Status and Mission Applicability of NASA's In-Space Propulsion Technology Project

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The In-Space Propulsion Technology (ISPT) project develops propulsion technologies that will enable or enhance NASA robotic science missions. Since 2001, the ISPT project developed and delivered products to assist technology infusion and quantify mission applicability and benefits through mission analysis and tools. These 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. This paper provides status of the technology development, near-term mission benefits, applicability, and availability of in-space propulsion technologies in the areas of advanced chemical thrusters, electric propulsion, aerocapture, and systems analysis tools. The current chemical propulsion investment is on the high-temperature Advanced Material Bipropellant Rocket (AMBR) engine providing higher performance for lower cost. 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, and the High Voltage Hall Accelerator (HiVHAC) thruster, which is a mid-term product specifically designed for a low-cost electric propulsion option. Aerocapture investments developed a family of thermal protections system materials and structures; guidance, navigation, and control models of blunt-body rigid aeroshells; atmospheric models for Earth, Titan, Mars and Venus; and models for aerothermal effects. In 2009 ISPT started the development of propulsion technologies that would enable future sample return missions. The paper describes the ISPT project's future focus on propulsion for sample return missions. The future technology development areas for ISPT is: Planetary Ascent Vehicles (PAV), with a Mars Ascent Vehicle (MAV) being the initial development focus; multi-mission technologies for Earth Entry Vehicles (MMEEV) needed for sample return missions from many different destinations; propulsion for Earth Return Vehicles (ERV), transfer stages to the destination, and Electric Propulsion for sample return and low cost missions; and Systems/Mission Analysis focused on sample return propulsion. The ISPT project is funded by NASA's Science Mission Directorate (SMD).

Nomenclature

ACPS = Advanced Chemical Propulsion System
AMBR = Advanced Materials Bipropellant Rocket
AXFS = Advanced Xenon Feed System

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BFM = Balanced Flow Meter
CONOPS = Concept of Operations
COPV = Composite Overwrap Pressure Vessel
CSSR = Comet Surface Sample Return
DCIU = Digital Control Interface Unit
DS-1 = Deep Space 1 spacecraft/mission
DSN = Deep Space Network
EDL = Entry, Descend, and Landing
EEV = Earth Entry Vehicle
EM = Engineering Model
El-Form = Electro-Form process
ELT = Extended Life Test
EMC = Electromagnetic Compatibility
EMI = Electromagnetic Interference
ERV = Earth Return Vehicle
FCM = Flow Control Module
GN&C = Guidance, Navigation and Control
GRC = Glenn Research Center
GSFC = Goddard Space Flight Center
HiPAT = High Performance Apogee Thruster
HiVHAC = High Voltage Hall Accelerator
HPA = High Pressure Assemblies
IPDT = Integrated Product Development Team
Ir/Re = Iridium coated rhenium material system for the combustion chamber
Isp = Specific impulse, second(s)
ISPT = In-Space Propulsion Technology project or office
JPL = Jet Propulsion Laboratory
JSC = Johnson Space Center
LaRC = Langley Research Center
LPA = Low-Pressure Assemblies
LTTT = Low-Thrust Trajectory Tool
MALTO = Mission Analysis Low Thrust Optimization
MAV = Mars Ascent Vehicle
MEP = Mars Exploration Program
MMEEV = Multi-Mission Earth Entry Vehicle
MSFC = Marshall Space Flight Center
MSR = Mars Sample Return
MR = Mixture Ratio
MRC = Mixture Ratio Control
MSL = Mars Science Laboratory
MTP = Mars Technology Program
N_2H_4 = Hydrazine—the fuel of the bipropellant
NASA = National Aeronautics and Space Administration
NEXT = NASA Evolutionary Xenon Thruster
NRA = NASA Research Announcement
NSTAR = NASA Solar Electric Propulsion Technology Readiness
NTO = Nitrogen Tetroxide—the oxidizer of the bipropellant
OPF = Outer Planets Flagship
OS = Orbiting Sample
PAV = Planetary Ascent Vehicles
PCM = Pressure Control Module
PDR = Preliminary Design Review
PM = Prototype Model
PMS = Propellant Management System
PPU = Power-Processing Unit
PSD = Planetary Science Division
ROSES = Research Opportunities in Space and Earth Science
REP = Radioisotope Electric Propulsion
RFI = Request For Information

SDT = Science Definition Team
SEP = Solar Electric Propulsion
SMD = Science Mission Directorate at NASA Headquarters
SMART-1 = SMART-1 spacecraft
SOA = State of the Art
SSE = Solar System Exploration
SNAP = Simulated N-body Analysis Program
TPS = Thermal Protection Systems
TRL = Technology Readiness Level
ΔV = Velocity increment for propulsion system or spacecraft

I. Introduction

THE ISPT project has developed in-space propulsion technologies since 2001 that can enable and/or benefit near and mid-term NASA science missions by significantly reducing cost, mass, and/or travel times. NASA Science Mission Directorate (SMD) missions seek to answer important science questions about our planet, the Solar System and beyond. The primary ISPT customer and the customer which determines ISPT investment priorities is SMD and in particular the Planetary Science Division within SMD. ISPT technologies will help deliver spacecraft to SMD's destinations of interest. However, any NASA, other US government, or commercial entity that needs in-space propulsion technology is also considered a potential ISPT customer.

The objective of the ISPT project is the development of new enabling propulsion technologies that cannot be reasonably achieved within the cost or schedule constraints of mission development timelines, specifically the requirement of achieving technology readiness level (TRL) 6 prior to preliminary design review (PDR). ISPT is NASA's only technology program that develops primary in-space propulsion technologies. Since the ISPT objective is to develop products that realize near-term and mid-term benefits, ISPT primarily focuses on technologies in the mid TRL range (TRL 3–6+ range) that 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. 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, advanced chemical thrusters, planetary ascent vehicles, Earth return vehicles, other advanced propulsion technologies, and mission/systems analysis tools.

The ISPT Project Office is located at the NASA Glenn Research Center (GRC) since late 2006 and manages the ISPT project for SMD. The program is implemented through task agreements with NASA centers, contracts with industry, and via grants with academic institutions. Implementing NASA centers include Ames Research Center (ARC), Glenn Research Center, Goddard Space Flight Center (GSFC), Langley Research Center (LaRC), Marshall Space Flight Center (MSFC) and the Jet Propulsion Laboratory (JPL). There are also numerous industry partners in the development of the ISPT products. It is one of ISPT's objectives that all ISPT products be ultimately manufactured by industry and made equally available to all potential users for missions and proposals. This may prove challenging as NASA science missions do not necessarily occur with sufficient frequency to support the continuity of industrial sources.

A. 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 2006 Solar System Exploration Roadmap identifies technology development needs for Solar System exploration, and describes transportation technologies as a highest priority (new developments are required for all or most roadmap missions). "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, and excerpts from the science community are discussed in more detail in Ref. 2.

II. Summary of Technology Development Areas

The ISPT project is currently managing the development efforts in four legacy technology areas. These include Advanced Chemical, Aerocapture, Electric Propulsion, and Systems/Mission Analysis. According to the most recent NASA SMD roadmaps, particularly the Solar System Exploration (SSE) Roadmap,[1] the highest priority propulsion technologies are Electric Propulsion and Aerocapture. Therefore, the ISPT priorities are reflected in the number of tasks and the level of investment in these areas.

Investments in electric propulsion (EP) technologies are currently focusing on completing NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, which was selected under a competitive solicitation for an EP system applicable to a

Flagship mission. NEXT 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 EP propulsion products such as the HiVHAC Hall thruster. The HiVHAC thruster is specifically designed to be a low cost, highly reliable thruster ideally suited for cost-capped missions like NASA Discovery missions. In addition, ISPT is pursuing the development of a lightweight reliable xenon flow control system as well as standardized EP component designs.

The primary investment in advanced chemical propulsion is in the development of the Advanced Material Bi-propellant Rocket (AMBR) engine. Advanced chemical propulsion investments include the demonstration of active-mixture-ratio-control and lightweight tank technology. The advanced chemical propulsion technologies have 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.

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.

As a result of funding constraints that arose in the spring of 2007, the ISPT project is focusing its legacy work on completing four of its highest priority products to TRL 6 by the end of fiscal year (FY) 2010. 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 TRL 6 in CY09 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 Announcement of Opportunity (AO) cycles to ensure transition to flight.
2) Complete aerocapture technology ground validation required for Titan mission by the end of CY09.
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.

In 2009 ISPT was tasked to start development of propulsion technologies that would enable future sample return missions. The future technology development areas for ISPT will be Planetary Ascent Vehicles (PAV) with a Mars Ascent Vehicle (MAV) being the initial development, multi-mission technologies for Earth Entry Vehicles (MMEEV), Electric Propulsion for sample return and low cost missions, propulsion for Earth Return Vehicles (ERV) including transfer stages to the destination, advanced propulsion technologies for sample return, and Systems/Mission Analysis focused on sample return propulsion. The work on the HiVHAC thruster will transition into developing a HiVHAC system under future Electric Propulsion for sample return (ERV and transfer stages) and low cost missions. The work on the lightweight tanks will transition into the future work under advanced propulsion technologies for sample return with direct applicability to a Mars Sample Return (MSR) mission and with general applicability to all future planetary spacecraft. The Aerocapture efforts will be merged with previous work related to Earth Entry Vehicles and will transition into the future multi-mission technologies for Earth Entry Vehicles (MMEEV). The Planetary Ascent Vehicles (PAV)/ Mars Ascent Vehicle (MAV) is a new development area to ISPT but will build upon and leverage the past MAV analysis and technology developments from the Mars Technology Program (MTP) and previous MSR studies.

III. Chemical Propulsion Technologies

The ISPT approach to the development of chemical propulsion technologies is evolutionary component 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 (Fig. 1), and tasks to improve mixture ratio control, and reliable lightweight tanks.

A. Development Status and Availability

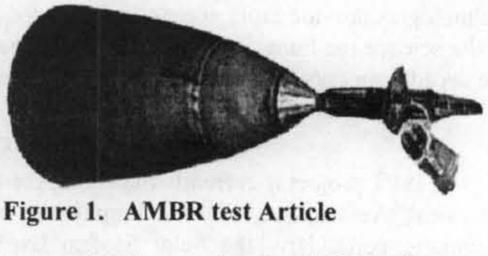


Figure 1. AMBR test Article

The primary investment within the advanced chemical propulsion technology area is the Advanced Materials Bipropellent Rocket (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 seven-second increase in I_{sp} for NTO/N2H4. This effort was awarded via a competitive process to Aerojet Corporation in FY2006. The current program includes manufacture and hot-fire tests of prototype engine(s) demonstrating increased performance and validating new manufacturing techniques. Additional information can be found in the AMBR information summary in the New Frontiers program library.[3,4]

B. AMBR Initial Performance Testing

The AMBR engine completed its performance testing in October 2008 (Fig. 2) and February 2009, and its long duration testing in June 2009. The results show an Isp of 333 seconds—the highest ever achieved for hydrazine/NTO propellant combination. This result represents a five second I_{sp} gain over the HiPAT engine, at a thrust of 140 lbf, mixture ratio of 1.1, chamber pressure of 195 psia, and oxidizer inlet pressure of 2505 psia. While these numbers differ from the original goal of 335 seconds I_{sp}, 200 lbf thrust, mixture ratio of 1.2, and an inlet pressure of 400 psia, the single-iteration results are very encouraging. They show that the engine, as currently operating, can benefit many space applications. Typically, planetary and commercial spacecraft operate at pressures more comparable to the lower 250 psia propellant inlet pressure obtained in the test.

Further, to prepare for potential immediate flight infusion, AMBR completed environmental tests that include vibration, shock, and life-firing tests. Finally, although desirable, the logical next step is not currently funded to improve the combustion chamber film cooling in order to operate closer to its original performance target.

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. Two hot-fire tests of the required system hardware (the Balanced Flow Meters) were held during the AMBR testing and results are being compiled at of July 2009.

Figure 2. AMBR hot fire performance test

Small investments were made to evaluate manufacturing techniques for thin liner composite overwrap pressure vessels (COPV). The task involves evaluating liner bonding and welding techniques. 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.

C. Mission Benefits

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[5] 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 cost reduction in the combustion chamber manufacturing 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. Fig. 3 shows potential payload increases due to the increased specific power for multiple missions. Note that these results were based on the initial AMBR target performance targets of 335 seconds Isp and 200 lbf thrust. Nevertheless, continued to use the target performance data and corresponding benefit analysis, one can use Fig. 3 to approximate the mass benefit. 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.

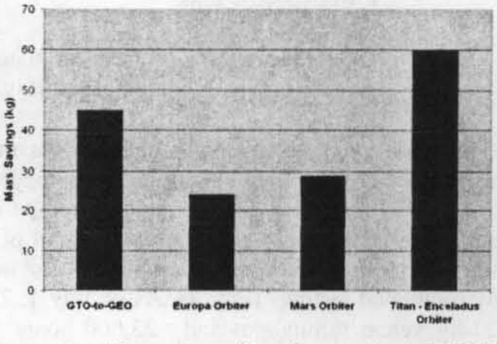


Figure 3. Mass benefits from the AMBR engine

The need for mixture ratio control (MRC) stems from the propulsion system margin that must be carried due to MR 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 increased mission duration. 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 state-of-the-art titanium tanks.

IV. Electric Propulsion Technologies

Solar Electric Propulsion (SEP) enables missions requiring large in-space velocity changes over time. 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 Saturn-Titan-Enceladus and the Neptune-Triton missions. In particular the Titan-Saturn System mission demonstrated that improvements to mass, trip-time, and launch flexibility provided by SEP resulted in significant benefits to the 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's Evolutionary Xenon Thruster (NEXT) Ion Propulsion System target at Flagship, New Frontiers and demanding Discovery missions under NASA's In-Space Propulsion Technology Program and development of a High-Voltage Hall Accelerator (HIVHAC) Hall Propulsion System to provide lower cost systems for cost-constrained Discovery and New Frontiers class missions. Leveraging and adaption of commercial SEP component technologies is helping to lower development and implementation costs for these systems.

Major science missions are demonstrating the growing acceptance of SEP for interplanetary transportation, including missions such as Dawn, SMART-1, and Hayabusa. Fully exploiting the low-thrust SEP technology requires trajectory design methods to cope with continuous thrusting rather than executing a few large thruster 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. The SSE Roadmap recommends "SEP technologies should be fully integrated with missions planning aerocapture."[1]

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 the Dawn mission can enable multiple destinations.

Investments within ISPT on electric propulsion primarily focused on the development of NEXT. ISPT 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.

A. Development Status and Availability

The GRC-led NEXT project was competitively selected to develop a nominal 40-cm gridded ion electric propulsion system.[6,7] The objectives of this development were to improve upon the state-of-art NASA Solar Electric Propulsion Technology Readiness (NSTAR) system flown on Deep Space-1 to enable flagship class missions by achieving:

- lower specific mass
- higher I_{sp} (4050 s)
- 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.

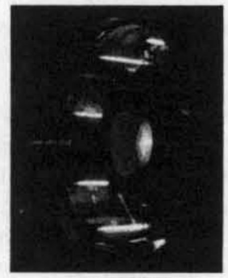


Figure 4. NEXT thermal vacuum testing at JPL.

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 (Fig. 4). As of July 1, 2009 the thruster achieved over 424-kg xenon throughput and >23,000 hours at multiple throttle conditions. 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 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 (Fig. 5). Six different power supplies are required to start and run the thruster with voltages reaching 1800 VDC and total power processing at 7 kW. L3 Communications designed and fabricated the NEXT Engineering Model (EM) PPU. After completing acceptance tests, the PPU was incorporated into the single-string integrated test. Environmental testing will follow including electromagnetic interference/electromagnetic compatibility (EMI/EMC) testing to characterize

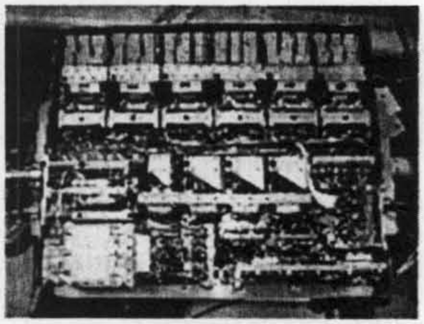


Figure 5. NEXT Engineering Model PPU

the capability and emissions of the unit.

A xenon feed system is being developed (Fig. 6). 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 constitutes 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.

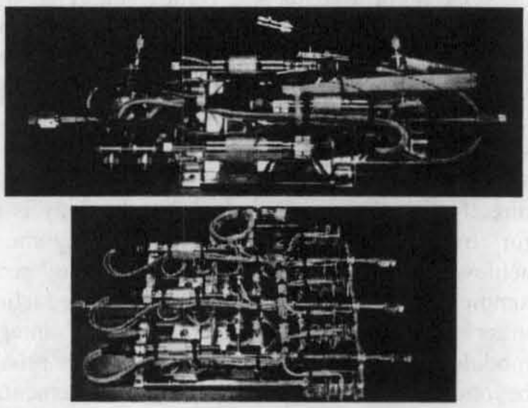


Figure 6. NEXT Xenon Feed system High and Low Pressure Assemblies

An engineering-model (EM) fidelity gimbal mechanism was developed that can articulate the thruster approximately 18 degrees in pitch and yaw (Fig. 7). The NEXT project team successfully demonstrated performance of the EM gimbal. The gimbal subsystem incorporates a design that 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 team completed development of the digital control interface unit (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 part of recent NEXT system developments. JPL, Aerojet and L3 Communications are providing major support for the project.

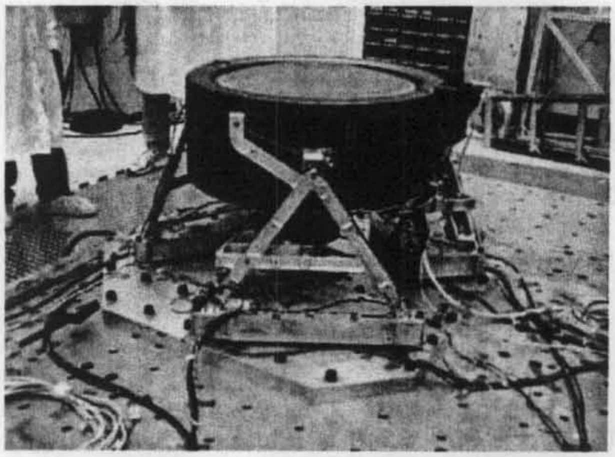


Figure 7. NEXT Thruster and Gimbal Mechanism

The integrated NEXT system was tested in relevant space conditions as a complete string. With the exception of the PPU environmental tests, this brings the system to a TRL level of 6 and makes it a candidate for all upcoming mission opportunities. The life test 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. Additional information on the NEXT system can be found in the NEXT Ion Propulsion System Information Summary in the New Frontiers program library.[3,8]

ISPT invested in the HiVHAC thruster.[9] 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 suited for the demands of Discovery class missions. Advancements in the HiVHAC thruster include a large throttle range allowing for a low power operation. It results in the potential for smaller solar arrays at cost savings, and a long-life capability to allow for greater total impulse with fewer thrusters. Again, it allows for cost benefits with less complex systems.

A laboratory model HiVHAC thruster is in wear testing (Fig. 8) and successfully achieved over 4750 h and over 100 kg of xenon throughput prior to being deliberately ended with remaining resources being devoted to the EM design. An engineering model thruster was designed and fabricated. Thruster assembly was initiated in July 2009 with hardware delivery for testing anticipated in August 2009. The test sequence will include performance acceptance tests, environmental tests and a long duration test in FY09/10. Given sufficient funding, the system could reach TRL 6 by 2010. Current plans include the design, fabrication and assembly of a full Hall propulsion system, but are pending final approval to proceed.

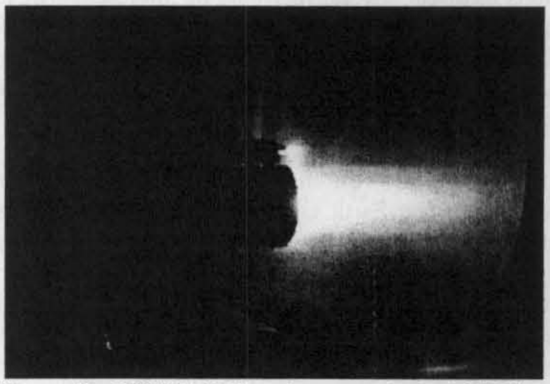


Figure 8. HiVHAC thruster wear test at GRC

NASA's In-Space Propulsion Technology project is investing in the Advanced Xenon Feed System (AXFS) for electric propulsion systems. The feed system is designed for an increased reliability with decrease in system mass, volume, and cost of SOA flight systems and comparable TRL 6 technology. The final development module, the pressure control module (PCM), was completed in 2007. The NRL completed functional and environmental testing of the VACCO PCM in September of 2008. Following the environmental testing, the PCM was integrated with the FCMs and an integrated AXFS with controller was delivered to the project. NASA GRC completed hot-fire testing of the AXFS (Fig. 9) with the HiVHAC Hall thruster successfully demonstrating hot-fire operation using closed-loop control with downstream pressure feedback and with the Hall thruster discharge current. Follow-on testing determines the viability of the AXFS to perform single-stage, single module, control from high pressure xenon directly to a thruster. The AXFS technology is ready for transition into a qualification program, and achieved its objective[10] by demonstrating accurate xenon control with significant system reduction in mass and volume through the use of integrated modules for low-cost control options and/or reliability beyond practical SOA technology implementation. The resultant feed system represents a dramatic improvement over the NSTAR flight feed system and also represents an additional 70 percent reduction in mass, 50 percent reduction in footprint, and 50 percent reduction in cost over the baseline NEXT feed system also at TRL 6. The project successfully completed the integrated system testing and advanced the modules to TRL 6.[10]

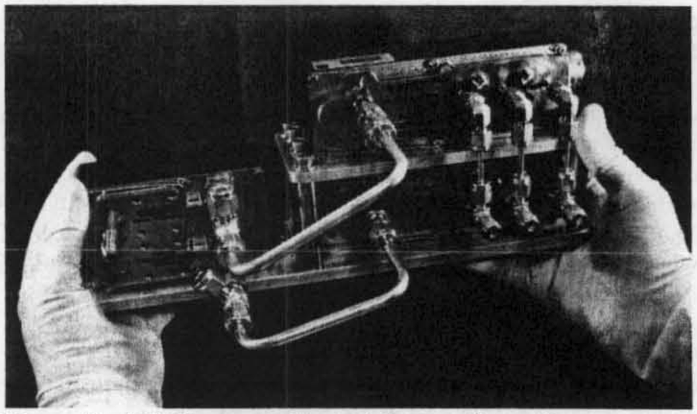


Figure 9. AXFS mounted in hot-fire configuration.

B. 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 ever developed. A single NEXT thruster:

- uses seven kilowatts of power,
- has an estimated propellant throughput capability of over 750 kg,
- has a lifetime of over 35,000 hours 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 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 mass, equivalent to doubling the science package, with only a single thruster. Reducing the number of thrusters reduces propulsion system complexity and spacecraft integration challenges.

The missions that are improved through the use of the NEXT thruster are those requiring 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 Ref. 11-12, the NSTAR thruster was able to complete the mission, but required large solar arrays and four or five thrusters to deliver the required payload. NEXT would be able to deliver 10 percent more total mass and require half the number of thrusters.

NEXT can not only deliver larger payloads, but can reduce trip times and 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 that both increase trip time and decrease 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 addresses the need for low-cost electric propulsion options. Studies[13] indicate that a low-power Hall thruster is not only cost enabling, but enhances performance 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 lower recurring cost than the SOA NSTAR thruster.

For the NEO mission evaluated, the HiVHAC thruster system delivered over 30 percent more mass than the NSTAR system. The performance increase accompanied a cost savings of approximately 25 percent over the SOA NSTAR system. The Dawn mission was evaluated, and the expected HIVHAC Hall thruster delivered approximately 14 percent more mass at substantially lower cost than SOA, or decreasing the solar array provided equivalent performance at even greater mission cost savings.[13]

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 open their options to highly inclined regions of space, sample return or multi-orbiter missions, or even deep-space rendezvous missions with more science and reduced trip times.

V. Aerocapture Technologies

Aerocapture represents a major advance over aerobraking techniques. Aerocapture is the process of entering the atmosphere of a target body to reduce the chemical propulsion requirements of orbit capture. Aerocapture is the next step beyond aerobraking, which relies on multiple passes high in the atmosphere to reduce orbital energy. It was used at Mars on multiple orbiter missions. Aerocapture, illustrated in Fig. 10, maximizes the benefit from the atmosphere by capturing in a single pass. Keys to successful aerocapture are accurate arrival state knowledge, validated atmospheric models, sufficient vehicle control authority (i.e. lift-to-drag ratio), and robust guidance during the maneuver.

The execution of the aerocapture maneuver itself is what enables the great mass savings over other orbital insertion methods. If the hardware subsystems are not mass efficient, or if performance is so poor that additional propellant is needed to adjust the final orbit, the benefits are significantly reduced. ISPT efforts in aerocapture subsystem technologies are focused on improving the efficiency and number of suitable alternatives for aeroshell structures and ablative thermal protection systems (TPS). These include development of families of low and medium density (14-36 lbs/ft^3) TPS, and the related sensors, development of a carbon-carbon rib-stiffened rigid aeroshell, and high temperature honeycomb structures and adhesives. Development occurred on inflatable decelerators via concept definition and initial design and testing of several inflatable decelerator candidates. Finally, progress is being made through improvement of models for atmospheres, aerothermal effects, and algorithms and testing of a flight-like guidance, navigation and control (GN&C) system.

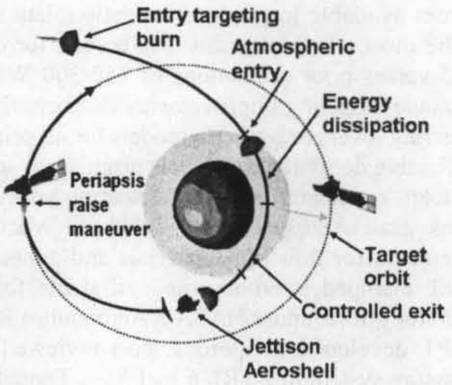


Figure 10. Illustration of the aerocapture

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 reduce the trip time and deliver a larger payload mass, enabling these missions to be implemented with the current generation of heavy lift launch vehicles. The SSE Roadmap recommends *"Aerocapture technologies and flight validation are a high priority to solar system exploration."*[1] And, the March 2008 OPAG meeting minutes recommends that *"Aerocapture is a key enabling technology for the outer solar system, particularly at Titan, and some gas giant planets"*[14]

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.

A. Development Status and Availability

The majority of investment in aerocapture technology occurred in advancing the TRL of efficient rigid aeroshell systems. A family of low-density TPS materials carrying the identifier "SRAM" was developed under a competitively awarded contract with Applied 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 on a 1 meter 70 degree blunt body aeroshell structure; shown in Fig. 11. Another ARA family of low- to medium-density TPS systems (PhenCarb) is phenolic-based, ranges in density between 20 and 36 lb/ft^3, and is applicable for heating rates between 200 and 1,500 W/cm^2.

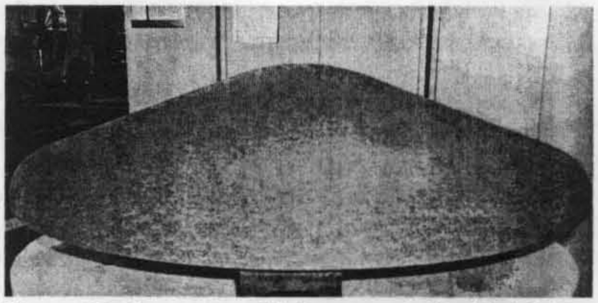


Figure 11. One meter ablative aeroshell with ARA's PhenCarb-20 TPS material.

In support of the rigid TPS system, ISPT funded testing of higher temperature adhesives and development of higher temperature composite structures effectively increasing the allowable bond-line temperature from 250°C to 325° or 400°C depending on the adhesive and composite construction. This work was performed by ATK, in the division formerly known as Composite Optics. Sensors that measure aeroshell recession with accuracy of hundredths of millimeters were developed at NASA's Ames Research Center and are 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.

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. When this system was mechanically tested to levels that are representative of expected aerocapture loading environments, the system response compared within 10 percent to the finite element model, validating that model for use in predicting system response to other environments. This effort was competitively awarded and completed in early 2007 by Lockheed Martin and their partner Carbon-Carbon Advanced Technologies (C-CAT), and resulted in a TRL-6 product applicable for use in multiple NASA science missions.

Ames Research Center developed and enhanced models that predict the entry thermal environments for aerocapture at Titan, Mars, Venus, and Neptune. 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 150-300 W/cm^2. Through multiple years of concentrated effort, researchers funded by ISPT made modeling improvements that benefit all future entry missions. ISPT funds supported the generation or update of engineering level atmospheric models for all primary aerocapture destinations except Earth.

Inflatable decelerator concepts promise an additional mass savings beyond expectations from rigid aeroshell systems. The ISPT team considered several competing concepts to understand and address the technical challenges with these types of systems. Ball Aerospace and Lockheed Martin teams developed first order fluid-structure models to understand the requirements for thin film materials and adhesives. Preliminary testing was conducted in concept preparation for trailing toroidal, clamped afterbody, and inflatable forebody decelerators. ISPT funded team members continue their inflatable decelerator efforts under NASA's Aeronautics Research Mission Directorate (ARMD).

ISPT developed a rigorous, peer-reviewed 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 is still following the ground development program 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.

Future plans are to complete the ground development of the ablative aeroshell system. This includes the improvement of 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 CY09. Additional information on ISPT developments in this technology area is in Ref. 15-20

B. Mission Benefits

The use of aerocapture was studied extensively, most notably for use at Titan, Neptune, Venus and Mars. Fig. 12 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). Alternatively, cost benefits are realized for multiple missions. When the overall system mass is reduced, the mission can utilize a smaller launch vehicle, saving tens of millions of dollars. Detailed mission assessment results are in Ref. 21-23.

The mission mass benefits to Mars are 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 enhances conjunction-class sample-return missions and large Mars orbiters. No new technology gaps were identified that would delay aerocapture implementation on such a mission.

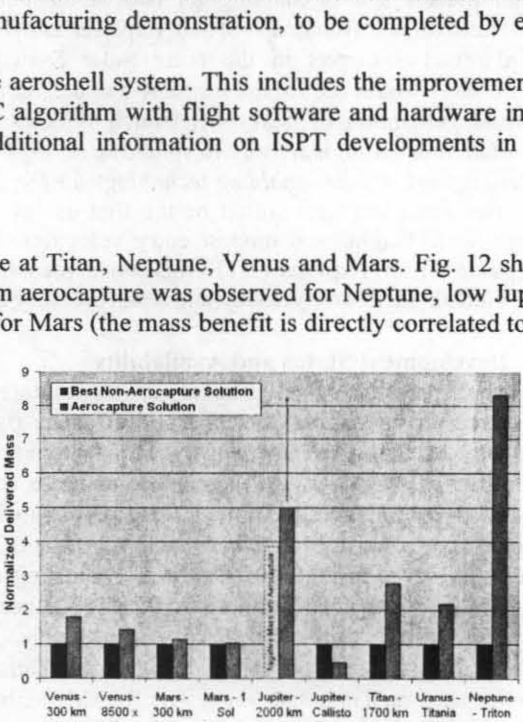
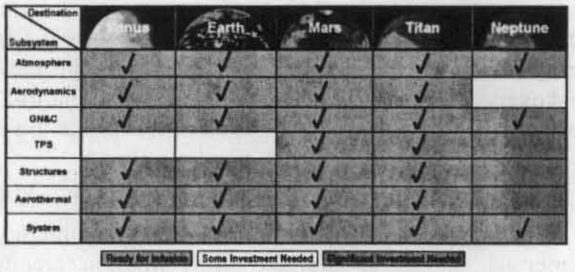


Figure 12. Aerocapture benefits for various targets.

Venus was studied extensively to identify any needs for TPS, guidance, atmospheric or heating models. Detailed analyses evaluated the potential for aerocapture for a Venus Discovery class mission. Aerocapture delivered more than 80 percent additional mass over aerobraking and more than 600 percent over a chemical insertion. Aerocapture reduces Deep Space Network (DSN) time by 121 days. No critical technology gaps were identified for aerocapture at Venus, but investments in TPS are recommended for achieving maximum mass benefits.

Titan was and continues to be of considerable scientific interest following the success of Cassini/Huygens. Because of its atmospheric structure, it is an ideal candidate for aerocapture. The recent Outer Planets Flagship (OPF) study considered aerocapture within the baseline mission concept since aerocapture has the capability to delivery more than double the scientific payload of the chemical alternative. Aerocapture may also play a key role in accomplishing a reduced Titan mission for a less-than-Flagship budget.

Aerocapture was proven repeatedly to be an enabling or strongly enhancing technology for several atmospheric targets. The ISPT project team 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 enhance a wide range of missions by reducing the mass of entry vehicles. Fig. 13 illustrates the remaining gaps required for technology infusion. All of the component subsystems are currently at or funded to reach TRL 6 in the next two years for multiple targets of interest. Aerocapture cannot reach TRL 6 for the system without space flight validation, and it is impossible to match the flight environment in ground facilities. Missions must be willing to accept the small risk of this shortfall, to realize the tremendous benefits of the technology. If they are not willing, Aerocapture will need to be validated in space before its first mission infusion. A space flight validation is expensive, but the costs will be recouped very quickly. The validation will immediately reduce the risk to the first user and will validate the maneuver for application to multiple, potentially lower-cost, missions to Titan, Mars, Venus, and Earth. Moreover, once Aerocapture is proven a reliable tool, it is anticipated that entirely new mission possibilities will be opened up.



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 13. Aerocapture readiness for various targets.

VI. Multi-Mission Earth Entry Vehicle

The Earth Entry Vehicle (EEV), that returns the Mars samples to our planet's surface, needs to be extremely reliable to meet the integrated probability of release goal of one in a million during any part of the atmospheric entry or surface impact. The EEV travels to Mars connected to the Orbiter/Earth Return Vehicle, waits for insertion of the Orbiting Sample, travels back to Earth as part of the Earth Return Vehicle (ERV), then is released and targeted for Earth impact. The EEV provides the thermal and acceleration environments necessary to maintain the samples for maximum scientific return.

Detailed studies show that to meet the stringent containment requirements of the mission, the Earth Entry Vehicle should possess particular design attributes. First, the vehicle must be "self-righting," so it will quickly stabilize itself in a heatshield-forward orientation if the release from the ERV, a micrometeoroid impact, or some other anomaly, cause it to enter the atmosphere in any other orientation. Second, the TPS of the heat shield needs to be robust enough to ensure a high level of reliability. Third, the EEV has no parachute or other deployable drag device, since the reliability of such a device is much less than required (the capsule would have to be designed to take an Earth impact load in the event of a failure of the drag device).

A, State-of-the-Art

In the 2000 timeframe, NASA teams developed a detailed conceptual design of the MSR Earth Entry Vehicle. This design was supported by wind tunnel and impact testing, and is seen in Fig. 14. The main features were a Carbon-Carbon structure, carbon foam impact absorption, a particular aftbody shape shown to be self-righting, and a carbon phenolic heatshield. The basic design is still valid today, but would need to be updated for any new mission requirements (such as sample mass, Orbiting Sample size, contamination mitigation strategy, temperature, and impact load). The design would benefit from materials and process improvements from the last 10 years. All of the component technologies are available today, with the exception of the carbon phenolic heatshield material. Our country has almost no supply of the heritage rayon used to make the historical carbon phenolic, which flew thousands of times in military applications and which

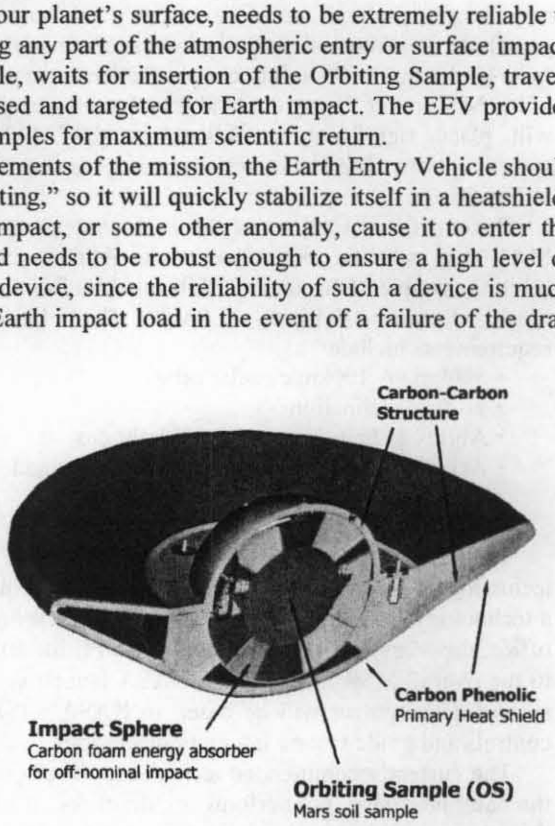


Figure 14. NASA's current EEV design.

forms the basis for the high reliability required for MSR. Rayon processes changed and the carbon phenolic made from new rayon has to be proven equivalent to the heritage material. New heatshield materials available today may be considered for their micrometeoroid tolerance. The current EEV design requires rigorous ground testing to ensure reliability, and construction of an Engineering Development Unit to validate systems engineering.

Detailed development schedules and costs were developed for the EEV. Within the development path, there are no low-TRL components or extreme risk items; the biggest challenge is to adequately prove the reliability of the components and the system. The current estimate to develop the EEV technology to TRL6 is approximately $41 million. This does not include a dedicated flight test, which many experts agree is needed to achieve the one-in-a-million *system* reliability, since the entry flight environment cannot be replicated in ground-based facilities. This is a fairly expensive flight test due to the high entry velocities that are required. One way to achieve a flight validation for little extra cost to NASA is to use the MSR EEV design, or at least the major components of the design, to return samples from another mission like New Frontiers or Discovery. NASA Headquarters managers and the In-Space Propulsion Technology (ISPT) team are pursuing this approach, but currently there are no manifested missions that are planning to use an MSR EEV design.

VII. Mars Ascent Vehicle

For many years, NASA and the science community were asking for a Mars Sample Return (MSR) mission. There were numerous studies to evaluate MSR mission architectures, technology needs and development plans, and top-level requirements. Because of the challenges, technologically and financially, of the MSR mission, NASA initiated a study to look at MSR propulsion technologies through the In-Space Propulsion Technology (ISPT) project office.[24] The objective of the ISPT project is to develop propulsion technologies that enhance or enable NASA science missions for the planetary science division by increasing performance while reducing cost, risk, and/or trip length. The largest propulsion risk element of the MSR mission is the Mars Ascent Vehicle (MAV).

The development of a major subsystem of the Mars Sample Return mission cannot be developed without a direct and in-depth analysis on technology sensitivities to the overall MSR architecture and the mission's concept of operations (CONOPS). The MSR architecture will dictate the physical and thermal environments, power requirements, system interface, etc. of the MAV system.

The current architecture for the MSR lander is to use the Mars Science Laboratory (MSL) entry, descent, and landing (EDL) system. The MSL EDL may require minor modifications, e.g. a larger parachute or additional propellant, to accommodate for a lander that will slightly exceed the lander mass of the MSL rover. Using the MSL sky crane concept will place significant restrictions on the MAV system options. The lander system concept is shown in Fig. 15.

Beyond the limitations of the EDL system, the MAV has specific requirements to deliver the orbiting sample (OS) in an orbit suitable for the Earth Return Vehicle (ERV). The basic requirements include:

- 500km +/- 100km circular orbit
- +/- 0.2° inclination
- Ability to launch from +/- 30° latitudes
- Accommodate ~5kg, 16cm diameter payload
- Continuous telemetry
- Storage for 90 Sols, potentially up to one year

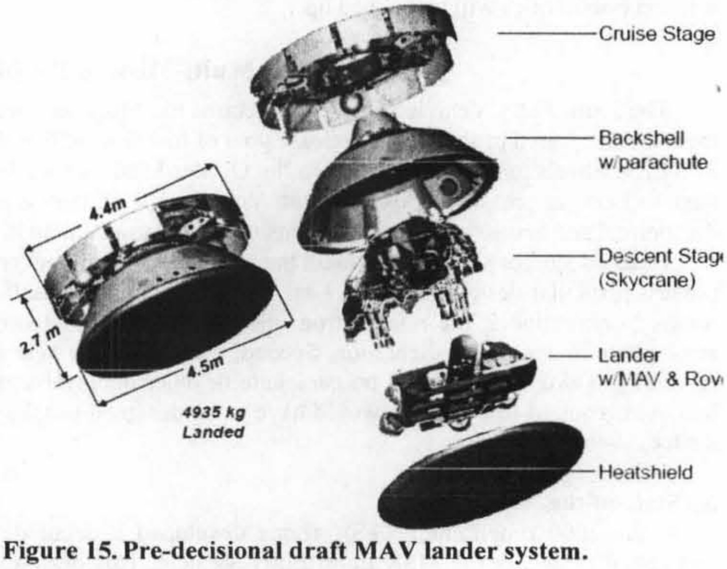


Figure 15. Pre-decisional draft MAV lander system.

The following technology development strategy is pre-decisional and is an approach under consideration. The strategy for technology development is the employment of an Integrated Product Development Team (IPDT) with updates as necessary to a technology steering community and host workshops as appropriate. The IPDT will consist of members from ISPT project office, the Mars Exploration Program at JPL for intimate knowledge of the system interfaces, requirements, and sensitivities to the overall MSR mission, and NASA launch vehicle system design and test support. Management of the subsystem and system development will be based in NASA's ISPT project with lead systems engineering support to maintain interface controls and guide system integration activities.

The current recommended technology development approach is to focus on the enabling and enhancing components of the baseline design, but perform smaller tasks on higher risk with higher payoff technology investments. It is recommended that the initial tasks clearly define the requirements of component technology and calculate the potential return on investment. Enabling technology and early exploratory risk mitigation tasks is prioritized followed by options for performance enhancement and mass reduction. The definition of component level requirements and interfaces, as well as potential payoff, are conducted through detailed collaborative engineering design, e.g. JPL Team X, studies. It is anticipated that the component level developments would be completed; potentially through the NASA Research Announcement (NRA) process.

After the completion of technology component level development, a system integrator is selected via an open competition to incorporate the component technologies into an integrated system for system level demonstrations and possible flight tests.

A notional near-term implementation plan, shown in Fig. 16, includes evaluating inputs from background studies, requests for information (RFIs), collaboration with the Mars Exploration Program, and collaborative engineering design studies to determine if enough information is available to make wise investments. Solicitations are prepared for exploratory risk mitigation tasks, enabling tasks, followed by enhancing technologies as funding permits.

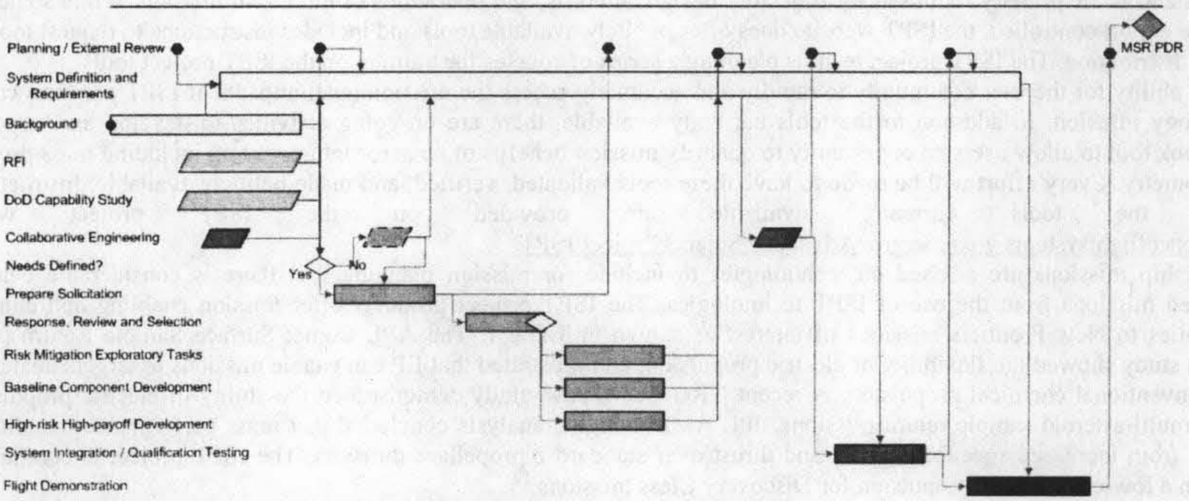


Figure 16. Notional technology development implementation strategy.

An RFI to identify new MAV related technologies was released in December 2008. A task with The Aerospace Corporation was initiated in January of 2009 to investigate military technology applicability to the MAV. There is potential for a collaborative engineering activity to identify state-of-the-art technologies for a detailed and complete mass equipment list of the baseline solution. The results of the studies are provided to the IPDT and potentially the larger community interested in MAV technologies, including potential system integrators. The IPDT and NASA management determines if enough information with high enough fidelity was obtained to make low-risk investments. The investments are prioritized for risk reduction and technology advancement. If the review team agrees to move forward, a solicitation is generated for exploratory tasks, risk mitigation efforts, baseline component technology advancement, and potentially tasks to better define or advance alternative concepts. After technology advancements, workshops or reviews are held to balance the investments as appropriate. When the component and subsystem technologies are far enough along, a system integrator is chosen to take the components at TRL 6 to a MAV system of TRL 5 with a system flight demonstration.

VIII. 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 increases confidence in the benefit of ISPT products both for mission planners as well as for potential proposal reviewers. Tool development efforts were completed on the Low-Thrust Trajectory Tool (LTTT) and 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 expertise to evaluate mission performance. Some of the heritage tools proved to be extremely valuable, but cannot perform direct optimization and require good initial guesses by the users. This leads to solutions difficult to verify quickly and independently. The ability to calculate the performance benefit of complex electric propulsion missions is intrinsic to the determination of propulsion system requirements. The ISPT office invested in multiple low-thrust trajectory tools that independently verifies 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 team is planning a series of courses for training on the ISPT project tools.

The ability for the user community to rapidly and accurately access 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 to allow users an opportunity to quantify mission benefits of an aerocapture system including mass properties and geometry. Every effort will be made to have these tools validated, verified, and made publicly available. Instructions to obtain the tools currently available are provided on the ISPT project website: http://spaceflightsystems.grc.nasa.gov/Advanced/ScienceProject/ISPT/

Flagship missions are advised on technologies to include for mission planning, but there is considerable benefit to competed missions from the use of ISPT technologies. The ISPT project products offer mission enabling and enhancing capabilities to New Frontiers missions of interest as shown in Table 1. The APL Comet Surface Sample Return (CSSR) mission study showed the flexibility of electric propulsion, and illustrated that EP can enable missions to targets unattainable with conventional chemical propulsion. A recent GRC COMPASS study demonstrated the ability of electric propulsion to enable multi-asteroid sample return missions. JPL AMBR engine analysis concluded that mass performance benefits were derived from increased specific impulse and thrust over standard bipropellant thrusters. The ISPT project is continuing to invest in a low-cost electric propulsion for Discovery Class missions.[10]

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*
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. • *Limited applicability for Trojan/Centaur flyby* • A mission targeting for a Trojan rendezvous requires significant post launch ΔV. • *High applicability for Trojan rendezvous* • *Radioisotope EP required for Centaur rendezvous*	• 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.* • A mission targeting for a Trojan rendezvous requires significant post launch ΔV. • *Applicable for rendezvous missions.*

IX. Technology Infusion

NASA recognizes that it is desirable to fly new technologies that could enable new scientific investigations or to enhance an investigation's science return. The SSE Roadmap states that NASA will strive to maximize the payoff from its technology investments, either by enabling individual missions or by enhancing classes of missions with creative solutions. Discovery, New Frontiers, and Flagship missions potentially provide opportunities to infuse advanced technologies developed by NASA, and advance NASA's technology base and enable a broader set of future missions. ISPT actively looks for infusion opportunities for the aerocapture technology area that is nearing TRL 6.

The ISPT project developed several technologies that are nearing TRL 6 and are potentially applicable to New Frontiers and Discovery missions. Three technologies in particular are the NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, the Advanced Material Bi-propellant Rocket (AMBR) engine, and Aerocapture. In order to benefit from its technology investments, NASA will be providing an incentive to encourage the infusion of NEXT system or the AMBR engine into mission proposals in response to the New Frontiers 3 Announcement of Opportunity (AO). Under this AO, proposers will be offered an option of adopting one of these two specific technologies for insertion into their missions. NASA will then share in the flight development costs of the proposed advanced technology, up to certain amounts specified in the AO depending upon which technology is proposed.

ISPT continues to look for other opportunities to infuse its technologies into other future mission opportunities. The ISPT project office and NEXT team personnel are actively supporting various flagship science definition team (SDT) studies such as those for Venus and outer planet flagship missions looking at Enceladus or the Titan-Saturn system. The Titan-Saturn System Mission study, a JPL-led Outer Planets Flagship mission concept study, has baselined a NEXT-based SEP system to provide the mass required to accomplish the desired science mission objectives. This was an SMD-directed and funded pre-phase A study. The Comet-Surface Sample Return Mission study, an APL led New Frontiers-class mission concept study, recommended a NEXT-based SEP mission as a preferred approach over a chemical propulsion mission concept. This was also an SMD-directed and funded pre-phase A study. The New Worlds Observer Mission concept study has baselined a NEXT-based SEP system to provide the capability required to accomplish the desired exoplanet detection and characterization science objectives. This is a pre-phase A study, which was awarded under the SMD Astrophysics Strategic Mission Concept Studies NRA. The NEXT team also supported APL on the Solar Probe mission.

X. Future Plans and Conclusions

Known future missions of interest for NASA and the science community will continue to demand propulsion systems with increasing performance and lower cost. The ISPT project is developing propulsion technologies for NASA missions to address this demand. Several of the technologies are at or nearing TRL 6 and are available for infusion into near-term science missions. ISPT continues to invest in these areas to complete current developments to TRL 6 in the next year.

Among these is the NEXT electric propulsion system. It is eligible for all future mission opportunities. ISPT is expecting to reach TRL 6 in the development of the high temperature bi-propellant chemical thruster by the end of 2009. Finally, an aerocapture system comprised of a blunt body TPS system, the GN&C, sensors and the supporting models is to achieve its technology readiness by the end of 2009. 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. Aerocapture and electric propulsion are frequently identified as enabling or enhancing technologies.

ISPT continues 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 is 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 in the design process of the Hall thruster, and through modular design and shared hardware for NEXT and other electric propulsion systems. In the aerocapture area, the development plan for the rigid technologies follows a development plan proposed to the ST9 mission. In the chemical and component area, development in materials and engine designs continues to improve performance and significantly reduce costs through advanced manufacturing techniques.

Future propulsion needs include an electric propulsion system that is 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 be optimized around a known constant input power. The future focus area is propulsion systems for sample return missions. These missions are inherently 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 used to capture at the destination.

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