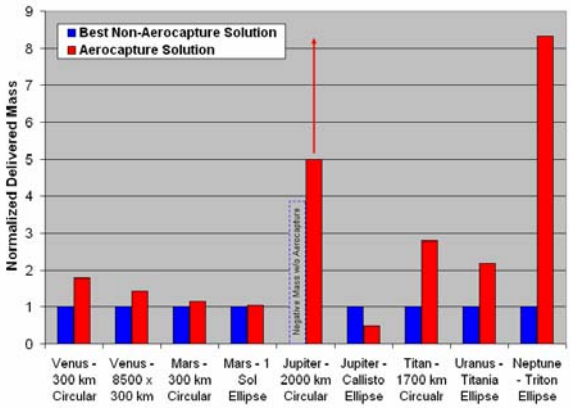


Figure 5. Aeropcapture benefits for various targets.

Venus was studied extensively to identify any needs for TPS, guidance, atmospheric or heating models. Detailed analyses also evaluated the potential for aerocapture for a Venus Discovery class mission. Aerocapture was shown to deliver more than 80 percent additional mass over aerobraking and more than 600 percent from a chemical insertion. Aerocapture also offers a reduction of 121 days of Deep Space Network (DSN) time. No critical technology gaps were identified for aerocapture at Venus.

Destination / Subsystem	Venus	Earth	Mars	Titan	Neptune
Atmosphere	✓	✓	✓	✓	✓
Aerodynamics	✓	✓	✓	✓	
GN&C	✓	✓	✓	✓	✓
TPS			✓	✓	
Structures	✓	✓	✓	✓	
Aerothermal	✓	✓	✓	✓	
System	✓	✓	✓	✓	✓

Ready for Infusion | Some Investment Needed | Significant Investment Needed

Figure 6. Aerocapture readiness for various targets.

Titan was of considerable scientific interest following the success of Cassini/Huygens. Because of its atmospheric conditions, it is an ideal candidate for aerocapture. The recent flagship study did consider aerocapture within the baseline mission concept since aerocapture has the capability to delivery more than double the mass of the chemical alternative. If selected, an aerocapture flight demo was identified as part of the mission technology development program.

Aerocapture was found repeatedly to be an enabling technology for several atmospheric targets of interest. The ISPT project continues to develop aerocapture technologies in preparation for a flight demonstration. Rapid aerocapture analysis tools are being developed and made available. The TPS materials developed through ISPT also enhance a wide range of missions by reducing the mass of entry vehicles. Figure 6 illustrates the remaining gaps required for technology infusion. The technology is currently at or funded to reach TRL 6 in the next two years for multiple targets of interest.

5. SYSTEMS ANALYSIS

Systems analysis is used during all phases of any propulsion hardware development. The systems analysis area serves two primary functions:

1. to help define the requirements for new technology development and the figures of merit to prioritize the return on investment,
2. to develop new tools to easily and accurately determine the mission benefits of new propulsion technologies allowing a more rapid infusion of the propulsion products.

Systems analysis is critical prior to investing in technology development. In today's environment, advanced technology must maintain its relevance through mission pull. Current systems analysis tasks include Radioisotope Electric Propulsion (REP) system requirements, lifetime qualification of gridded-ion and Hall thrusters, active mixture ratio control, and the evaluation of commercial electric propulsion systems for possible application to science mission needs.

The second focus of the systems analysis project area is the development and maintenance of tools for the mission and systems analyses. Improved and updated tools are critical to clearly understand and quantify mission and system level impacts of advanced propulsion technologies. Having a common set of tools also increases confidence in the benefit of ISPT products both for mission planners as well as for potential proposal reviewers. Significant tool development efforts were completed on the Low-Thrust Trajectory Tool (LTTT), the Advanced Chemical Propulsion System (ACPS) tool.

Low-thrust trajectory analyses are critical to the infusion of new electric propulsion technology. Low-thrust trajectory analysis is typically more complex than chemical propulsion solutions. It requires significant expertise to evaluate mission performance. Some of the heritage tools have proven to be extremely valuable, but cannot perform direct optimization and require good initial guesses by the users.

This can lead to solutions difficult to verify quickly and independently.

The ability to calculate the performance benefit of complex electric propulsion missions is also intrinsic to the determination of propulsion system requirements. To that end, the ISPT office invested in multiple low-thrust trajectory tools that can independently verify low thrust trajectories at various degrees of fidelity.

The ISPT low-thrust trajectory tools suite includes Mystic, the Mission Analysis Low Thrust Optimization (MALTO) program, Copernicus, and Simulated N-body Analysis Program (SNAP). SNAP is a high fidelity propagator. MALTO is a medium fidelity tool for trajectory analysis and mission design. Copernicus is suitable for both low and high fidelity analyses as a generalized spacecraft trajectory design and optimization program. Mystic is a high fidelity tool capable of N-body analysis and is the primary tool used for trajectory design, analysis, and operations of the Dawn mission. While some of the tools are export controlled, the ISPT website does offer publicly available tools and includes instructions to request tools with limited distribution. The ISPT project is planning a series of courses for training on the ISPT project tools.

The ability for the user community to assess rapidly and accurately the mission level impacts of ISPT products can ease technology infusion. In addition to the tools currently available, there are on-going activities to develop an Aerocapture Quicklook tool, an Integrated Aero-assist tool, and an effort to establish a standard for electric-propulsion thruster lifetime qualification; including lifetime modeling tools. Every effort will be made to have these tools validated, verified, and made publicly available.

Flagship missions are often advised on technologies to include for mission planning, but there is also considerable benefit to competed missions from the use of ISPT technologies. Some options to the New Frontiers targets of the ISPT products ready for infusion with the present AO are shown in Table 1.

6. FUTURE PLANS

Known future missions of interest for NASA and the science community continues to demand propulsion systems with increasing performance and lower cost. Aerocapture and electric propulsion are frequently identified as enabling or enhancing technologies. ISPT will continue to invest in these areas to complete current developments to TRL 6 in the next 1-3 years. ISPT will also continue to look for ways to reduce system level costs and enhance the infusion process.

The cost of life testing of electric propulsion thrusters is one area where the savings are expected to be significant. Standardizing on common components or sub systems and utilizing modular stages for multiple missions may be a way to reduce propulsion system costs.

Performance enhancements tasks are anticipated in the area of electric propulsion through design and material improvements to achieve longer thruster life. Costs are being addressed right from the design process, in the case of the Hall thruster, and also through modular design approaches and shared hardware for NEXT and other electric propulsion systems.

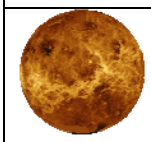
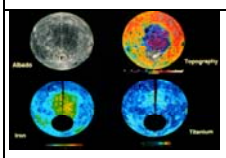
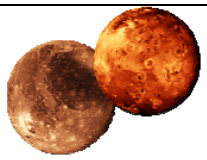
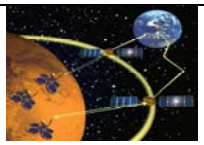
In the aerocapture area, the development plan for the rigid technologies follows a highly regarded development plan as proposed to the ST9 mission. In the chemical and component area, development is anticipated in materials and engine designs that continue to improve performance and significantly reduce costs through advanced manufacturing techniques.

Future propulsion needs may include an electric propulsion system that would be powered by a radioisotope-powered generator. Current EP systems are designed for widely varying input power levels to account for the spacecraft's motion around the solar system. If the vehicle does not need to rely on solar power, then the propulsion system could be simpler and lighter. The system can also be optimized around a known constant input power. Another future focus area may be propulsion systems for sample return missions. These missions inherently are propulsion intensive. Several of the ISPT technology areas may be involved in a single sample return mission. The mission may use EP for transfer to, and possibly back from, the destination. Chemical propulsion would be utilized for the ascent and descent to the surface. Aeroshells would be used for earth re-entry and an aerocapture maneuver may be used to capture at the destination.

7. CONCLUSIONS

The ISPT project has been developing propulsion technologies for NASA missions. Several of the technologies are at or nearing TRL 6 and are available for infusion into near-term science missions. Among these is the NEXT electric propulsion system, and it is eligible for all future mission opportunities. ISPT is also expecting to reach TRL 6 in the development of the high temperature bi-propellant chemical thruster in the first quarter of FY09. Finally, an aerocapture system comprised of a blunt body TPS system, the GN&C, sensors and the supporting models is also expected to achieve its technology readiness in the very near term. Regardless, if the mission requires electric propulsion, aerocapture, or a conventional chemical system, ISPT technology has the potential to provide significant mission benefits including reduced cost, risk, and trip times, while increasing the overall science capability and mission performance.

Table 1: Options for ISPT Technologies for Recommended New Frontiers Missions.

	NEXT Benefits	AMBR Benefits
 CSSR	• Small body rendezvous and sample return missions have significant ΔV requirements. Chemical propulsion has many limitations alleviated by electric propulsion: • Electric propulsion improves: • Total Spacecraft Mass • Propellant Mass Fraction • Launch, mission flexibility • Enables additional targets • *High degree of applicability for CSSR*	• Small body rendezvous and sample return missions have significant ΔV requirements. If a chemically feasible target is chosen, the improved ISP would have clear benefits with little added risk. • AMBR improves: • Propellant Mass Fraction • Spacecraft margin/risk • *High degree of applicability for a chemical CSSR*
 **VISE**	• NEXT could perform significant drag makeup for lower altitude or potentially tethered sensor operation. • Returning atmospheric samples to Earth could be enabled by electric propulsion. NEXT can best use the available solar power. • *Limited VISE Applicability*	• A Venus In-Situ Explorer will likely benefit from direct entry and therefore not require any significant deep space maneuvers. • An orbiter mission would benefit from AMBR's improved performance. • *Limited VISE Applicability*
 **ABSR**	• Similar to SMART, NEXT could enable a low-thrust transfer from LEO to LLO enabling considerable launch vehicle savings. • Studies have also illustrated the advantages of landing and leveraging SEP power for Aitken Basin exploration. • *Limited ABSR Applicability*	• Dependant on mission architecture and lander and ascent stage mass, AMBR may have appropriate thrust and throttle-ability. • A bipropellant engine may add unnecessary complexity to ABSR. • *Limited ABSR Applicability*
 Asteroid SR	• Small body rendezvous and sample return missions have significant ΔV requirements. Chemical propulsion has many limitations alleviated by electric propulsion: • Electric propulsion improves: • Total Spacecraft Mass • Propellant Mass Fraction • Launch, mission flexibility • Enables additional targets • *High degree of applicability for Asteroid SR*	• Asteroid SR chemical mission are extremely target dependent. Some asteroids are easier to reach than the moon, while many are chemically infeasible. • For targets applicable to chemical bi-propellant engines, AMBR would be appropriate. • *High degree of applicability for a subset of ASR*
 **Ganymede or Io Observer**	• Orbiter missions to Ganymede and Io are propulsive challenges that could benefit from electric propulsion. The required gravity assists to allow the mission chemically may exceed New Frontiers mission operations cost limitation. • Limited published analyses on Ganymede and Io Mission architectures. Analysis needed. • *Applicable for Observers*	• Orbiter missions to Ganymede and Io are propulsive challenges that could benefit from engine performance. Any chemical solution would clearly benefit from a bi-propellant AMBR class engine. • Limited published analyses on Ganymede and Io Mission architectures. Analysis needed. • *Applicable for Observers*
 Trojan/ Centaur	• The use of NEXT for a Trojan and Centaur flyby would only allow for added velocity prior to the steep power decline as the vehicle travels further from the sun. • If the mission were attempted with nuclear power, Radioisotope EP would be appropriate. • *Limited applicability*	• Trojan and Centaur chemical flyby missions obtain their necessary velocities by the launch vehicle and not require significant deep space maneuvers. • *AMBR is not applicable for flyby mission.*
 **Network Science**	• The applicability of NEXT for Mars Network Science is largely dependent on the deployment and implementation architecture. NEXT has potential for large plane planet-centric maneuvers chemically challenging. Direct entry likely sufficient. • *Very limited applicability*	• If mass and controlled descent requirements are appropriate, AMBR may have limited applicability. • Limited published analyses on network architecture. • *Not applicable*

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