

Aerocapture Technology Developments from NASA's In-Space Propulsion Technology Program

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Abstract- This paper will explain the investment strategy, the role of detailed systems analysis, and the hardware and modeling developments that have resulted from the past 5 years of work under NASA's In-Space Propulsion Program (ISPT) Aerocapture investment area. The organizations that have been funded by ISPT over that time period received awards from a 2002 NASA Research Announcement. They are: Lockheed Martin Space Systems, Applied Research Associates, Inc., Ball Aerospace, NASA's Ames Research Center, and NASA's Langley Research Center. Their accomplishments include improved understanding of entry aerothermal environments, particularly at Titan, demonstration of aerocapture guidance algorithm robustness at multiple bodies, manufacture and test of a 2-meter Carbon-Carbon "hot structure," development and test of evolutionary, high-temperature structural systems with efficient ablative materials, and development of aerothermal sensors that will fly on the Mars Science Laboratory in 2009. Due in large part to this sustained ISPT support for Aerocapture, the technology is ready to be validated in flight.

I. INTRODUCTION

Since 2001, NASA's Science Mission Directorate (SMD) has been investing in technologies that can decrease the mass, cost, and trip times associated with planetary science missions, through the In-Space Propulsion Technology (ISPT) Program. A high-priority technology within the ISPT portfolio is Aerocapture, which is the process of using a body's atmosphere to slow an incoming spacecraft and place it into a useful science orbit (Fig. 1).

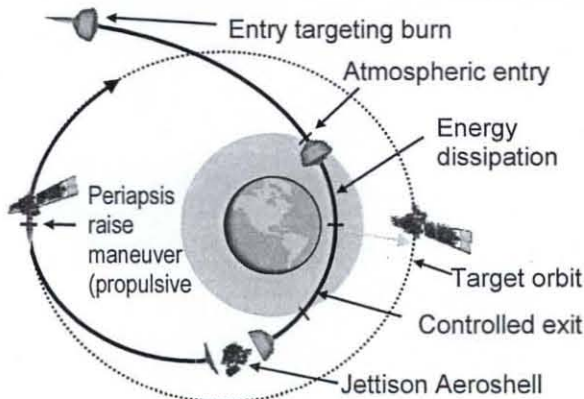


Fig. 1. Aerocapture Maneuver

Aerocapture differs from aerobraking, a flight-proven technique, in that the final orbit is established after only one atmospheric pass, compared to hundreds. Aerocapture can save hundreds of kilograms of propellant mass compared to traditional orbit capture methods, allowing the vehicle to carry more science payload, to be injected using a smaller launch vehicle, or to inject at a higher energy and reach its destination faster. Aerocapture can be used at the eight destinations in the Solar System that have significant atmospheres, and the maneuver is either enabling or enhancing for almost all scientifically robust missions to these bodies [1].

II. DEVELOPMENT STRATEGY

The ISPT Program's charter is to develop propulsion technologies from Technology Readiness level (TRL) 3 through TRL 6. ISPT is not a basic research program, nor does it build flight hardware for science mission implementation. A technology is "finished" when it is adopted for use, or infused, on a NASA science mission. The term "ready for infusion" is often used; however, such an assessment is subjective and is dependent on the degree to which the technology enables the mission, as well as the mission's risk posture. As a result, the first step in the technology development process is to understand the customers (i.e., the upcoming science missions), their requirements, and their risk tolerance. In some cases, this is difficult because the missions are openly competed (such as Mars Scout, Discovery, or New Frontiers) and are not well-defined in advance. The SMD Roadmap, the Decadal Survey, and other guiding documents can be used to identify targets and general mission classes, so that the technology performance requirements can be defined. For instance, if Titan is a key target of interest and the scientific objectives involve long-term mapping, we know that an orbiter would be a key element of the mission, even though the exact mapping orbit may not be defined. We can also deduce (though not easily) that an orbiter mission to Titan might appear in the Flagship mission class, and that the risk tolerance would be quite low on such a once-per-decade, multi-billion-dollar endeavor.

A. Systems Analyses

After identifying candidate missions, ISPT invests significantly in systems analyses, which can range from engineering-level benefit analyses to detailed systems definitions. These studies are invaluable for the purposes of guiding the technology investments to get the most benefit from limited funding. Within the Aerocapture area, systems studies for aerocaptured orbiters at Titan, Neptune, Venus, and Mars were completed between 2002 and 2006 [2-5]. These studies were conducted by a multi-Center NASA team consisting of experts in the component Aerocapture disciplines: aerodynamics, aerothermodynamics, atmospheric modeling, guidance, navigation and control, flight dynamics, structures, thermal protection systems, and packaging and integration. In the cases of Titan and Neptune, these studies were peer-reviewed by an independent panel of experts. The NASA Technical Memoranda and published papers that document these efforts reflect a significant step forward in maturing Aerocapture for SMD, as almost all previous work had focused on performing the maneuver at either Mars or Earth. The studies were critical to establishing aerocapture feasibility at the new destinations. The analytical aerocapture guidance algorithm's robustness was proven in 4-degree-of-freedom Monte Carlo simulations that included conservative uncertainties in initial state, vehicle aerodynamics, and atmospheric density. This work formed the basis of the claim that an aerocapture flight validation that uses this guidance scheme will prove aerocapture for use at any destination in the Solar System. Advances in modeling tools and methods were another significant product of these studies, and these advances are in use today on other NASA flight programs and projects, such as Orion and the Mars Science Laboratory (MSL).

B. Technology Assessment Group (TAG) Meetings

Another important part of developing a technology maturation strategy is assessing the state-of-the-art (SOA). Roughly annually, each ISPT technology area conducts a meeting with the experts in its community. The purpose of these gatherings is to assess the SOA in the various disciplines or product lines within the technology, to identify performance gaps between the SOA and the required capability for the target missions, and to devise plans for filling those gaps. Within Aerocapture, four such Technology Assessment Group or TAG meetings have been held, in 2002, 2004, 2005, and 2007. The last two TAGs have been held in conjunction with the Joint Army Navy NASA Air Force (JANNAF) Propulsion Meeting, which is on an 18-month schedule. The objectives of the TAG meetings have changed over the years, as the SOA and the gaps for rigid, blunt-body aerocapture have become well-known in the community and have not changed significantly over a 1- or 2-year timeframe. The Aerocapture area maintains a list of gaps that have been identified by previous TAGs, and funds tasks to address

those as the budget allows. Over the time period from 2003 to 2006, however, only a very small funding wedge was available for funding new tasks; most of the budget was allocated to the ongoing tasks, obtained as described below in subsection C. Recently, the TAG meeting has been more focused on communicating to the community what has been accomplished, and getting feedback on what additional risk reduction work can be done to actually make the subsystems acceptable for use on real scientific missions. The exception is in the area of inflatable decelerators, which are still new enough that maturation plans are not fully developed, and each accomplished task significantly advances the SOA.

C. Solicitations and Awards

As part of SMD, most of the work sponsored by the ISPT Program is selected through open competition among U. S. industry, academia, and government entities, including NASA organizations. At the point of the first NRA release in 2002 (called "Cycle 1"), Titan and Neptune aerocapture were the reference missions to which proposers were asked to work. These were chosen as the bounding cases in terms of aerothermal loads and guidance challenges. In that competition, advances in efficient aeroshell structures and thermal protection systems were sought, as well as entry system instrumentation, and the use of lower-TRL trailing ballutes. Six awards totaling \$5-\$8 M per year resulted from that first NRA; all but one of the tasks were completed in 2006 or early 2007. Overall, this set of tasks was funded at required levels over the periods of performance; some schedule delays occurred due to test facility constraints.

In 2003, the Aerocapture investment area participated in its second NRA (called "Cycle 2"), but at a much reduced funding level and scope. Concept studies for attached afterbody ballutes and inflatable forebody decelerators for Titan and Neptune aerocapture were solicited. Two awards resulted, and both came to completion in early 2007. Funding for these awards was very unstable, and resulted in contract extensions for little or no funding. This was not a reflection on the principal investigators (they made remarkable strides with very few resources) but rather was a result of declining ISPT funds. The complete list of awards and performing organizations is shown in Table 1.

The products from the first two Aerocapture NRAs represent significant advances in the state-of-the-art subsystems used for planetary entry. This section will highlight those advances and provide references from which to obtain more detailed information.

III. TECHNOLOGY PRODUCTS

The bulk of the effort resulting from the Cycle 1 NRA was on TPS materials and lightweight structures. Although the Aerocapture maneuver itself is the primary method for saving mass on the missions of interest, every kilogram counts. On MSL, for example, the heatshield instrumentation system is allocated only 15 kg, which severely limits the data collected.

TABLE 1
AEROCAPTURE AWARDS AND LEAD ORGANIZATIONS

| Task Title | Lead | Major Products |
|--|-------------------------------|---|
| Aeroshell Development for Aerocapture | NASA-ARC | <ul style="list-style-type: none"> Thermal Protection System (TPS) response models for Titan TPS concepts and heating predictions for other small-body destinations |
| Microsensor & Instrumentation Technology for Aerocapture | NASA-ARC | <ul style="list-style-type: none"> Heat flux & recession sensors ready for use in Titan and other small-body aerocapture environments Integrated aeroshell sensor suite |
| Advanced Ablator Families for Aeroassist Missions | Applied Research Associates | <ul style="list-style-type: none"> Fully tested & characterized ablator options utilizing low-cost manufacturing techniques Tests of integrated low-mass structures & ablators |
| High-Temperature Structures for Reduced Aeroshell Mass | NASA-LaRC | <ul style="list-style-type: none"> Reduced mass aeroshell composite structures, tested for Aerocapture environment Validation of ablator/structure interface using high-temp adhesives 3 (1-meter) rigid aeroshell test articles, thermally tested and validated against FEM |
| Aerocapture Technologies | Lockheed Martin Space Systems | <ul style="list-style-type: none"> Development of 2 structural/TPS concepts using traditional and advanced materials and manufacturing techniques (1 SLA, 1 C-C) 1 (2-meter) rigid aeroshell article, mechanically tested to Titan Aerocapture loads |
| Technology Development of Ballute Aerocapture | Ball Aerospace | <ul style="list-style-type: none"> Trailing ballute system concepts for Titan and Neptune Ground test verification of ballute manufacturing and packaging |
| Clamped Afterbody Decelerator (Cycle 2) | Ball Aerospace | <ul style="list-style-type: none"> Systems design, technology challenges of inflatable afterbody ballute deceleration system Builds on previous work with Gossamer Program |
| Inflatable Forebody Aerocapture Concepts (Cycle 2) | Lockheed Martin Space Systems | <ul style="list-style-type: none"> Systems design, technology challenges of inflatable aeroshell system Builds on previous work for Mars Program |

If future heatshields could allocate just a few more kilograms to instrumentation, the additional data return would be significant.

The first step in saving mass is a better understanding of the flight environment. In most instances, entry vehicles carry large margins on the thermal protection systems, particularly on the backshell, or aftbody, of the vehicle where the flight environment is much less understood. The heating rates are low (typically less than 5 W/cm²), but the surface area is high, and extra mass on the backshell can lead to lower vehicle stability margins. At NASA's Ames Research Center, part of their Cycle 1 task was to reduce uncertainties in the aerothermal environments of aerocapture vehicles. As a result of that varied work, almost 50 papers were published, and many were peer-reviewed. The team, led by principal investigator Michael Wright, has contributed significantly to the current understanding of the Titan entry environment. Their computational fluid dynamics (CFD) model validation work, supported by ground testing and data from the Cassini-Huygens mission, has reduced the prediction of peak heating during aerocapture by over 90% since the ISPT Titan systems analysis study of 2002. Another significant contribution was the team's application of Monte Carlo methods to CFD modeling, a technique now possible with modern-day computing speeds and parallel processing [6]. This breakthrough method can help guide investments toward resolving modeling uncertainties that contribute the most to a particular application. For instance, if the Monte Carlo method indicates that the largest uncertainty in the heating environment of a Mars entry vehicle is catalycity, then investing in tests to quantify that phenomenon would lead to a significantly better understanding of the environment

and ultimately to lower thermal protection system margins (i.e., mass).

Aerothermal modeling at NASA-Ames will continue in the future under ISPT, with researchers investigating Mars and Venus gas chemistry, the advantages of alternative entry vehicle shapes, and the gaseous products of ablative materials during entry. Many of the model improvements and methods developed by the Ames team are being used on flight projects such as Orion and Mars Science Laboratory, and we expect that infusion to continue for many years.

The ISPT hardware products thus far, aimed at saving aerocapture system mass, can be classified as evolutionary improvements upon the state of the art, using previous Mars and Earth entry vehicles as the basis. Inflatable decelerators could be considered a revolutionary technology. Below, we will describe the blunt, rigid aeroshell advancements.

Lockheed Martin Space Systems in Denver, Colorado has supplied NASA with every Mars entry heatshield since Mars Viking. The SOA comes from the Mars Exploration Rover (MER), which consists of Super Lightweight Ablator (SLA)-561V bonded to a structure made of graphite composite facesheets and an aluminum honeycomb core. The areal density of this system, which is designed to not exceed 250° Celsius (C) at the structure/TPS interface (called the bondline), is 2.07 lb/ft². One way to achieve mass savings is to raise the allowable bondline temperature, allowing more heat to get through the TPS, which lowers the TPS thickness requirement. Thermal soak is very important to aerocapture, since heat loads are typically greater than for a direct entry mission. With their Cycle 1 award, Lockheed was able to complete systems analysis, materials laboratory testing, arcjet testing, and model validation of a new "warm structure" aeroshell system. The new aeroshell structure, with a bondline that can withstand 316° C, is constructed of composite facesheets of T300/EX1551, and a composite core. The thickness of the SLA-561V is then reduced, for an overall areal density of 1.78 lb/ft², 14% lighter than that of MER (see Fig. 2).

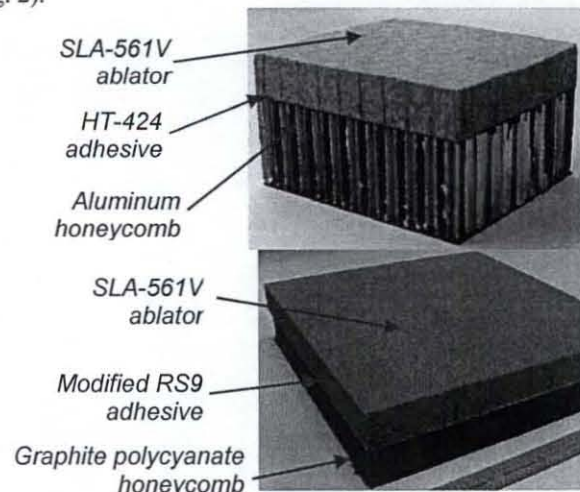


Fig. 2. Lockheed MER vs warm structure

This improved system was tested in the arcjet at NASA-Ames up to 387 W/cm^2 and would be suitable for a Titan or Mars aerocapture maneuver [7].

The second significant advancement from Lockheed is a "hot structure" aeroshell system. It is different from the traditional Mars system in that the TPS is not bonded to the front of the aeroshell; a composite structure takes the mechanical loads and heat of entry, and insulation inside the aeroshell protects the payload. The composite aeroshell, built by Carbon-Carbon Advanced Technologies (C-CAT), has co-cured ribs and stringers for stiffness (see Fig. 3). C-CAT manufactured a 2-meter diameter, 70° sphere-cone aeroshell, which was tested in a pressure bag load-test fixture to the qualification levels of a Titan aerocapture.

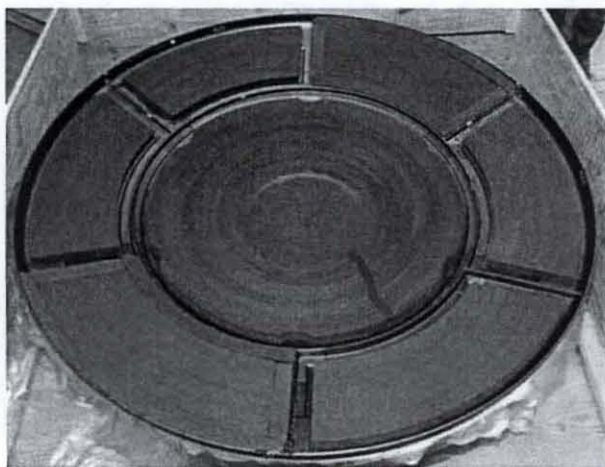


Fig. 3. LMA 2-meter carbon-carbon aeroshell (inside view)

The article showed no signs of damage during or after loading, and the resulting strains matched those predicted with finite element analysis to within 10%. The load test coupled with the modeling validated the mechanical performance of the article, while coupon-level arcjet and radiant lamp testing was used to verify the thermal performance of the system. In total, the aeroshell system consists of the composite structure, high-efficiency Calcarb insulation, an 11-layer multi-layer insulation, and an enhancing high-temperature outer coating to delay the temperature pulse and the onset of ablation. The carbon-carbon aeroshell system, with an areal density of 2.50 lb/ft^2 , is over 30% lighter than the Genesis sample return capsule heatshield and is suitable for use up to heating rates of 700 W/cm^2 [7]. Both the warm structure and hot structure aeroshell systems from Lockheed are now at a TRL of 5+, and are ready for proposal or mission infusion with some application-specific development work.

Another major ISPT development in low-mass heatshield technology has been a team effort between the NASA-Langley Research Center, subcontractor ATK Space Systems in San Diego (formerly Composite Optics), and Applied Research Associates, Inc. The Cycle 1 award

to Langley was to identify and test candidate high-temperature adhesives that could be used for the bondline between an aeroshell structure and ablator, again to reduce the thickness of the TPS and hence the mass of the entire system. Once the best-performing adhesives were identified through coupon tests, larger-scale structures and high-efficiency ablators were bonded together and tested thermally to verify bond integrity. Through numerous lap-shear tests on adhesive candidates, the heritage adhesive, HT-424, was proven to have capabilities much above the SOA 250°C limit. To take the bondline beyond 325°C , however, a new structure would have to be used, because the aluminum core of a traditional aeroshell structure would start to lose integrity. ATK, through comprehensive component testing, devised new composite facesheets which, when coupled with a Titanium honeycomb core, can be used to a bondline temperature of up to 400°C . The bond between the structure and TPS at this temperature has been thermo-structurally tested on 12-inch and 24-inch square panels and will be tested in a 1-meter aeroshell configuration in summer 2007. If successful, this system could reduce overall aeroshell mass by about 30% from SOA.

This mass savings does not result from a higher bondline temperature alone. The other key ingredient is an efficient, lightweight ablator, such as that developed by Applied Research Associates, Inc. (ARA). ARA has been producing such ablators in "family systems" for over 10 years. A silicone-based family, called "SRAM" (silicone-reinforced ablative material) has four members that range in density from 0.22 to 0.38 g/cm^3 (14 to 24 lb/ft^3), SRAM-14, SRAM-17, SRAM-20, and SRAM-24. ARA also produces a phenolic-based family, called "PhenCarb," ranging from 0.32 to 0.58 g/cm^3 (20 to 36 lb/ft^3). A family system is a set of related materials in which the constituent amounts are varied slightly to give an incremental change in performance. The advantage of a family system is that as requirements change over the life of a mission, an entire new TPS is not required; another member of the family can be used with confidence because its properties and performance are well-characterized and predictable. Overall, the SRAM and PhenCarb families perform in the heating range from 50 to 1300 W/cm^2 , suitable for most small-body aerocapture and direct entry missions. The ARA ablators have established response models, have been extensively arcjet tested, and are examined fully in [8].

The culmination of the Langley, ATK, and ARA effort is the manufacture of three 1-meter diameter, 70° sphere-cone aeroshells, which will be thermo-structurally tested at the Sandia National Laboratories' National Solar Thermal Test Facility (the "solar tower") in summer 2007 (see Figs. 4 & 5).

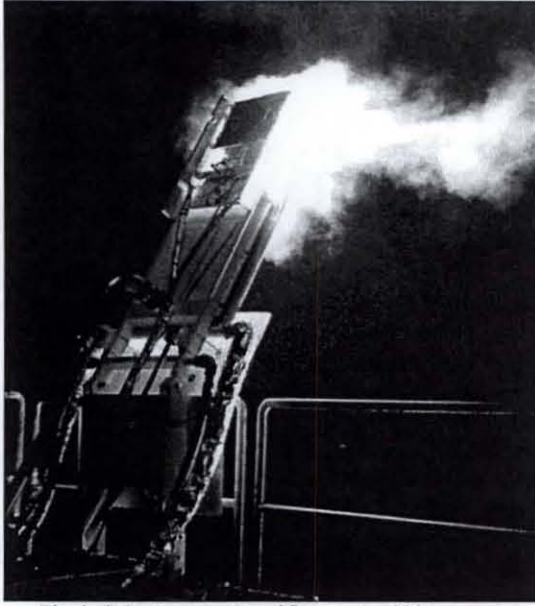


Fig. 4. Solar tower testing of flat structure/ablator panel

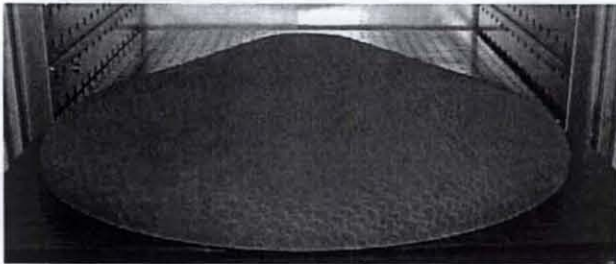


Fig. 5. One meter aeroshell ready for solar tower test

The SRAM-20 TPS over ATK-produced structure was baselined in the ST9 Aerocapture proposal to the New Millennium Program (NMP). The detailed plan, cost, and schedule for maturing this aeroshell system to flight readiness was deemed appropriate and well-defined by the ST9 proposal review teams. Although Aerocapture was not chosen as the technology to be matured by ST9, there are plans within ISPT to implement as much of the ground development proposed for ST9 as possible. This includes manufacturing a 2.65-meter aeroshell with SRAM-20 ablator, to be instrumented and flight qualification tested by 2010.

The final component of the lightweight rigid aeroshell development is environment and performance sensors. There have been efforts for many years in the entry system community to have sensors included on heatshields so that returned data can be used to update models and ultimately reduce mass margins. The data sought can be used to enhance understanding in 3 key areas: the aerothermal environment, the TPS performance, and the vehicle's aerodynamic performance. Better understanding the aerothermal environment requires temperature and pressure measurements at the surface of the vehicle. The TPS performance models need data not only from the surface

but in-depth in the ablator, typically through use of thermocouple stacks and recession sensors. Finally, aerodynamic validation is best achieved through a flush air data system, or FADS, which is a cross-shaped configuration of 5, 7, 9, or 11 pressure taps at the TPS surface. Without this differential pressure measurement, we must always assume the vehicle aerodynamics in order to fully resolve the entry states, including determining the dynamic pressure and winds. Thermocouple stacks integrated into TPS are TRL 9 and widely used in arcjet testing. Recession measurements were made by analog resistance ablation detectors (ARADs) on the Galileo Jupiter probe, and the returned data showed the designers that the TPS did not recede as expected. NASA-Ames, under their Cycle 1 award from ISPT, has modernized the ARAD and built a new, more reliable recession sensor called "HEAT," the hollow aerothermal ablation temperature detector. The pressure measurements needed for a FADS have been implemented in the Space Shuttle nosecone, but not in a highly ablative material. There is a project underway (the Mars Entry, Descent, and Landing Instrumentation project, or MEDLI) to instrument the Mars Science Laboratory aeroshell with thermocouples, HEATs, and a 7-port FADS. Unfortunately, no measurements will be taken on the backshell of the vehicle, due to schedule constraints. The use of the HEAT sensor for this application marks the first ISPT mission infusion, and if this instrumentation effort is successful, it should pave the way for all future vehicles to return valuable data during entry.

ISPT Aerocapture has also invested at a lower level in the revolutionary entry technology of inflatable decelerators. Contracts with Lockheed and Ball Aerospace, resulting from Cycle 1 and Cycle 2 NRA awards, have significantly contributed to the body of knowledge of these systems. Inflatables have the advantage of being lighter than rigid aeroshells (at least in assessments made thus far), of being stowed until just before entry, therefore allowing orbiters a clear view to Earth and space during cruise, and of being volumetrically efficient while stowed. Not only are inflatable decelerators useful for aerocapture, they can be used to slow direct entry spacecraft high in the atmosphere to allow access to more landing sites, or to enable unique science opportunities in the upper atmosphere.

The Ball Aerospace team made significant progress on trailing and clamped ballutes (thin-film, drag-only devices). Concept studies, materials testing, wind tunnel tests, and coupled fluid/structure modeling were all included in the ISPT-funded work. These efforts advanced the concepts to a TRL of 3+, so more work is needed, but feasibility for Titan and Mars aerocapture has been clearly established [9]. The Lockheed Martin team concentrated their efforts on an inflatable forebody aeroshell, which uses bank angle control like a rigid aerocapture vehicle. The team identified a 7.5-meter "higher TRL" option that they believe is feasible with existing materials technology. Again, more work is needed in materials testing, structural development, modeling, and deployment and flight tests [10].

IV. FLIGHT VALIDATION STATUS

Although ISPT has advanced aerocapture technology significantly, it may still be perceived as too risky for first-use on an expensive science mission. A flight validation is needed, to lower the risk for the first customer. A nationwide team led by the NASA-Jet Propulsion Laboratory (JPL) competed over the past 4 years against four other competitors for a chance to validate aerocapture technology through NASA's New Millennium Program. The resulting proposal, for which ISPT was a co-funding partner, was not ultimately selected, but it was a significant product in the advancement of the technology and forms the basis of many future ISPT investments. The ST9 concept was simple: Launch a 1.2-meter-diameter blunt body (60°) vehicle from Earth as a Delta II secondary payload, to an apogee between 10,000 km and 36,000 km. Allow it to enter the atmosphere at about 10 km/s, autonomously control its bank angle throughout the atmospheric pass to remove about 2 km/s, and autonomously perform a perigee raise maneuver on the first apogee to establish a safe orbit from which to download the data collected during flight. Use the data to validate the aerothermal, aerodynamic, flight dynamics, and TPS response models that will be used to design future aerocapture vehicles. The 3-axis controlled vehicle, shown in Fig. 6, has an aeroshell structure from ATK, SRAM TPS from ARA, and embedded instruments from NASA-Ames, all to be funded and delivered by ISPT, culminating the developments of the Cycle 1 tasks. As announced by NASA Headquarters in late March 2007, the Aerocapture proposal was not selected for ST9. The results of a rigorous review process indicated that it was a very high-quality proposal, receiving 14 major and minor strengths, 2 minor weaknesses, and no major weaknesses on the technical and management sections. The project was judged to be feasible, with low implementation risk. The two "new" technologies to be validated on the flight, which were competitively selected during the proposal development process, were the analytic guidance algorithm from Ball Aerospace and the SRAM TPS from Applied Research Associates. The maturation plans for these components were carefully developed and peer reviewed by experts external to the team. ISPT plans to implement these maturation plans over the next few years to reduce cost and risk for a future flight opportunity.

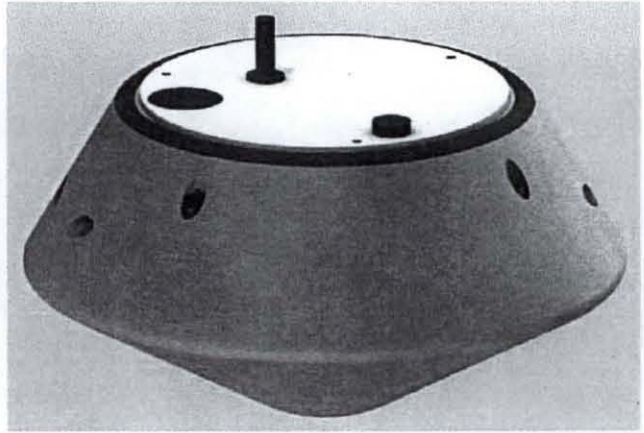


Fig. 6. Proposed ST9 aerocapture vehicle

V. CONCLUSIONS

ISPT Aerocapture investments have yielded significant, flight-ready products that are applicable to aerocapture, direct entry, and sample return missions. From systems studies that prove aerocapture feasibility and set requirements, to improved modeling capabilities, lightweight aeroshell developments, and sensor technologies, the program has had an impact on entry systems that will continue for many years. What remains is to flight validate the entire system before first mission use.

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