# STATUS OF NASA IN-SPACE PROPULSION TECHNOLOGIES AND THEIR INFUSION POTENTIAL*

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## ABSTRACT

Since 2001, the In-Space Propulsion Technology (ISPT) program has been developing in-space propulsion technologies that will enable or enhance NASA robotic science missions. These in-space propulsion technologies have broad applicability to future competed Discovery and New Frontiers mission solicitations, and are potentially enabling for future NASA flagship and sample return missions currently being considered. This paper provides status of the technology development of several in-space propulsion technologies that are ready for infusion into future missions. The technologies that are ready for flight infusion are: 1) the high-temperature Advanced Material Bipropellant Rocket (AMBR) engine providing higher performance; 2) NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, a 0.6-7 kW throttle-able gridded ion system; and 3) Aerocapture technology development with investments in a family of thermal protection system (TPS) materials and structures; guidance, navigation, and control (GN&C) models of blunt-body rigid aeroshells; and aerothermal effect models. Two component technologies that will be ready for flight infusion in FY12/13 are 1) Advanced Xenon Flow Control System, and 2) ultra-lightweight propellant tank technology advancements and their infusion potential will be also discussed. The paper will also describe the ISPT project's future focus on propulsion for sample return missions: 1) Mars Ascent Vehicles (MAV); 2) multi-mission technologies for Earth Entry Vehicles (MMEEV) needed for sample return missions from many different destinations; and 3) electric propulsion for sample return and low cost missions. These technologies are more vehicle-focused, and present a different set of technology infusion challenges. Systems/Mission Analysis focused on developing tools and assessing the application of propulsion technologies to a wide variety of mission concepts.

## INTRODUCTION

NASA's Science Mission Directorate (SMD) missions seek to answer important science questions about our planet, the Solar System and beyond. To meet NASA's future science mission needs, the goal of the ISPT Program is the development of new enabling propulsion technologies that cannot be reasonably achieved within the cost or schedule constraints of mission development timelines. For the last 10 years the In-Space Propulsion Technology (ISPT) Program has been developing in-space propulsion technologies that will enable and/or benefit near and mid-term NASA robotic science missions by significantly reducing cost, mass, and/or travel times. ISPT technologies will help deliver spacecraft to SMD's destinations of interest. In 2009, the ISPT program was tasked to also start development of propulsion technologies that would enable future sample return missions.

An objective of ISPT is to develop capabilities that realize near-term and mid-term benefits. The Program primarily focuses on technologies in the mid TRL range (TRL 3 to 6+ range) that have a reasonable chance of reaching maturity in 4–6 years. The objective is to achieve technology readiness level (TRL) 6 and reduce risk sufficiently for mission infusion. The project strongly emphasizes developing propulsion products for NASA flight missions, that will be ultimately manufactured by industry and made equally available to all potential users for missions and proposals.

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The ISPT priorities and products are tied closely to the science roadmaps, the SMD's science plan, and the decadal surveys. ISPT therefore emphasizes technology development with mission pull. In 2006, the Solar System Exploration (SSE) Roadmap[1] identified technology development needs for Solar System exploration, and described transportation technologies as highest priority, with the highest priority propulsion technologies being electric propulsion and aerocapture. Excerpts from the science community are discussed in Ref. 2. Initially, ISPT's responsibility was to develop technologies for Planetary Science Flagship missions (large-class, typically > $1B), but in 2006 the focus evolved to technology investments that would be applicable to New Frontiers (medium-class, typically $500M- $1B) and Discovery (small-class, typically, <$500M) competed missions. So, aerocapture (the use of aerodynamic drag for orbit capture) and electric propulsion continued to be a priority, but the refocus activity recommended a long-life lower-power Hall system.

Looking towards ISPT's future, the 2011 Planetary Science Decadal Survey [3] was released March 2011, and will provide guidance for ISPT's future technology investments. The Decadal Survey made many references to ISPT technologies such as aerocapture, NEXT, AMBR, and astrodynamics, mission trajectory and planning tools. This Decadal Survey validated the technology investments ISPT has been making over the last 10 years, and provides ISPT with a new focus for the next 10 to 20 years.

The Decadal Survey supported NASA developing a multi-mission technology investment program that will "preserve its focus on fundamental system capabilities rather than solely on individual technology tasks." The Decadal Survey highlighted the NEXT system development as an example of this "integrated approach" of "advancement of solar electric propulsion systems to enable wide variety of new missions throughout the solar system." The Decadal Survey also recommended "making similar equivalent systems investments" in the advanced Ultraflex solar array technology and aerocapture. The Decadal Survey discussed the importance of developing those system technologies to TRL 6.

One recommendation in the Decadal Survey was for "a balanced mix of Discovery, New Frontiers, and Flagship missions, enabling both a steady stream of new discoveries and the capability to address larger challenges like sample return missions and outer planet exploration." These broad mission needs would in turn require a balanced set of multi-mission technologies and integrated system capabilities. The Decadal Survey acknowledges that a "robust Discovery and New Frontiers Program would be substantially enhanced by such a commitment to multi-mission technologies." The Decadal Survey also identified the highest priority Flagship mission as the Mars Sample Return (MSR) campaign.

## TECHNOLOGY DEVELOPMENT OVERVIEW

The In-Space Propulsion Technology (ISPT) program emphasizes technology development with mission pull. In the near-term, the ISPT goal will be to develop propulsion technologies that are applicable from large sample return missions through New Frontiers and Discovery-class missions. Sample return missions for example could be quite varied, from collecting and bringing back samples of comets or asteroids, to soil, rocks, or atmosphere from planets or moons. The current technology investment areas for ISPT are: 1) Propulsion System Technologies, 2) Sample Return Technologies, 3) Entry Vehicle Technologies (EVT), 4) Spacecraft Bus Technologies, and 5) System and mission analysis and tools. This paper provides a brief overview of ISPT, describing the planning and development status of key technologies in these areas (Figure 1).

The focus of the Propulsion System Technologies area is divided into: 1) NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, 2) Electric propulsion for sample return and low cost Discovery-class missions, 3) Advanced chemical propulsion and propulsion system components, and 4) Developing propulsion system requirements for Earth Return Vehicles (ERV) and low TRL advanced propulsion technologies. The high-temperature Advanced Material Bipropellant Rocket (AMBR) engine, providing higher performance (fuel efficiency and thrust), was completed in 2009 as part of the program's advanced chemical propulsion activities. In 2012, the program will soon complete the development of the NEXT ion engine system, and will continue work on a High-Voltage Hall Accelerator (HIVHAC) Hall thruster development. The HIVHAC thruster could then transition into a development of a Hall electric propulsion system applicable to sample return (ERV and transfer stages) and low-cost Discovery missions.

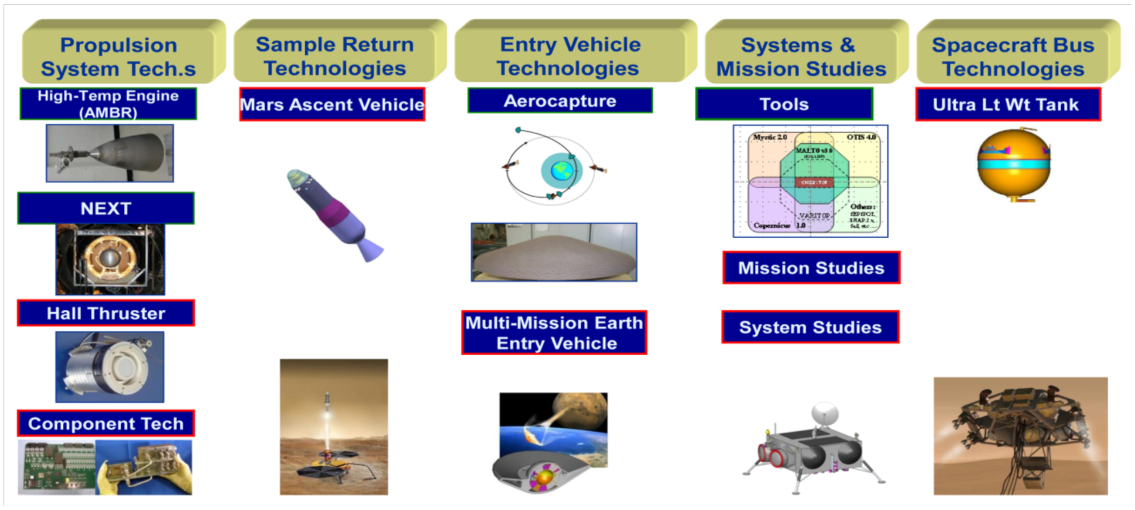


**Figure 1. Current technology investment areas for ISPT**

The primary focus of the Sample Return Technology area is the technology development for a Mars Ascent Vehicle (MAV). The Mars Ascent Vehicle (MAV) is a new development area to ISPT, but builds upon and leverages the past MAV analysis and technology developments from the Mars Technology Program (MTP) and previous Mars Sample Return (MSR) studies. The MAV is a key component of any future MSR mission.

The Entry Vehicle Technology (EVT) area is divided into three main areas: 1) Aerocapture, 2) Multi-mission technologies for Earth Entry Vehicles (MMEEV), and 3) Planetary probes and impactors. ISPT's earlier Aerocapture efforts will be concluded in 2011, and ISPT is working to find opportunities to transition the technology into future flight opportunities. The Aerocapture experience base and capability will be leveraged with previous work related to Earth Entry Vehicles (EEV) and transitioned into the future multi-mission technologies for Earth Entry Vehicles (MMEEV).

Spacecraft Bus Technologies area is currently leveraging previous work on the lightweight propellant-tanks. This work will develop inspection techniques and aims to ultimately develop flight qualified propellant tanks that result in a substantially lower mass propellant tank. While the initial application of this technology as a drop-in replacement for the Skycrane propellant tanks is directly for a Mars Sample Return (MSR) mission, it will have general applicability to all future planetary spacecraft.

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 is on developing reference missions and conducting mission sensitivities to assist technology gap identification or application. These In-Space Propulsion technologies are applicable and potentially enabling for future NASA flagship and sample return missions currently under consideration, as well as having broad applicability to future Discovery and New Frontiers mission solicitations. For more background on ISPT, please see Ref. 4, 5, 6.

## RESULTS AND DISCUSSION

### NASA'S EVOLUTIONARY XENON THRUSTER (NEXT)

Solar Electric Propulsion (SEP) enables missions requiring large post launch ΔV. SEP has applications to rendezvous and sample-return missions to small bodies and fast trajectories towards the outer planets. 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 place of fly-bys, and as planned in the Dawn mission, can enable multiple destinations.

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.

The GRC-led NEXT project was competitively selected to develop a nominal 40-cm gridded-ion electric propulsion system.[5] The objectives of this development were to improve upon the state-of-art (SOA) NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) system flown on Deep Space-1 to enable flagship class missions by achieving the performance characteristics listed in Table 1.

**Table 1. Performance comparison of NSTAR and NEXT ion thrusters**

| Characteristic | NSTAR (SOA) | NEXT |
|---|---|---|
| Max. Thruster Power (kW) | 2.3 | 6.9 |
| Max. Thrust (mN) | 91 | 236 |
| Throttle Range (Max./Min. Thrust) | 4.9 | 13.8 |
| Max. Specific Impulse (sec) | 3120 | 4190 |
| Total Impulse (x$10^6$ N-sec) | >5 | >18 |
| Propellant Throughput (kg) | 200 | 750 |

The ion propulsion system components developed under the NEXT task include the ion thruster, the power-processing unit (PPU), the feed system, and a gimbal mechanism. The NEXT project is developing prototype-model (PM) fidelity thrusters through Aerojet Corporation. In addition to the technical goals, the project has the goal of transitioning thruster-manufacturing capability with predictable yields to an industrial source. To prove out the performance and life of the NEXT thruster, a series of tests have, or are being, performed. The NEXT PM thruster completed a short-duration test in which overall ion-engine performance was steady with no indication of performance degradation. A NEXT PM thruster has also passed qualification level environmental testing (Figure 2). As of November 1, 2011 the Long Duration Test (LDT) of the NEXT engineering model (EM) thruster achieved over 650-kg xenon throughput, 24.5 x $10^6$ N-s of total impulse, and over 38,000 hours at multiple throttle conditions. The NEXT LDT wear test demonstrates the largest total impulse ever achieved by a gridded-ion thruster. ISPT funding for the thruster life test continues through FY12 and FY13 with the aim of demonstrating thruster operation through the anticipated first failure mode, structural failure of the ion optics, which is anticipated >750 kg of xenon throughput at full power conditions.[7] A post-test inspection of the hardware will be conducted in FY13.

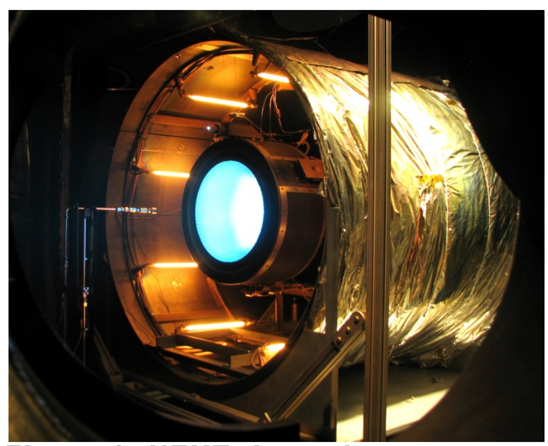

**Figure 2. NEXT thermal vacuum testing at JPL**

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 NEXT thruster can enable lower cost implementation by eliminating system complexity. Comparisons between the State-of-the-Art (SOA) NSTAR thruster and the NEXT thruster are shown in Table 1.

The missions that are improved through the use of the NEXT thruster are those requiring significant post-launch $\Delta$V, 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. Electric propulsion enables a much wider range of feasible targets. Specifically for Temple 1 in Ref. 5 the NSTAR thruster is able to complete the mission, but requires large solar arrays and four or five thrusters to deliver the required payload. NEXT would be able to deliver ten percent more total mass and require half the number of thrusters.

One of the challenges of developing the NEXT ion propulsion system has been the development of the Engineering Model PPU. The unit has experienced a series of part problem that have required extensive investigations to resolve and implement corrective actions.[8] The first part problem was a diode failure in the beam module output supply. In this instance the investigation team discovered that a diode procured from a second vendor did not have the same electrical characteristics as the diodes from the primary source. The electrical characteristics published on the specification sheet were acceptable, however, the electrical specifications, like reverse-recovery time, which were not listed in the part specification sheet, were not acceptable for the particular design application. The corrective action was to replace the second-source diodes. A second part problem was the catastrophic failure of the multi-layer ceramic (MLC) capacitor in multiple beam power supplies. The investigation process in this case required a larger team that investigated all branches of the fault tree. The corrective actions identified that a custom-built MLC had piezoelectric properties that made it susceptible to an oscillating current in the beam supply circuit. The corrective actions in this case were to replace the custom-build MLC capacitor as well as to eliminate the oscillating current. Recently another part problem was uncovered, which manifested itself as a shorted diode. The preliminary diagnosis was that a void in the printed circuit board may have contributed to an overvoltage condition on the diode which caused it to short. However, the preliminary conclusions still need to be confirmed with x-ray inspection of the printed circuit board. The corrective actions for the diode and MLC capacitor issues have been implemented in the EM PPU and have been demonstrated to resolve the problems. The investigation continues for the latest diode/printed circuit board problem. It should be noted that such part problems are not unique and technology development projects are used to flush out these kinds of issues, which are normally seen in the transition-to-flight hardware development phase.

Additional information on the NEXT system can be found in the NEXT Ion Propulsion System Information Summary in the New Frontiers and Discovery Program libraries.[7,9,10]

## ELECTRIC PROPULSION FOR SAMPLE RETURN AND DISCOVERY-CLASS MISSIONS

ISPT is investing in Sample Return Propulsion technologies for applications such as Earth-Return Vehicles for large and small bodies. The first example leverages the development of a High-Voltage Hall Accelerator (HIVHAC) Hall thruster into a lower-cost electric propulsion system.[11,12] 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 some Discovery-class missions and sample return applications. Advancements in the HIVHAC thruster include a large throttle range from 0.3–3.5 kW 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. It allows for cost benefits with a reduced part count resulting in less complex and lower cost propulsion system.

**Figure 3. HIVHAC thruster Engineering Model**

Wear tests of the NASA-103M.XL thruster validated and demonstrated a means to mitigate discharge channel erosion as a life limiting mechanism in Hall thrusters. The thruster, shown in Figure 3, operated in excess of 5500 hours (115 kg of xenon throughput) at a higher specific impulse (thruster operating voltage) as compared to SOA Hall thrusters.

Components for two Engineering Model (EM) thrusters were designed and fabricated. Preliminary performance mapping of the EM thruster at various operating conditions was performed at NASA Glenn Research Center (GRC).[11,12] The EM thruster hardware was operated in vacuum test environments for operations and performance assessments. The results indicated that several design changes were needed to resolve problems with thermal design, boron-nitride advancement mechanisms, magnetic topology, and high voltage isolation. A list of rework items was compiled and design corrections have been identified and evaluated by either analysis and/or test. The design improvements were implemented in a reworked engineering model design, which is designated as EM-R. Vacuum Facility 12 (VF-12) will be used to conduct the official performance acceptance test (PAT), given the pumping speed and resulting vacuum chamber background pressure. However, leaks in the liquid nitrogen shroud have hampered facility availability for testing. As a result EM-R operation and performance tests have been conducted in a smaller vacuum facility to demonstrate effectiveness of hardware design changes. The results are promising, however, and indicate that performance and operational requirements should be met with EM-R hardware.

In the future, the test sequence will include formal performance acceptance tests in VF-12, environmental tests (both vibration and thermal vacuum), mechanism checkout tests, short duration wear test, and starting a long duration wear test in FY12. Current plans include the design, fabrication and assembly of a full Hall propulsion system, but are pending final approval to proceed.

In addition to the thruster development, the HIVHAC project is evaluating power processing unit (PPU) and xenon feed system XFS development options that were sponsored by other projects but can apply directly to a HIVHAC system. The goal is to advance the TRL level of a Hall propulsion system to level 6 in preparation for a first flight.

The functional requirements of a HIVHAC PPU are operation over a power throttling range of 300 to 3,800 W, over a range of output voltages between 200 and 700 V, and output currents between 1.4 and 5 A as the input varies over a range of 80 to 160 V. A performance map across these demanding conditions was generated for one candidate option[11,12] that is being developed through NASA Small Business Innovation Research (SBIR) Program. Beyond conventional feed system options, one option for feed systems that was demonstrated with the Hall thruster is the advanced xenon feed system, developed by VACCO.

To continue to simplify and reduce the cost of the HIVHAC system, the ISPT project has invested in its reliable, lightweight, and low-cost xenon flow control system.[13] A follow-on contract was awarded to VACCO as a joint ISPT and Air Force effort to qualify a Hall system module. This module would significantly reduce the cost, mass, and volume of a Hall thruster xenon control system while maintaining high reliability and decreasing tank residuals. This is the first time the ISPT project has advanced a component technology to TRL 8 to further reduce the risk and cost of the first user. The new Hall module is shown in Figure 4. The Hall module is scheduled to complete its qualification program in March 2012. The module is then planned for inclusion in a long duration test as an integrated string test of the HIVHAC system. A second unit (an acceptance tested flight unit) has been ordered and should be delivered in December 2012.

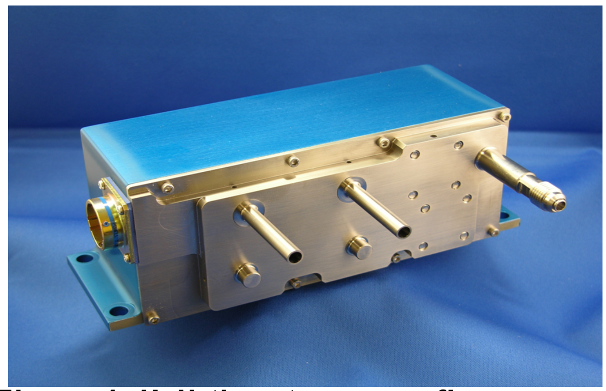

**Figure 4. Hall thruster xenon flow control module.**

For the Near-Earth Object (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.[11, 12]

The second technology example of a Sample Return Propulsion Technology is the BPT-4000 Hall thruster development. ISPT has invested in a life-test extension of the thruster to improve total impulse demonstrated capabilities. Under evaluation is the operation of this thruster design at higher operating voltages, which improve thruster specific impulse. There are mission studies that indicate that BPT-4000 is directly applicable to ERV and Discovery-class missions.

PROPULSION COMPONENT TECHNOLOGIES

ISPT invests in the evolution of component technologies that offer significant performance improvements without increasing system level risk. Two component technologies currently receiving investments are xenon feed systems (discussed in the previous section) and Ultra-Light Tank Technology (ULTT).

The ISPT Program has been investing in ultra lightweight tank technology (ULTT) led by JPL. The ULTT efforts in the past have focused on manufacturability and non-destructive evaluation of the lightweight tanks. The tank effort

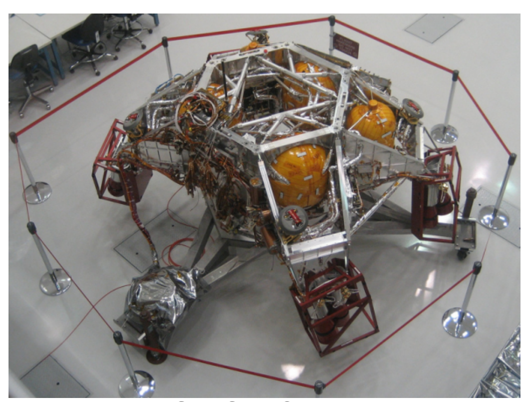

**Figure 5. MSL SkyCrane**

continues to validate defect-detection techniques to maintain NASA standard compliance for ultra-thin wall tanks with follow-on potential to develop and qualify positive expulsive ultra light-weight tanks specifically for the MSL SkyCrane. The SkyCrane tanks could offer mass savings on the order of 24 kg, which is dependent on the final tank wall thickness. The mass reduction would increase the landed mass capability of SkyCrane for a relatively low cost per kg. The SkyCrane Entry Descent Lander (EDL) system is planned for the 2018 NASA/European Space Agency Mars mission and for the Mars Sample Return (MSR) mission. Both are highly mass constrained. The Mars Science Laboratory (MSL) SkyCrane, with large propellant tanks, is shown in Figure 5. While this particular tank designs will be qualified for the SkyCrane application, the ultra-lightweight technology will be broadly applicable for a wide range of future science missions. Propulsion tanks remain the highest dry-mass reduction potential within chemical propulsion systems, and this technology would significantly push the state-of-the-art with the promise of a 2X improvement over conventional tank designs.

The development effort is divided into two main tasks: a Non-Destructive Inspection (NDI) task and the ultra-lightweight tank design/manufacturing/testing task. The NDI task has completed an initial assessment of several NDI techniques, such as eddy-current and surface wave ultrasonic techniques. The results from the tests indicate that these techniques are adequate to find crack as small 0.003 inches in the titanium lining. The objective for the NDI task is to establish the crack size that can be detected consistently using these new methods. The ultra-lightweight tank development task would incorporate the NDI technique in the manufacturing and qualification of the new tank. In order for the tank design to be a success, the approach must demonstrate "safe life". "Safe life" for non-toxic materials only requires proving a design will leak-before-burst, while "safe life" for toxic liquids, like hydrazine, is more stringent. The NDI technique must be able to detect small cracks in the thin liners, then the NDI results need to be verified, by test, that worst-case crack growth will not grow to failure. Evaluation of the NDI techniques have been completed and manufacturing of the NDI samples is underway. In parallel the ultra-lightweight development work will be completed through a contracted effort with ATK, the suppliers of the MSL tanks. The work will be divided into several phases: design, manufacturing and acceptance/qualification tests. The test phase will include cyclic testing of the flawed liner tank design to demonstrate leak-before-burst and safe life requirements. The design phase has been initiated with the Preliminary Design Review (PDR) anticipated in January 2012. The development effort will need to be completed by August 2013 in order to maintain a 6-month schedule margin for the spacecraft PDR for Mars 2018, which is anticipated in February of 2014.

## MULTI-MISSION EARTH ENTRY VEHICLE (MMEEV)

The Multi-Mission Earth Entry Vehicle (MMEEV) is a flexible design concept which can be optimized or tailored by any sample return mission, including lunar, asteroid, comet, and planetary (e.g. Mars), to meet that mission's specific requirements. The Mars Sample Return (MSR) Earth Entry Vehicle (EEV) design, which due to planetary protection requirements is designed to be the most reliable space vehicle ever flown, provides an effective foundation for many sample return missions. By leveraging common design elements, this approach can significantly reduce the risk and associated cost in development across all sample return missions. It provides significant feed-forward risk reduction in the form of technology development, testing, and even flight experience.

The current MMEEV parametric configuration is presented in Figure 6 (basic vehicle architecture). Because each individual sample return mission may have a unique set of performance metrics of highest interest, the goal is to provide a qualitative performance comparison across a specified trade space. Each sample return mission can then select the most desirable design point from which to begin a more optimized design.

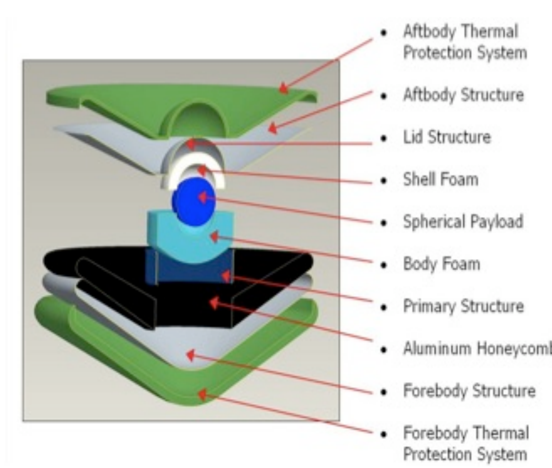


**Figure 6. Basic MMEEV architecture**

Continued development of the MMEEV models is planned to include: more sophisticated parametric configuration models, including payload accommodation; higher fidelity impact dynamics model (e.g. finite-element model); updated aerodynamics models based on ground (e.g. wind tunnel and ballistic range) testing as well as Computational Fluid Dynamics (CFD) analysis; and high fidelity TPS mass/thickness sizing models for additional candidate TPS materials (PICA and carbon phenolic are currently supported). MMEEV performance studies will continue with the eventual integration of the MMEEV models into the "Multi-Mission Systems Analysis for Planetary Entry" (M-SAPE) Tool, a prototype EDL analysis tool, originally developed in support of ISPT aerocapture studies. M-SAPE's capabilities are currently being expanded to include landing, and the code will support mission studies to any celestial body with an atmosphere. The M-SAPE tool contains low-, mid-, and high-fidelity models, and the user can specify the level of analysis to be performed. High-fidelity, validated thermal protection system response models and trajectory simulation tools are incorporated into the baseline tool. Plans for the next 2 years of development include ground tests to validate the other tool modules; in particular, the impact foam characteristics under thermal loads, and the impact dynamics. To improve the fidelity of the system analysis, a preliminary thermal soak model has been developed at NASA-Ames to understand the thermal environment of the returned sample canister after the vehicle undergoes the heat pulse and waits to be recovered. Samples from various comets, asteroids, and planets may have differing thermal requirements, and this analysis will help determine if active thermal control is needed or if the MMEEV design needs to be changed for some applications. Another critical analysis recently completed is a micrometeoroid and orbital debris (MMOD) impact assessment from NASA-JSC. The probability of impact during some mission profiles may drive the need for an MMOD shield, which will significantly affect the vehicle system design.

The biggest challenge for any space vehicle, including the MMEEV, is to adequately prove the reliability of the components, subsystems, and the flight system as a whole. The current estimate to develop the EEV technology for MSR to TRL 6 is approximately $41 million. This does not include a dedicated flight test which, many experts agree, is needed to achieve the $10^{-6}$ probability of failure, because the entry flight environment cannot be completely replicated in ground-based facilities. One way to achieve a flight validation for little extra cost to NASA is to use the MMEEV design concept, or at least the major components of the design, in sample return missions likely to fly prior to MSR, such as 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.

AEROCAPTURE

Aerocapture is the process of entering the atmosphere of a target body to practically eliminate the chemical propulsion requirements of orbit capture. Aerocapture is the next step beyond aerobraking, which relies on multiple passes high in the atmosphere using the spacecraft's drag to reduce orbital energy. Aerobraking has been used at Mars on multiple orbiter missions. Aerocapture, illustrated in Figure 7, maximizes the benefit from the atmosphere by capturing into orbit in a single pass. Aerocapture represents a major advance over aerobraking techniques by flying at a lower altitude where the atmosphere is more dense. 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. A lightweight thermal protection system and structure will maximize the aerocapture mass benefits.

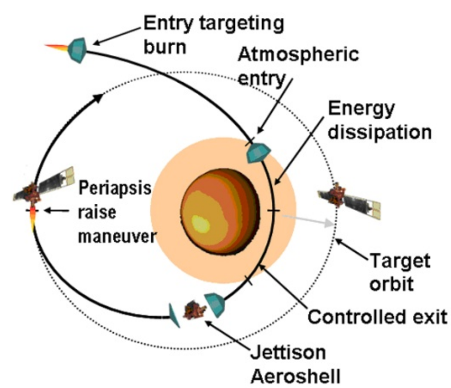


**Figure 7. Illustration of the aerocapture maneuver.**

Decelerating the vehicle with aerodynamic drag enables 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 can be 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. 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

**Figure 8. Fit check of TPS modules on 2.65-m aeroshell.**

aeroshell, and currently, a 2.65-meter aeroshell featuring high-temperature honeycomb structures and adhesives (Figure 8). Recent developments by other NASA programs on inflatable decelerators have leveraged previous ISPT investments, including concept definition and initial design and testing of several inflatable decelerator candidates that could utilize Aerocapture in the future. Finally, progress has also been made through improvement of models for atmospheres, aerothermal effects, and algorithms and hardware-in-the-loop testing of a flight-like guidance, navigation and control (GN&C) system.

Aerocapture has been proven repeatedly in detailed analyses to be an enabling or strongly enhancing technology for several atmospheric targets. The ISPT project team continues to mature aerocapture components in preparation for a flight demonstration, and rapid aerocapture analysis tools are being developed and made available to a wider user community. The TPS materials developed through ISPT enhance a wide range of missions by reducing the mass of entry vehicles. Some of the remaining gaps for technology infusion are efficient TPS for Venus and high-speed Earth return. All of the other component subsystems for an aerocapture vehicle are currently at or funded to reach TRL 6 in the next year. This assessment of technology readiness is detailed in Ref. 14. The structures and TPS subsystems as well as the aerodynamic and aerothermodynamic tools and methods can be applied to small-scale entry missions even if the aerocapture maneuver is not utilized.

The Aerocapture system cannot reach TRL 6 without space flight validation, because it is impossible to match the flight environment in ground facilities. This validation can be accomplished by utilizing Aerocapture on a science mission, or by a dedicated space flight validation experiment. NASA's Science Mission Directorate has incentivized the use of Aerocapture in its recent Discovery Announcement of Opportunity. Since a Discovery mission utilizing Aerocapture was not selected, other opportunities will be sought to validate this technology in space. A space flight validation is expensive, but the costs will be recouped very quickly if just one mission's launch vehicle cost is reduced as a result of the lower mass requirement enabled by Aerocapture. The validation immediately reduces the risk to the first user and matures 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 missions will become possible. Additional information on Aerocapture technology developments can be found in the Discovery Program library.[9] Using Aerocapture produces significant cost benefits 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 can be found in the Aerocapture-related references in Ref. 5.

## MARS ASCENT VEHICLE (MAV)

For many years, NASA and the science community asked 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) Program Office. The objective of the ISPT Program 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).

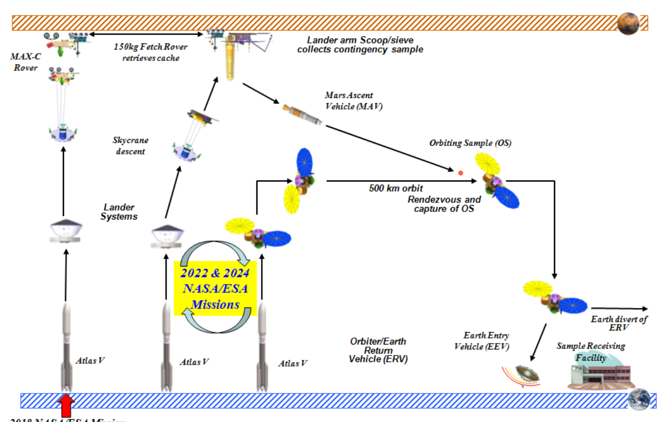


**Figure 9. MSR baseline architecture**

The current architecture (Figure 9) for the MSR Lander is to use the Mars Science Laboratory (MSL) entry, descent, and landing (EDL) system.[15] Using the MSL sky crane concept places significant environmental, physical envelope and mass limitations on the MAV system options.

Beyond the limitations of the EDL system, the MAV (Figure 10) has specific requirements to deliver the orbiting sample (OS) into an orbit suitable for the Earth Return Vehicle (ERV). The basic requirements include:

- Ability to launch from latitudes between 15$^{o}$ S and 25$^{o}$N
- A final orbit with a periapsis > 460km and an apoapsis < 580km
- A final orbit inclination of 45$^{o}$ +/- 0.2$^{o}$
- Accommodate ~5kg, 16cm diameter sample container
- Provide sufficient telemetry to discern off-nominal performance

Through the NASA Research Announcement (NRA) process, the ISPT project solicited MAV system designs and plans to initiate propulsion system development. Multiple contractors were selected to proceed in October of 2010 and efforts were initiated in February 2011. Awards were made to ATK, Lockheed Martin, and Northrop Grumman to develop MAV concepts using solid-solid, solid-liquid, and liquid-liquid 1$^{st}$ and 2$^{nd}$ stage propulsion systems respectively. During the NRA efforts, the contractors completed Principal Investigator (PI) led collaborative engineering designs of the MAV and will begin contract options to develop the required technologies in early FY 12. Additionally, Firestar Technologies has been working under an SBIR to develop a propulsion system applicable to the MAV based on a Nitrous Oxide Fuel Blend implementation.

NASA also performed system design studies with JPL's Team-X and GRC's COMPASS teams. The collaborative designs included a system level optimization using the industry designs, but also an internal "leveled" design to allow comparison of system mass, complexity, and maturity. The trades included the MAV support systems and lander impacts to minimize the total landed mass and not simply the MAV. The preliminary results of the studies indicate that the baseline solid-solid system appears to offer the lowest mass solution but may have challenges achieving the required orbit dispersion accuracies, the solid-liquid option has a slightly higher mass, imposing more thermal requirements on the lander, but can reduce dispersion errors, and the liquid-liquid option has the highest mass growth potential due to its mass fraction relative to a solid motor, but requires the least lander resources and has very tight dispersions. The NOFBx system evaluation should be completed in November, 2011. The baseline MAV concept design is shown in Figure 11. The baseline design is pre-decisional and for understanding design trades and sensitivities; it does not represent any concept selection.

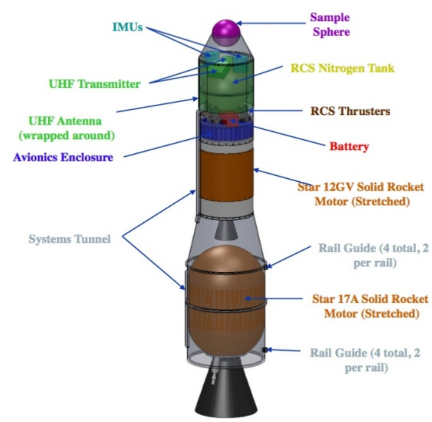


**Figure 11. Baseline MAV Concept Design**

In addition to performance, each of the MAV concepts has been evaluated for risk and technology maturation has been recommended; primarily in the propulsion elements. The ongoing NRA work will initially focus on the key risks of the individual propulsion systems at the component level. All of the MAV concepts are moving forward at various levels. The project hopes to achieve a milestone in late FY12 to address the key risks of each option and determine the final viability of various concepts. If the concepts are viable with respect to mass, volume, and risks, an integrated propulsion stage demonstration is planned to conclude in FY14. If sufficient risk can be reduced through the NRA, NASA may potentially solicit an engineering model MAV development with an objective of a vehicle terrestrial flight demonstration. In order to meet the planned Mars Sample Return lander launch date in 2024, it is desired to complete the first EM MAV demonstration in 2018.

ADVANCED CHEMICAL PROPULSION

ISPT's approach to the development of chemical propulsion technologies is primarily the evolution of subcomponent technologies that still offers significant performance improvements, with minimal risk. The mission benefits in 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. Ref. [16] has a thorough description of the complete Advanced Chemical Propulsion effort that was concluded in 2009.

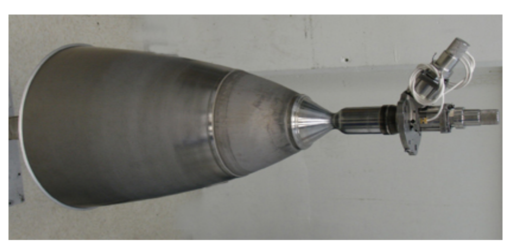

**Figure 12. AMBR engine test article**

The single largest investment within the advanced chemical propulsion technology area was the Advanced Materials Bipropellant Rocket (AMBR) engine (Figure 12), which was awarded, through a competitive process, to Aerojet Corporation in FY2006. The AMBR engine is a high temperature thruster that aimed to address cost and manufacturability challenges of using iridium coated rhenium chambers. The project[4] included the manufacture and hot-fire tests of a prototype engine demonstrating increase performance and validating new manufacturing techniques. Performance testing was conducted on the AMBR engine in October 2008 and February 2009 with long duration testing in June 2009. The thruster demonstrated an $I_{sp}$ of 333 seconds, which is the highest ever achieved for hydrazine/NTO (nitrogen tetroxide) propellant combination. The project also completed vibration, shock, and long duration testing to raise the TRL to 6.[17] Additional information is found in the AMBR information summary in the New Frontiers and Discovery program libraries.[9],[18]]

SYSTEMS/MISSION 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. Systems analysis is used to identify the future mission needs for decadal missions and discovery mission DRMs. The mission studies identify technology gaps and are then used to quantify mission benefits at the system level. This allows studies to guide the investments and define metrics for the technology advancements. Recent systems analysis efforts have included quantitative assessment of higher specific impulse Hall thrusters,[19] higher thrust-to-power gridded-ion engines, and evaluation of monopropellant system anomalies to assess failure modes and potential mitigation options. In addition to informing project decisions, the mission design studies also provide an opportunity to work with the science / user community.

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 allow the potential mission users to quantify the benefits and understand implementation of new technologies. 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. For example, low-thrust trajectory analyses are critical to the infusion of new electric propulsion technology. The ability to calculate the performance benefit of complex electric propulsion missions is intrinsic to the determination of propulsion system requirements. Improved mission design tools have repeatable demonstrated the ability to enable greater science with reduces risk and/or reduced transit times. Every effort is made to have the In-Space Propulsion Technology program tools validated, verified, and made publicly available. Instructions to obtain the tools currently available are provided on the ISPT project website.[20]
http://spaceflightsystems.grc.nasa.gov/Advanced/ScienceProject/ISPT/

The ISPT office invested in multiple low-thrust trajectory tools that independently verify low thrust trajectories at various degrees of fidelity. The ISPT low-thrust trajectory tools suite includes Mystic[21], the Mission Analysis Low Thrust Optimization (MALTO)[22] program, Copernicus,[23] 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 continuing its series of courses for training on the ISPT project tools. On-going tool advancements include providing MALTO and Mystic all platforms, bug fixes, and increased capabilities. Updates for MALTO and Mystic were completed for Linux and Mac operating platforms and Copernicus v3.0 for the PC in October 2011.

The Aerocapture Quicklook Tool, formally the multidisciplinary tool for Systems Analysis of Planetary EDL (SAPE) is also available for the user community. SAPE is a Python based multidisciplinary analysis tool for entry, decent, and landing (EDL) at Venus, Earth, Mars, Jupiter, Saturn, Uranus, Neptune, and Titan. The purpose of the SAPE is to provide a method of rapid assessment of aerocapture or EDL system performance, characteristics, and requirements. SAPE includes integrated analysis modules for geometry, trajectory, aerodynamics, aerothermal, thermal protection system, and structural sizing. For Aerocapture and EDL system designs, systems analysis teams typically include systems engineers and disciplinary specific experts in flight mechanics, aerodynamics, aerothermodynamics, structural analysis, and thermal protection systems (TPS). The systems analysis process may take from several weeks to years to complete. While the role of discipline experts cannot be replaced by any tool, the integrated capabilities of SAPE can automate and streamline several parts of the analysis process significantly reducing the time and cost, or preliminary assessment. SAPE continues to receive investment for assessment of Earth Entry Vehicles.

TECHNOLOGY INFUSION

Since 2001, the In-Space Propulsion Technology (ISPT) program has been developing in-space propulsion technologies that will have broad applicability to future competed Discovery and New Frontiers mission solicitations, and are potentially enabling for future NASA flagship and sample return missions currently being considered. This paper described the status of the technology development of several in-space propulsion technologies that are ready for infusion into future missions. The technologies that are ready for flight infusion are: 1) the high-temperature Advanced Material Bipropellant Rocket (AMBR) engine providing higher performance; 2) NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, a 0.6-7 kW throttle-able gridded ion system; and 3) Aerocapture technology development with investments in a family of thermal protection system (TPS) materials and structures; guidance, navigation, and control (GN&C) models of blunt-body rigid aeroshells; and aerothermal effect models.

NASA recognizes that it is desirable to fly new technologies that enable new scientific investigations or to enhance an investigation's science return. The Solar System Exploration (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.

To benefit from its technology investments, NASA provided incentives for infusion of new technological capabilities that it had developed in the most recent New Frontiers and Discovery competed mission solicitations. The incentives for NEXT, AMBR, Aerocapture, and the Advanced Stirling Radioisotope Power System (ASRG) were in the form of increases to the cost cap for the mission, or providing the ASRG as Government Furnished Equipment (GFE). AMBR stands for the Advanced Materials Bi-propellant Rocket engine, which ISPT and Aerojet completed the development to TRL 6 in 2009. The Decadal Survey states "these technologies continue to be of high value to a wide variety of solar system missions." And that "NASA should continue to provide incentives for these technologies until they are demonstrated in flight." The 2011 Planetary Decadal Survey strongly supported continuing to incentivize these technologies until they are flown.[3] As funding and priorities allow, ISPT will strive to maintain the capabilities associated with NEXT, AMBR, and aerocapture.

Beyond the New Frontiers and Discovery opportunities, ISPT continues to seek opportunities to infuse NEXT, AMBR, Aerocapture, and its other technologies into a wide range of possible future mission opportunities. The ISPT project office and NEXT team personnel are actively supporting various flagship science definition team (SDT) studies. See the ISPT Overview paper in the 2011 IEEE Aerospace Conference for more details regarding these studies.[4,5] ISPT will continue to help in identifying the technology development that is required to accomplish the future missions being contemplated.

The paper also described the ISPT project's efforts to develop propulsion for sample return missions: 1) Mars Ascent Vehicles (MAV); 2) multi-mission technologies for Earth Entry Vehicles (MMEEV) needed for sample return missions from many different destinations; 3) propulsion for Earth Return Vehicles (ERV) and transfer stages, and electric propulsion for sample return and low cost missions. These technologies are more vehicle-focused, and present a different set of technology infusion challenges. Two technologies that will be ready for flight infusion in FY12/13 are Advanced Xenon Flow Control System and ultra-lightweight propellant tank technology advancements and their infusion potential were also discussed.

## FUTURE PLANS AND CONCLUSION

The future focus areas for ISPT are propulsion systems for sample return missions. Activity in these technology development areas continues in 2011 and increases in 2012 and 2013. The direction focuses on: 1) Planetary Ascent Vehicles; 2) multi-mission technologies for Earth Entry Vehicles required for sample return missions; and 3) electric and chemical propulsion for Earth Return Vehicles, transfer stages, and low cost

Discovery-class missions. These sample return missions are inherently propulsion intensive. Several of the earlier ISPT technology areas may also be involved in a single sample return mission. The mission may use Electric Propulsion for transfer to, and possibly back from, the destination. Chemical propulsion may be utilized for the ascent and descent to the surface. Aeroshells may be used for Earth re-entry and an aerocapture maneuver used to capture at the destination. Future sample return missions of interest for NASA and the science community, and those that are yet to be conceived, continue to demand propulsion systems with increasing performance and lower cost. This paper addressed how the ISPT project is starting to develop propulsion technologies for NASA's future sample-return missions.

## ACKNOWLEDGMENTS

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# STATUS OF NASA IN-SPACE PROPULSION TECHNOLOGIES AND THEIR INFUSION POTENTIAL

ABSTRACT

Since 2001, the In-Space Propulsion Technology (ISPT) program has been developing in-space propulsion technologies that will enable or enhance NASA robotic science missions. These in-space propulsion technologies have broad applicability to future competed Discovery and New Frontiers mission solicitations, and are potentially enabling for future NASA flagship and sample return missions currently being considered. This paper provides status of the technology development of several in-space propulsion technologies that are ready for infusion into future missions. The technologies that are ready for flight infusion are: 1) the high-temperature Advanced Material Bipropellant Rocket (AMBR) engine providing higher performance; 2) NASA's Evolutionary Xenon Thruster (NEXT) ion propulsion system, a 0.6-7 kW throttle-able gridded ion system; and 3) Aerocapture technology development with investments in a family of thermal protection system (TPS) materials and structures; guidance, navigation, and control (GN&C) models of blunt-body rigid aeroshells; and aerothermal effect models. Two component technologies that will be ready for flight infusion in FY12/13 are 1) Advanced Xenon Flow Control System, and 2) ultra-lightweight propellant tank technology advancements and their infusion potential will be also discussed. The paper will also describe the ISPT project's future focus on propulsion for sample return missions: 1) Mars Ascent Vehicles (MAV); 2) multi-mission technologies for Earth Entry Vehicles (MMEEV) needed for sample return missions from many different destinations; and 3) electric propulsion for sample return and low cost missions. These technologies are more vehicle-focused, and present a different set of technology infusion challenges. Systems/Mission Analysis focused on developing tools and assessing the application of propulsion technologies to a wide variety of mission concepts.

# Status of NASA In-Space Propulsion Technologies and Their Infusion Potential

**David Anderson**
**Eric Pencil**
**Dan Vento**
**Todd Peterson**
**John Dankanich**
**David Hahne**
**Michelle Munk**

**JANNAF Propulsion Meeting**
**December 5-9, 2011**
**Huntsville, Alabama**

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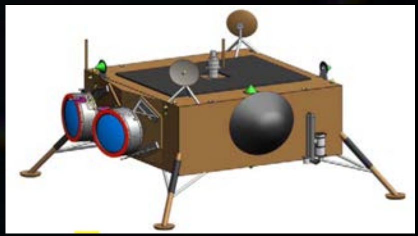


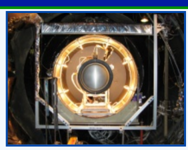
***ISPT Objective***: *"Develop in-space propulsion technologies that enable or benefit near to mid-term NASA science missions by significantly reducing travel times required for transit to distant bodies, increasing scientific payload capability or reducing mission costs."*

*→ ISP will enable access to more challenging and interesting science destinations, including enabling sample return missions.*

## Propulsion System Tech.s

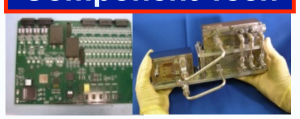
**High-Temp Engine (AMBR)**

**NEXT**



**Hall Thruster**

**Component Tech**

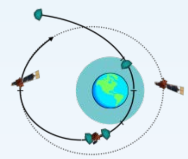


## Sample Return Technologies

**Mars Ascent Vehicle**

## Entry Vehicle Technologies

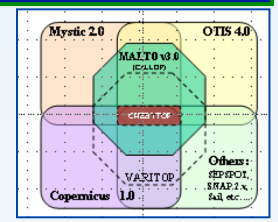
**Aerocapture**



**Multi-Mission Earth Entry Vehicle**

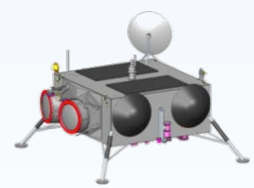
## Systems & Mission Studies

**Tools**



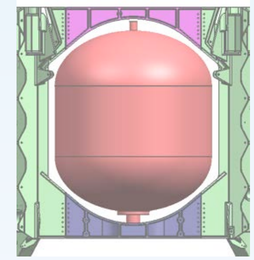

**Mission Studies**

**System Studies**



## Spacecraft Bus Technologies

**Ultra Lt Wt Tank**



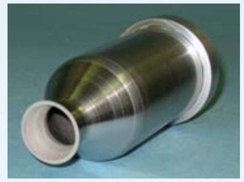
- The ISPT project addresses the primary propulsion technology needs for the agency's future robotic science missions.
- The current ISPT focus is on TRL 3-6+ product development

# Advanced Materials Bipropellant Rocket (AMBR)

## Objective

- Improve the HiPAT bipropellant engine Isp performance by fully exploiting the benefits of advanced thrust chamber materials

- Performance
  - * 333 seconds Isp with NTO/N2H4
  - * Over 1 hour operating (firing) time
  - * 140 lbf thrust
  - * 3-10 years mission life (goal)
  - * Lower cost (up to 30% savings on the chamber)



Completed EL-Form Ir/Re Chamber

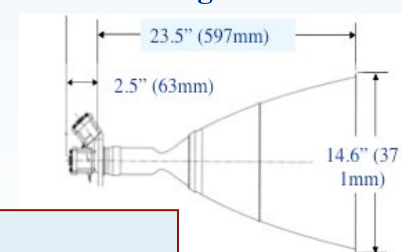
| Total Propulsion System Mass Reduction (Kg) | | | | | |
|---|---|---|---|---|---|
| Isp (sec) | 320 | 325 | 330 | **332.5** | 335 |
| GTO to GEO | 0 | 16 | 30 | **37** | 45 |
| Europa Orbiter | NA | 0 | 12 | **16** | 24 |
| Mars Orbiter | N/A | 0 | 14 | **22** | 29 |
| T-E Orbiter | N/A | 0 | 29 | **45** | 60 |


- **Performance Tests**
  - Completed 89 engine starts
  - 9,138s of total firing time (152.3 minutes)
    - 2,700s (45 minutes) longest single burn duration
  - 3,935°F (2,160°C) steady state chamber temperature
  - 99 – 289 psia operating chamber pressure
  - 333.5 seconds maximum specific impulse
  - Defined complete operational range

- **Environmental Tests**
  - Passed qualification level vibration test
  - Passed shock test

- **Future Use**
  - Commercial interest, DoD interest, constellation interest, and decadal studies

**AMBR Engine Dimensions**




***The AMBR technology is an improvement upon the existing HiPAT™ engine***

- The HiPAT™ engine is one of the Aerojet Corporation's R-4D Family of thrusters
- The R-4D family of thrusters carries the heritage: >1000 engines delivered, >650 flown, 100% success

# NEXT: Expanding SEP Applications For SMD Missions

Objective: Improve the performance and life of gridded ion engines to reduce user costs and enhance/enable a broad range of NASA SMD missions


NEXT gridded ion thruster


NEXT PM ion thruster operation at NASA GRC

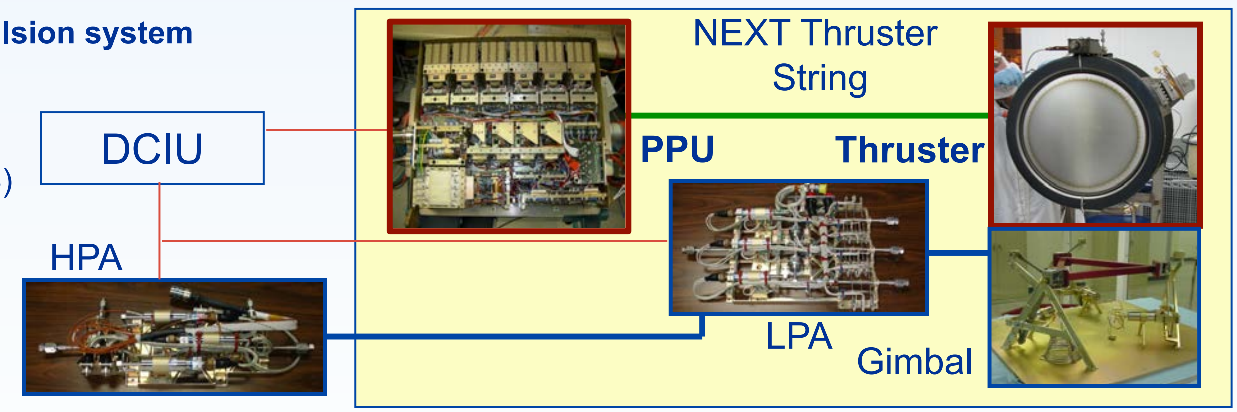
| Thruster Attribute | |
|---|---|
| **Thruster power range, kW** | **0.5 - 6.9** |
| **Max. Specific Impulse, s** | **4,190** |
| **Thrust range, mN** | **26 - 236** |
| **Propellant Throughput, kg** | **450*** |
| **Mass (with harness), kg** | **13.5** |
| **Envelope dimensions, cm** | **43.5 x 58.0** |
| Power Processing Unit Attribute | |
| **Power Processing Unit mass, kg** | **33.9** |
| **Envelope dimensions, cm** | **42 x 53 x 14** |
| **Input voltage range, V** | **80 - 160** |
| Feed System Attribute | |
| **High Pressure Assembly mass, kg** | **1.9** |
| **Low Pressure Assembly mass, kg** | **3.1** |

**NEXT addresses the entire ion propulsion system**

- Gridded ion thruster
- Power processing unit (PPU)
- Propellant management system (PMS)
- System integration (including gimbal and control functions)

**Primary Partners**

- NASA Glenn Research Center: Lead
- JPL, Aerojet Corp., L3 Comm.

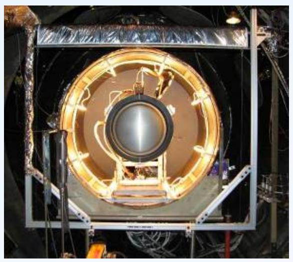


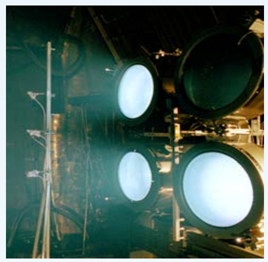

* Rated Capability Goal 300Kg → Design/Qualification Goal (1.5x Rated) 450Kg
Projected 1st Failure >750Kg → Potential Rated Capability 500Kg

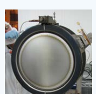
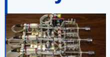
# NEXT TRL6 Status and Mission Benefits

## NEXT is Nearing TRL6 Validation

- Single-String System Integration Test: **Complete**
- Multi-String System Integration Test: **Complete**
- Thruster Life Test: **Completed** goal of 450Kg throughput
  - ***>38,000 hours and >650 kg of xenon processed as of 11/01/2011***
  - Life Test will continue through 750Kg or first failure





| • Critical tests have been completed, or are imminent, on high fidelity hardware | PM1  | PM1R  | PPU  | Feed System  | Gimbal  |
|---|---|---|---|---|---|
| **Functional & Performance Testing** | Complete | Complete | Complete | Complete | Complete |
| **Qual-Level Vibration Test** | Complete | Complete | Not planned | Complete | Complete |
| **Qual-Level Thermal / Vacuum Test** | Complete | Complete | TBD* | Complete | Not planned |

* Pending completion of NEXT PPU MLC capacitor investigation and recovery

## NEXT Mission Benefits & Applicability

| CHARACTERISTIC | NSTAR (SOA) | NEXT | Improve-ment | NEXT BENEFIT |
|---|---|---|---|---|
| Max. Thruster Power (kW) | 2.3 | 6.9 | 3x | Enables high power missions with fewer thruster strings |
| Max. Thrust (mN) | 91 | 236 | 2.6x | |
| Throttling Range (Max./Min. Thrust) | 4.9 | 13.8 | 3x | Allows use over broader range of distances from Sun |
| Max. Specific Impulse (sec) | 3120 | 4190 | 32% | Reduces propellant mass, enabling more payload and/or lighter spacecraft |
| Total Impulse ($10^6$ N-sec) | 4.6 | >18 | >3.9x | Enables low power, high $\Delta$V Discovery-class missions with a single thruster |
| Propellant Throughput (kg) | 150 | 450 | 3x | |

| Mission | Performance Finding |
|---|---|
| **Discovery** - Small Body Missions | **Higher net payload mass with fewer thrusters** than NSTAR system |
| **New Frontiers -**<br>· Comet Surface Sample Return<br>· Titan Direct Lander | CSSR: **Higher net payload mass** than NSTAR, with, **simpler EP System**: 2+1 NEXT vs 4+1 NSTAR thrusters<br>Titan: > 700 kg entry package with 1+1 NEXT system |
| **Flagship** - Saturn System Missions<br>• Titan<br>• Enceladus | > 2400 kg to Saturn Orbit Insertion with 1+1 NEXT system, EGA + Atlas V EELV - **Doubles delivered mass of chemical/JGA approach**<br>> 4000 kg to Saturn Orbit Insertion with 3+1 NEXT system, EGA + Delta IV Heavy |

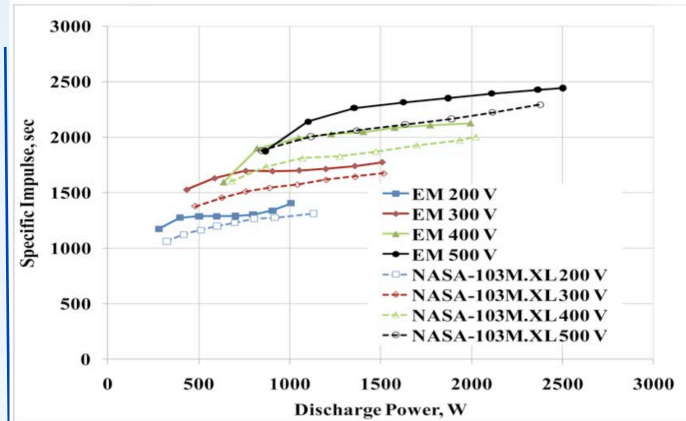
# High Voltage Hall Accelerator (HIVHAC)

## for low cost Discovery-class and Sample Return Missions

### Objective

Develop low power, long-life Hall thrusters to reduce the cost of Discovery-class missions compared to SOA ion and hall thrusters

| Input Power | 0.3 - 3.5 kW |
|---|---|
| Specific Impulse | 1600 - 2700 s |
| Efficiency | > 55% @ 3.5 kW |
| Thrust | 20 – 150 mN |
| Propellant Throughput | > 300 kg |
| Specific Mass | 2.4 kg/kW |
| Operational Life | > 10,000 hrs |




HIVHAC EM

### Approach

**Hall thruster numerical erosion models**

- Implement advanced numerical simulations of Hall thruster channel erosion, and evaluate against experimental data

**Thruster fabrication and extended life test**

- NASA-103M (ASOA) Hall thruster with in-situ replacement of channel ceramic walls to improve Xenon throughput to 300-kg
- Incorporate lessons-learned from NASA-103M.XL wear test into the design of an EM 3.5 kW HIVHAC thruster

**Primary Partners**

- NASA Glenn Research Center: Lead
- Aerojet Corp.

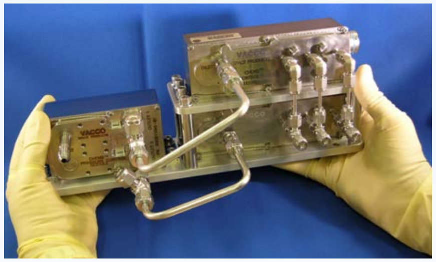
### Key Milestones/Accomplishments

- **NASA-103M wear test** started at GRC Sept 2006 with >100 kg and >4750 hours of life accumulated (34% of goal)
  - Novel channel replacement mechanism demo'ed in FY07
  - Thrust degradation over life has been characterized in FY07
  - Novel channel replacement mechanism demonstrated at additional throttle points in FY08
  - Thermal environment characterized over throttle table and used in design of EM thruster in FY08
- **Preliminary Design Review** of EM thruster completed August 2008.
- **EM Hardware assembly** completed July 2009.
- **EM test sequence** in FY10/FY11 will include performance acceptance tests, environmental tests & long duration test.

# Advanced Xenon Feed System (AXFS)

## OBJECTIVE

- ISPT award a contract with VACCO industries to develop a modular Advanced Xenon Flow System (AXFS) with significant reductions in mass, cost, and volume over SOA while increasing system reliability.
  - Flow control accuracy error < 3% EOL
  - System designed to operate NEXT
  - Complete feed system and controller
  - TRL 6 testing
  - Award for two FCMs, 1 PCM, 1 controller with LabVIEW software



VACCO AXFS

Dawn Feed System

## STATUS

- The ISPT project has invested in an AXFS, developed by VACCO Industries:
- Completed limited qualification level environmental testing
  - Demonstrated hot-fire operation
  - Pressure control
  - Current control
- Demonstrated 70% reduction in Mass,
- 50% reduction in footprint, and
- Expected 50% cost reduction over NEXT SOA PMS.

- **The VACCO AXFS is ready for technology infusion.**

| | NSTAR | NEXT | AXFS | XFCM |
|---|---|---|---|---|
| Mass, kg | 11.4 | 5.0 | 1.5 | 1.25 |
| Estimate Footprint, $cm^2$ | 1,900* | 1,654 | 800 | 115 |
| # Channels Controlled | 2 | 3 | 3 | 2 |
| Duration to Throttle, min | 45 | <1 | <1 | <1 |
| Average Power (Max), W | | 7.9(81) | <0.01 | <0.01 |

* Does not include plenum tanks

The AXFS was a small investment on feed system technology independent of NEXT to leverage commercial investments and push the limits of technology without adding risk to the NEXT project.

# Xenon Flow System Options for HIVHAC


VACCO XFCM

- **The HIVHAC project goal is to use a low-cost light-weight XFS**
- A number of XFSs are available for integration with the HIVHAC thruster including the Moog flight qualified BPT-4000 XFS (TRL 9), the Aerojet manufactured NEXT thruster XFS (TRL 6), and the VACCO advanced XFS (TRL 6) developed under a NRA selection.
- The VACCO XFS represents a dramatic improvement over the NSTAR flight feed system and also represents an additional 70% reduction in mass, 50% reduction in footprint, and 50% reduction in cost over the baseline NEXT XFS
- HIVHAC thruster hot-fire testing with the VACCO XFS was performed last year for three thruster-XFS configurations to verify the XFS integrated operation with a Hall thruster
- As a result of the successful testing of the HIVHAC thruster with the VACCO XFS, NASA GRC and the AFRL are acquiring a flight-like VACCO xenon control module (XCM) for integration with the HIVHAC thruster LDT, the goal is to use the LDT as an opportunity to qualify the VACCO flight XCM over extended operation

# Lightweight Tanks for future planetary missions

## Description

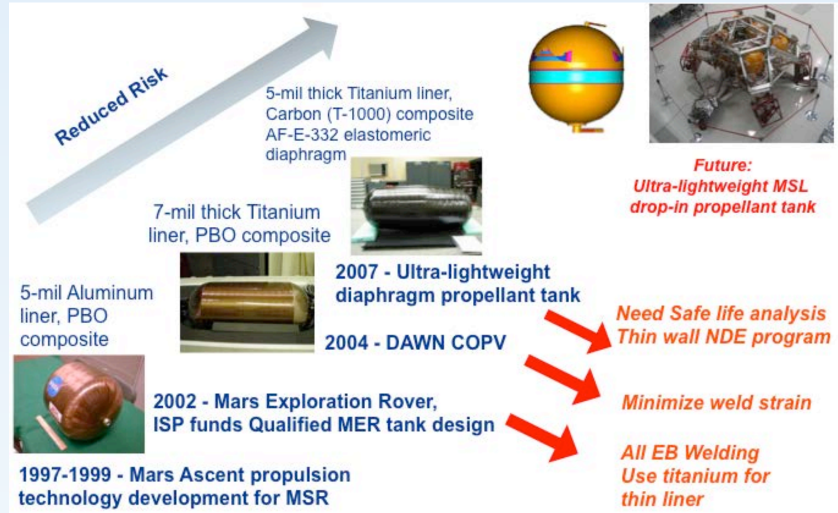
- This effort aims to develop the Composite Overwrapped Pressure Vessel (COPV) tanks for propellants and pressurants for Mars Sample Return (MSR) mission
- Tanks are most often the heaviest component on a spacecraft
- Currently component technologies are maturing and ready to be “harvested”

## Objective

- To develop and qualify ultra-lightweight propellant and pressurant tanks sized for MSL/MSR Skycrane
- Goal:  Achieve highest mass saving with reliability

## Benefits

- 20-30 kg mass savings are achievable for 3 tanks sized for the Skycrane
  - Mass savings can be passed on to the scientific payload or increase mass margin
- Broad impact to virtually ALL space missions as most use liquid propellants or pressurant
  - Europa Explorer tank mass can be reduced by 60 kg

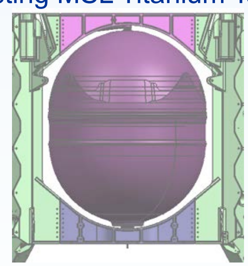



## Approach

- To build and test three (3) Skycrane size tanks
- To ready the tanks for 2018 flight demonstration

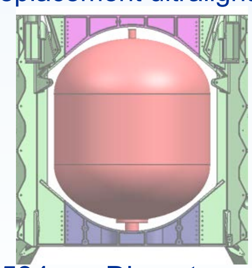
**Descent Stage Propellant Tanks**

Existing MSL Titanium Tank



594mm Diameter, ~720mm Tall

Drop in replacement ultralight tank



594mm Diameter, 684mm Tall

# Two part effort: NDI and tank development

- Effort to develop composite pressure vessel is divided into two parallel activities
  - Critical Non-Destructive Inspection (NDI) effort: to establish what crack size can be detected consistently (probability of detection demonstration) using new methods (eddy current or lamb wave seen as best options)
  - JPL in-house activity
    - FY11/FY12 work plan includes evaluation of NDI techniques, fabrication of test coupons w/ defects, evaluation of defects w/ candidate NDI techniques.
    - Design, manufacture (using techniques worked out on previous programs and the NDI being developed above), and test a new tank design for a Mars 2018 lander mission
  - ATK contracted activity

**Indication of .006” deep crack**

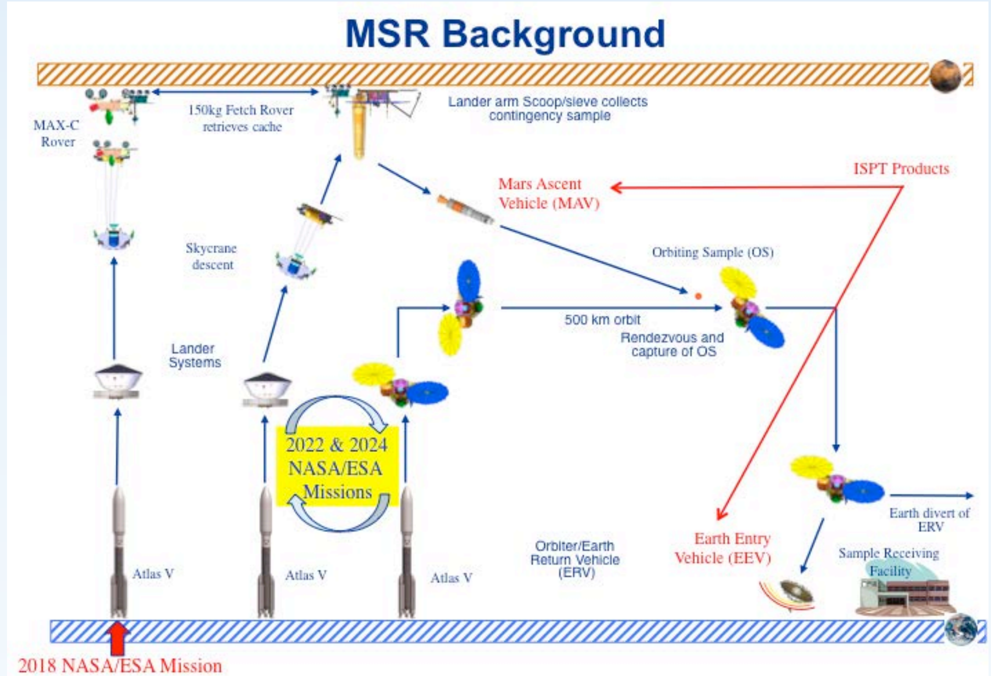
Eddy current NDI technique

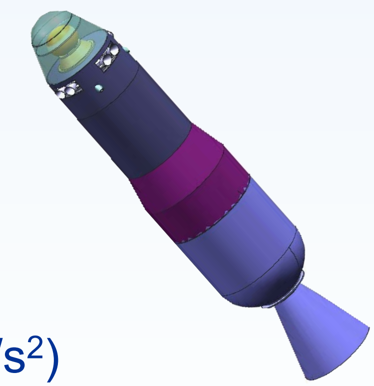


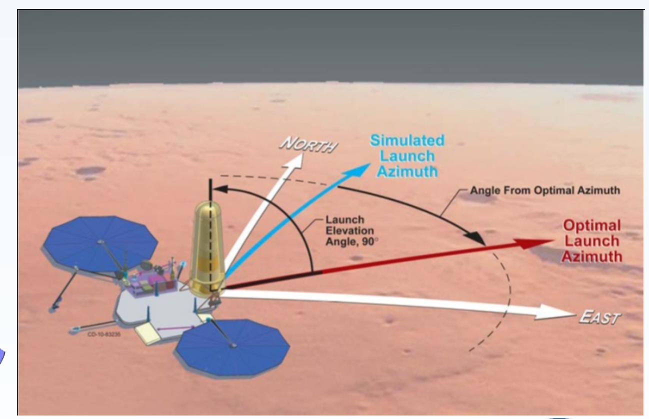
Surface wave ultrasonic NDI technique

# Mars Ascent Vehicle (MAV) Top Level Requirements

- Launch to Mars orbit
  - 500 km ±100 km
  - 45° latitude
  - Delta V > 3.3 km/s
- MAV spends 90 + sols on Martian surface
- 5 kg Orbiting Sample (OS), with 0.5-1.0 kg of samples
- Single-fault tolerant avionics & thermal control
- Telemetry system operational through payload separation
- Adequate data link margin to orbiter at 4400 km altitude
- Desire to meet interface requirements of MSL EDL
- EDL produces ≥ 20 g's (200 m/s$^2$)

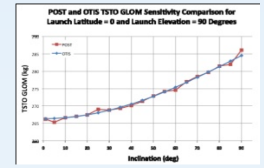




# MAV Notional Development Plan

- **Phase 1: Early investment (~$4M funded by ROSES NRA, 6 month studies)**
  - System definition and development studies (~6 months)
  - Propulsion subsystem development and tests for select MAV concepts (~3 years)



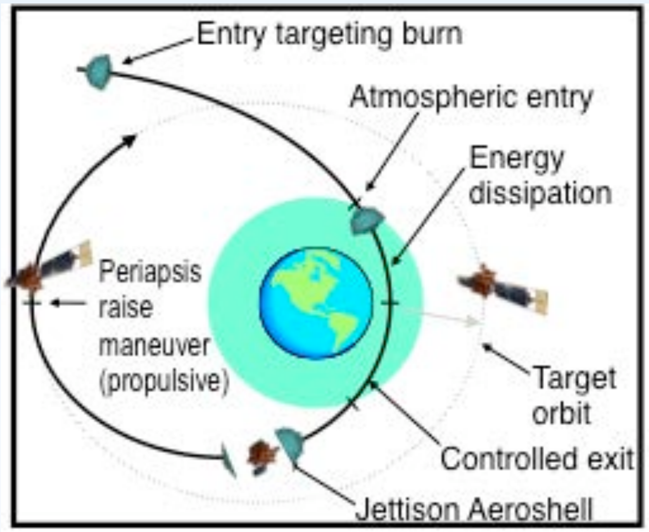

- **Phase 2: Component technology development to TRL 6 and system architecture selections (~3 years, ~$40M, may include follow-on options)**
  - Develop component technologies to reach TRL6
  - Test components' performance in realistic temperatures, storage, EDL g-loads as appropriate
  - Culminates in the final downselect to a single concept, whose high-risk components have known performance and survivability characteristics
- **Phase 3: Integrate and develop a MAV. Perform integrated testing and qualification. (~5 years, ~$210M, includes Phase 3 options)**
  - Perform three high-altitude flight tests to assure at least two successful tests and measure performance prior to MSR lander PDR.
  - At least one flight test must be performed on unit that has successfully completed environmental qualification/life testing

- **Flight Project responsibilities, after completion of technology program:**
  - Update design based on test results, fabricate flight unit hardware, spare, and interface test articles (mechanical, electrical/testbed), complete flight acceptance test, and deliver to ATLO

# Aerocapture Overview and Benefits

**Description**

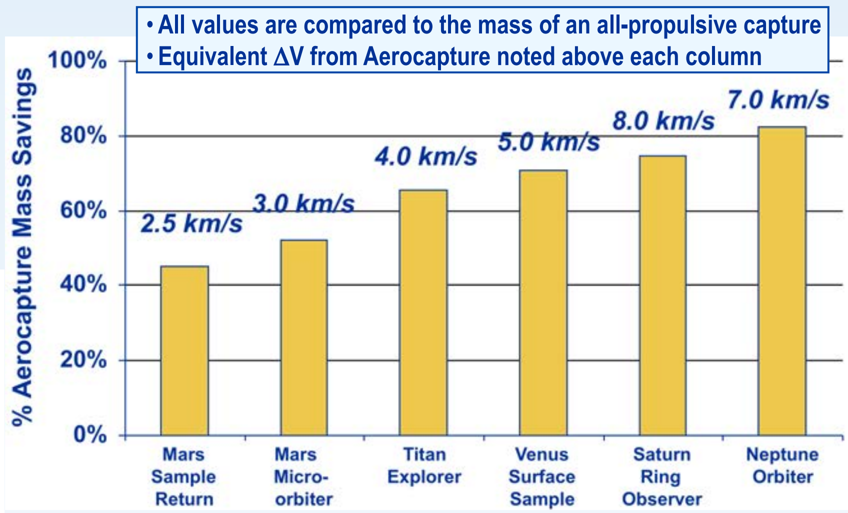
- Aerocapture is a spaceflight maneuver executed upon arrival at a body in which atmospheric drag, instead of propulsive fuel, is used to decelerate the spacecraft into a specific orbit.
- Aerocapture is a natural extension of other commonly-used flight maneuvers using atmospheres: aeroentry and aerobraking.




**Objective**

- To develop Aerocapture systems for exploration of the Solar System and to validate those systems in their relevant environments
- Raise Aerocapture propulsion to TRL 6+ through the development of subsystems, operations tools, and system level validation and verification

**Benefits**



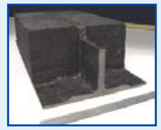

**Discipline Areas**

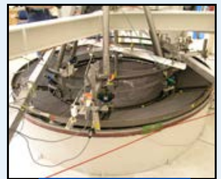
- Aerocapture builds upon well established entry system design processes and tools:
  - Atmospheric modeling
  - GN&C algorithm advancement
  - Materials development
  - Aerodynamics
  - Aerothermodynamic modeling
  - Systems engineering and integration
  - Rigid aeroshell technology including: TPS, structures, adhesives and sensors
  - Inflatable deceleration system concepts

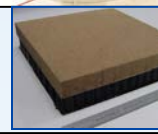
# Aerocapture Technology Development Products

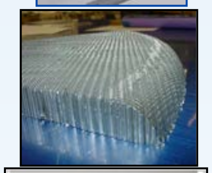
Elements at TRL6 and Ready to Infuse

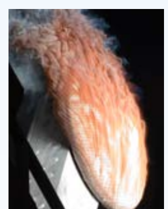
- **Rigid aeroshell and TPS products**
  - **Carbon-Carbon hot structure**
    - 2-meter rib-stiffened 70-deg aeroshell tested and finite element model validated, capable up to 700 W/cm$^2$, 30% lighter than Genesis capsule equivalent
  - **High-temperature aeroshell structures** (composite and honeycomb sandwich):
    - Composite honeycomb and modified adhesives raise TPS bondline by 65˚C, system stagnation tested to over 300 W/cm$^2$, 15% lighter than MER
    - Titanium honeycomb and modified facesheet resins and fibers, coupon tested and manufactured at 2.65-meter scale, raises bondline by 150˚C, reducing system mass up to 30% over traditional
  - **Ablative Thermal Protection System Materials**
    - “Family system” approach provides range of densities and robustness levels for wide range of applications: 50 to 1,100 W/cm$^2$
    - Extensive arcjet testing, application at flat-panel, 1-meter, and 2.65-meter (pending) scales

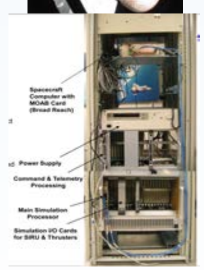












- **Aerocapture Guidance and Control Hardware-in-the-Loop Testbed**:
  - Real-Time simulation testbench written in flight software code, hosted on flight space computer with flight or flight-like interfaces
  - Demonstrates execution within flight-like avionics system, verifies communication paths and the absence of timing issues
  - Brings Analytic Predictor-Corrector Algorithm to TRL6
- **Aerothermal and atmospheric codes**
  - Improved aerothermal prediction capabilities, particularly by validating codes through ground test of fundamental physics
  - Engineering-level atmospheric models developed and improved for nearly every destination in the Solar System; incorporated directly into high-fidelity flight dynamics simulations
- **Aerocapture Quick-Look Tool**
  - End-to-end engineering-level conceptual design and trade tool for assessing aerocapture concepts
  - Available through LaRC software request process

# Multi-Mission Earth Entry Vehicle (MMEEV) Technology

## Description

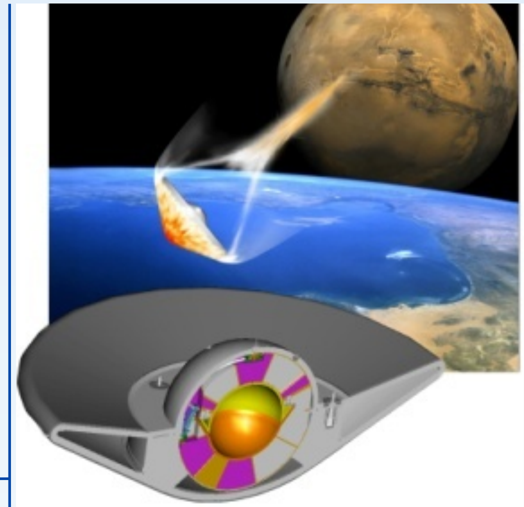
- Earth Entry Vehicles (EEVs) are necessary for bringing samples of material from our Solar System safely back to Earth's surface.
- The Multi-Mission EEV approach seeks to develop and implement common design principles on multiple missions such as New Frontiers, Discovery, and eventual planetary sample returns.

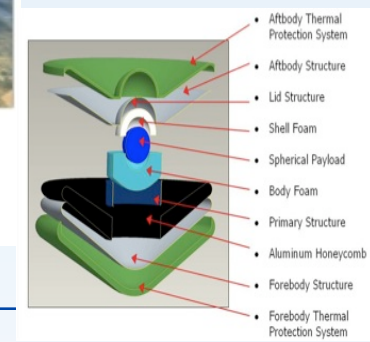
## Objective

- To develop technologies that enable new sample return missions
- To apply common design features to multiple flights, to improve reliability to the $10^{-6}$ level

## Benefits

- Maximize efficient use of technology investments, saving Agency costs over the long term
- Establish validation data for risk reduction on future missions that require extremely high probabilities of success.





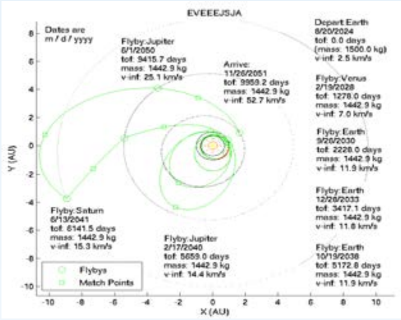

## Discipline Areas

- Materials development
- Aerodynamics
- Aerothermodynamic modeling
- Systems engineering and integration
- Advanced materials for TPS, structures, and impact protection
- Thermal control
- Mechanical Design/Packaging
- Systems Engineering

# Mission Design Tools / Systems Analysis

**In order to infuse new technologies, users must be able to assess the payoff.**

- Sponsored development of Mystic, MALTO, Copernicus, and OTIS
  - Initiated because results could not be independently validated
- Held MALTO training course in 2008
- Held Copernicus training course in 2009
- OTIS training as needed (WebEx, most recent summer 2011)
- Aerocapture Quicklook Tool Released in 2010




**Mission / system design studies define technology requirements**

- Critical to quantify mission benefits before hardware investment
- Mission design for NEXT requirements
- Refocus Study led to NEXT throttle table extension
- Refocus Study led to HiVHAC power range, life requirement
- Decadal study support quantified science benefit for SEP, REP, and AMBR engine technology


**"If we want people to buy cars, they need to learn to drive." - Oleson**

# ISPT Technology Infusion

- NEXT and AMBR incentivized on the last New Frontiers AO
- NEXT, AMBR, and Aerocapture incentivized on the last Discovery AO
- Conducting and participating on systems and mission studies looking at technology applicability to future mission concepts/DRM's
- Developing tools to aid the use of new technologies
- Learning that mission implementers and technology developers have different perceptions/expectations of when technologies are ready for technology infusion into a mission proposal
  - The Planetary Science Technology Review Panel recommending an independent heritage and TRL assessment process

# ISPT Technology Infusion

- ISPT is pursuing opportunities to take technologies beyond TRL6
  - Developed HEAT sensors for Mars Science Laboratory (MSL) as part of MSL Entry, Descent, and Landing Instrumentation (MEDLI)
  - Working to develop and fabricate 2 flight qualified AXFS. Interest has increased due to pursuing the flight qualification step!
  - Ultra-Light Weight Propellant Tanks
    - 2002 - Mars Exploration Rover, ISP funds Qualified MER tank design
    - Currently developing flight-qualified ultra-light weight propellant tanks as a drop-in replacement for Skycrane on 2018 Mars mission.
      - Mission pull/applicability important to get the technology qualified. Once this tank design has been qualified, the "validated" technology will be broadly applicable to most spacecraft.

- ISPT has several technologies which are ready for infusion
- ISPT has several more technologies which will be ready tech infusion in the next several years
- ISPT is assessing the next set of technologies to enable future planetary science missions