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

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Abstract—The In-Space Propulsion Technology 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 paper provides 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. Aerocapture investments have 1) improved models for: guidance, navigation, and control 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 have focused on completing the NEXT ion propulsion system, a 0.6-7kW throttle-able gridded ion system. The primary chemical propulsion investment is on a high-temperature storable bi-propellant rocket engine providing higher performance for lower cost. Development status of mid-term technology, the low-cost HiVHAC Hall thruster is also presented. 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.

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1. INTRODUCTION

The In-Space Propulsion Technology (ISPT) Project, funded by NASA's Science Mission Directorate (SMD), 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.

Aerocapture investments have 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 have been made in understanding and applying inflatable aerocapture concepts. Aerocapture technology was a contender for flight validation on NASA's New Millennium ST9 mission.

Investments in electric propulsion (EP) technologies have focused on completing NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, a 0.6-7kW throttle-able gridded ion system suitable for future Discovery, New Frontiers, and flagship missions. Also discussed are the developments in other electric propulsion products such as the HiVHAC Hall thruster, a 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 have included the demonstration of active mixture ratio control, lightweight tank technology manufacturing and non-destructive evaluation techniques, and the development of the Advanced Material Bi-propellant Rocket (AMBR). The advanced chemical propulsion technologies also have an opportunity for rapid technology infusion with minimal risk and broad mission applicability.

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Solar sails and emerging propulsion technologies are currently not funded by ISPT investments but considerable progress has been made in the technologies in prior years. The solar sail technology area has 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.

Funding constraints has led the ISPT project to focus it's on-going efforts 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. And, 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 TRL6 by FY09.

4) Complete development of the HiVHAC Hall thruster to TRL 6 by the end of FY10.

2. 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 but Earth departure and attitude/reaction control systems are not currently in the project scope. Given that the ISPT objective is to develop products that realize near- 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 is managed for SMD by the ISPT project office at NASA Glenn Research Center (GRC) and implemented through task agreements with implementing 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 have included 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 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.

3. 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 aero-braking, which relies on multiply passes higher in the atmosphere to reduce orbital energy. Aerocapture, illustrated in figure 1, maximizes the benefit from the atmosphere through a single pass. Keys to successful aerocapture are lightweight thermal protection systems, accurate atmospheric models, and sufficient guidance during the maneuver.

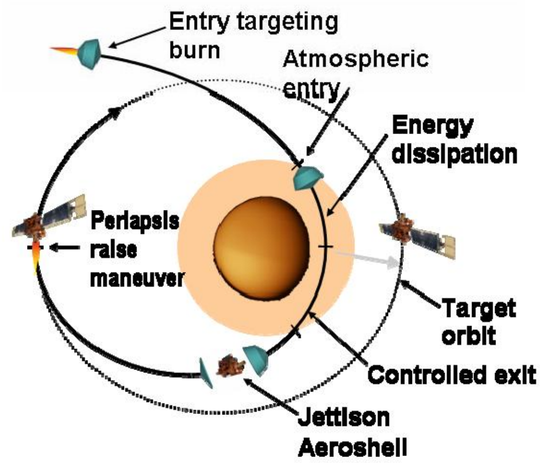

Figure 1. Illustration of the aerocapture maneuver.

Efforts in aerocapture related technologies have included development of families of low & medium density (14 - 32 lbs/ft^3) thermal protection systems and the related sensors, development of a carbon-carbon rib-stiffened rigid aeroshell, higher temperature structures and adhesives. Development is also occurring 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 GN&C system.

Development Status and Availability

The majority of investment in aerocapture technology has occurred in furthering the TRL of the rigid aeroshell systems. A family of low-density TPS materials carrying the identifier "SRAM" have been developed under a competitively awarded contract with Advanced Research Associates (ARA) These have a density range between 14/ft^3 and 24lb/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 and could eventually be used on missions with destinations to small bodies such Titan and Mars. The SRAM family of ablators has been tested both in arcjet and solar tower facilities at the coupon level; 1 ft and 2 ft square flat panels, and very recently on a 1m blunt body aeroshell structure; shown in figure 2. The family of medium density TPS systems 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 has 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 an accuracy of hundredths of millimeters have also been developed and are currently planned for use on the Mars Science Laboratory (MSL) mission.

Models that predict the thermal environments that will be seen by the TPS system have been developed and enhanced. One feature in particular has revealed that previous heating estimates have been overly conservative. Coupled models updated with the most current 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. ISPT is also updating the atmospheric models for all planetary bodies except Earth.

A rigorous plan was developed as part of the ST9 New Millennium Proposal to take the ablative aerocapture system to a TRL 6 by FY09. Though no proposal was selected, the ground development program will still be followed by ISPT thereby preparing the technology for a flight demo.

Figure 2. One meter ablative aeroshell with ARA's PhenCarb 20 TPS material.

Another advancement enabled by ISPT funding is the development of a Carbon-Carbon aeroshell that has been 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% mass density improvement over the same size Genesis-like aeroshell. This product has been mechanically tested to levels that are representative of expected environments. In fact all testing has been completed to the levels of system testing that have historically been required of these types of systems before flight. This effort was competitively awarded and recently completed by Lockheed Martin.

Inflatable decelerator concepts promise an additional mass savings even beyond what is expected from rigid aeroshell systems. This has prompted ISPT to consider several competing concepts and begin understanding and addressing the technical challenges with these types of systems. First order thermal models have been developed by Ball Aerospace-led and Lockheed Martin-led teams to begin understanding the requirements for thin film materials and adhesives and preliminary testing has been conducted in concept preparation for trailing toroidal, clamped afterbody, and inflatable forebody decelerators .

Future plans are to complete the ground development of the ablative aeroshell system. This includes continuation of improving aerothermal models, atmospheric models and real-time testing GN&C algorithms with flight software and hardware in the loop. The GN&C work is expected to be completed in FY09.

Additional information on ISPT developments in this technology area can be found in references [2-7].

Mission Benefits

The use of aerocapture has been studied extensively, most notably for use at Titan, Neptune, Venus and Mars. Anticipated increases in delivered mass are shown in figure 3. The largest benefit from aerocapture was observed for Neptune, low Jupiter orbits, followed by Titan, Uranus, Venus, and then only marginal gains for Mars. Detailed mission assessment results can be found in references [8-10].

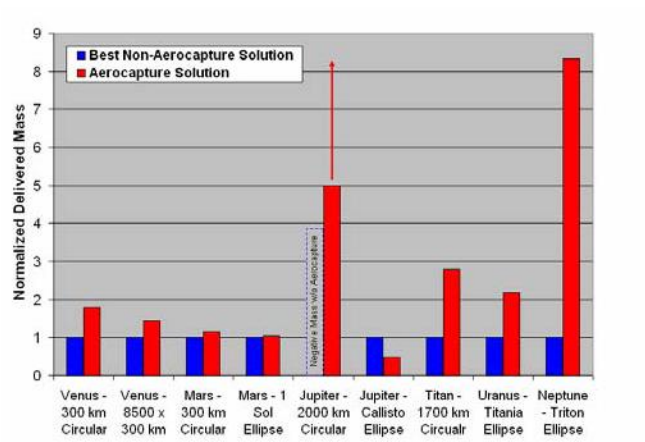

Figure 3. Aeropcature benefits for various targets.

Even though the mission benefits to Mars are only expected to be on the order of 5-15%, the benefits can be enabling. Detailed mission and cost analyses have been conducted for various Mars opportunities by a multi-center team from ARC, JPL, JSC, LaRC, and MSFC. An opposition class sample return mission can be enabled in less than two years through the use of aerocapture. Aerocapture is significantly enhancing for conjunction-class sample-return missions, and in general for large Mars orbiters. Also, no new technology gaps have been identified.

Venus has also been 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% additional mass over aero-braking and more than 600% from a chemical insertion. Aerocapture also offers a reduction of 121 days of Deep Space Network (DSN) time. No critical technology gaps have been identified for aerocapture at Venus.

Titan has been of considerable scientific interest following the success of Cassini. Because of its atmospheric conditions, it is an ideal candidate for aerocapture. The recent flagship study does have aerocapture within the baseline mission concept and chemical capture was not considered a viable option as aerocapture has the capability to delivery more than double the mass of the chemical alternative. If selected, a flight demo has been identified as part of the mission technology development program.

Aerocapture has been repeatedly found to be an enabling technology for several atmospheric targets of interest. The ISPT project has continued 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 can also enhance a wide range of missions by reducing the mass of entry vehicles. Figure 4 illustrates the remaining gaps required for technology infusion. The technology is currently at or is funded to reach TRL6 in the next two years for multiple targets of interest.

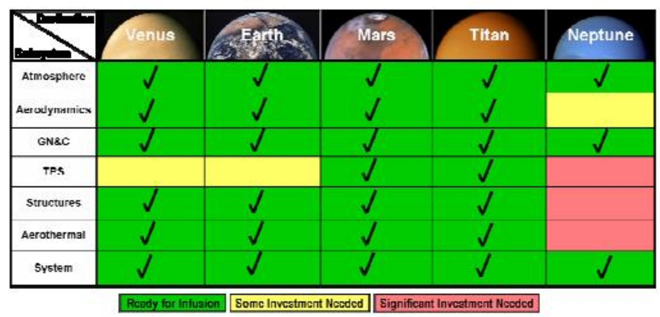

Figure 4. Aerocapture readiness for various targets.

4. 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 have primarily focused on the development of NEXT, with 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.

Development Status and Availability

The GRC-led NEXT project was competitively selected to develop a nominal 40cm gridded ion electric propulsion system [11]. The objectives of this development were to improve upon the state-of-art NSTAR system flown on Deep Space-1 by achieving lower specific mass, higher Isp (4050s), greater throughput (current estimates exceed 700kg of xenon) and increasing the power handling capability (6.9kw), thrust (240mN), and throttle range (12:1) to enable flagship class missions. The ion propulsion system components being 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 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 which has passed qualification level environmental testing. Refer to Figure 5. As of December 1st, 2007 the thruster has achieved over 271 kg xenon throughput and 13,200 hrs of full power operation. The NEXT wear test has demonstrated the largest total impulse ever achieved by a gridded ion thruster and far exceeds the 75 kg throughput experienced by DS-1 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 1800V DC and total power processing at 7kW. The NEXT EM PPU was designed and fabricated by L3 Comm ETI, Inc. After completing acceptance tests the PPU will be incorporated into the single string integrated test and then move onto environmental testing 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 considered the propellant management system (PMS). PMS development is complete and the system has passed all performance and environmental objectives. The system is single fault tolerant, 50% lighter that the SOA system and can regulate xenon flow to the various components to better than 3% accuracy.

An engineering-model fidelity gimbal mechanism has also been 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 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 would be 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 have also been a part of recent NEXT system developments. Major support for the project has been provided by JPL, Aerojet and L3 Comm.

The integrated NEXT system will be tested in relevant space conditions as a complete string. This will bring the system to a TRL level of 6 and make it a candidate for all upcoming mission opportunities. The demonstration of life by test has already demonstrated sufficient throughput for many science destinations of interest. The test is planned to continue into the coming years validating greater total impulse capability until achieving the targeted throughput of 450kg.

ISPT has also invested in the HiVHAC thruster [12]. HiVHAC is the first NASA electric propulsion thruster specifically designed as a low-cost electric propulsion option targeting Discovery and New Frontiers missions and perhaps even 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, resulting 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 thruster, again allowing for lower complexity systems with significant cost benefits.

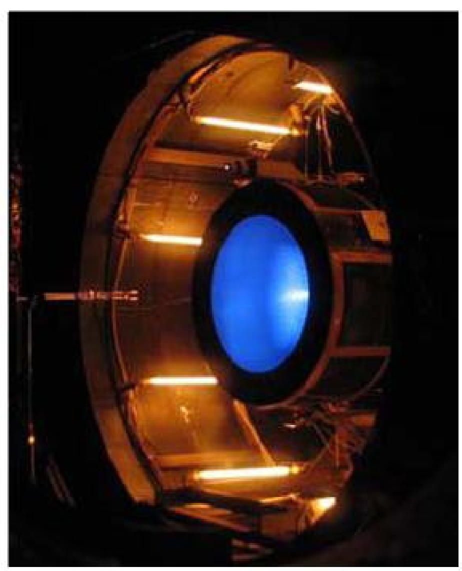

Figure 5. NEXT thermal vacuum testing at JPL.

A laboratory model HiVHAC thruster is currently in wear testing and has successfully achieved over 4100 hrs and approximately 88kg of xenon throughput as of December 1st, 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 has been 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. Two FCMs have been delivered 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 expected to have significantly increased reliability with both parallel and series redundancy against performance accuracy and mission loss accompanied by both a mass and volume reduction of approximately 80% and 90% respectively over the NEXT feed system. The flow control module has 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 the summer of 2008.

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 can use seven kilowatts of power, has an estimated propellant throughput capability of over 700 kg, a lifetime of over 35,000 hours of full power operation, and a total impulse capability of approximately 30 million Newton-seconds, or about three times that of the SOA DAWN thrusters. This performance leads to significant benefits for a wide range of potential mission applications.

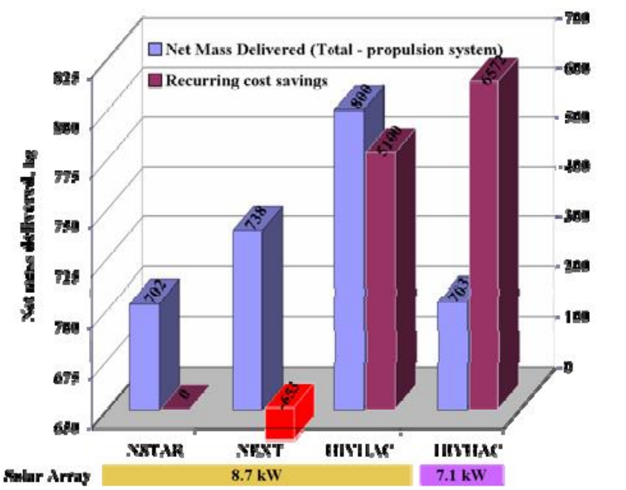

Figure 6. Mass and cost comparison for DAWN mission.

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 have delivered more mass, equivalent to doubling the science package, by performing the complete mission with only a single thruster. Reducing the number of thrusters can significantly reduce 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 has been 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 [13-14], 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 delivery 10% more total mass and required half the number of thrusters.

NEXT can not only delivery 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 decreasing 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 which 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 [15] have indicated that a low-power Hall thruster is not only cost enabling, but can be 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 a both a greater throughput capability and also 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% more mass than the NSTAR system. Also, the performance increase accompanied a recurring cost savings of approximately 25% over the SOA NSTAR system. The expected performance and cost benefits of a low power Hall thruster applicable to small missions is reflected in Figure 6. The expected HiVHAC Hall thruster would be able to deliver approximately 14% 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.

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 also 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.

5. 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 has focused on items that can 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.

Development Status and Availability

Mixture Ratio (MR) control is a concept to either reduce the residuals propellants that must be 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 have been 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 summer of 2008.

Small investments have also been 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 end product is intended to be 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.

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 and expanding the operating environment to higher temperatures with the goal of achieving a 6s increase in Isp for NTO/N2H4 and 10s for NTO/MMH. This effort was awarded via a competitive process to Aerojet Corporation in FY2006. The current program will manufacture and hot-fire test two engines demonstrating the increased performance and validating the new manufacturing techniques.

Mission Benefits

As stated previously, the mission benefits in the area of advanced chemical propulsion can be synergistic, and the cumulative effects have tremendous potential. The individual subsystems can be infused individually for reduced risk, or combined for considerable payload mass benefits.

The use of MR control has been studied extensively, and 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 can allow 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 mission requiring large ΔV maneuvers, which 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 expected on the order of 2.5% of the propellant mass, or net tank mass savings of 50% over SOA titanium tanks.

The AMBR engine development [16] will also significantly benefit missions with large propulsion maneuvers through the reduction of wet mass. Also, the AMBR engine is expected to have over a 30% reduction in cost along with an increase in performance. The mission mass benefits are dependent on the mission-required ΔV, but are easily on the

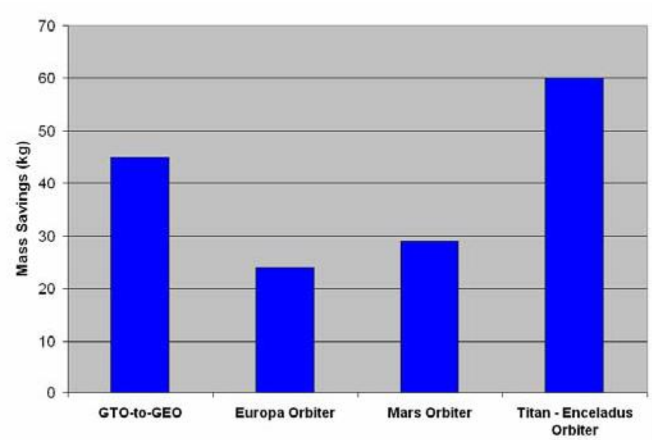

Figure 7. Mass benefits from the AMBR engine.

order of the scientific instrument packages flown on previous missions. Figure 7 shows potential payload increases due to the increased specific power for multiple missions. For a mission like Cassini, the number of thrusters can be reduced by having a higher thrust engine reducing complexity. The system would also deliver additional mass, over 50 kg; which would equate to a potential increase in scientific payload by 100%.

6. SYSTEMS ANALYSIS

Systems analysis is used during all phases of any propulsion hardware development. The systems analysis area serves two primary functions: to help define the requirements for new technology development and the figures of merit to prioritize the return on investment, and 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 System (REPS) 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 have been 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, and 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 quickly and independently verify.

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 has invested into 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, and 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 ability for the user community to rapidly and accurately assess the mission level impacts of ISP technologies can ease technology infusion. In addition to the tools currently available, there are on-going activities to develope 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.

7. FUTURE PLANS

Known future missions of interest for NASA and the science community will continue 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 also 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 will follow 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 can be made 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.

8. 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 an aerocapture system comprised of a blunt body TPS system, the GN&C, sensors and the supporting models. The NEXT electric propulsion system is also expected to achieve TRL 6 in early FY08 and is eligible for all future mission opportunities. Finally, ISPT is also expecting to reach TRL 6 in the development of the high temperature bi-propellant chemical thruster. 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.

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