Aerocapture Information Summary for Discovery Missions
November 2009

The following information is provided as an overview and as the starting point for exploring the benefits of utilizing Aerocapture technology. It is not meant to be an exhaustive treatment of all possible applications of the available technology components. The cost, mass, and trip time benefits of aerocapture are great for planetary orbiters. However, there are many other creative and innovative ways to utilize either aerocapture or the entry system components that are now available, to accomplish different types of missions such as atmospheric samplers, single or multiple probes, or planetary moon observation. One of the key benefits not usually recognized is that instead of enabling additional payload to be sent on a given mission, the mass savings of aerocapture could allow a smaller, more inexpensive launch vehicle to do the same mission. This could translate to a huge cost savings that could enable the mission to meet a cost cap, have more funding available for risk reduction, or have more funding in reserves.

1.0 Introduction

Aerocapture is the process of entering the atmosphere of a target body to reduce the chemical propulsion requirements of orbit capture. Aerocapture is a step beyond aerobraking, which still requires large propulsive systems for an orbit insertion burn and then relies on multiple passes high in an atmosphere to reduce orbital energy. Aerocapture, illustrated in figure 1, maximizes the benefit from the atmosphere by capturing in a single pass. Keys to efficient and successful aerocapture are lightweight aeroshell and thermal protection systems, accurate atmospheric models, and sufficient control during the maneuver.

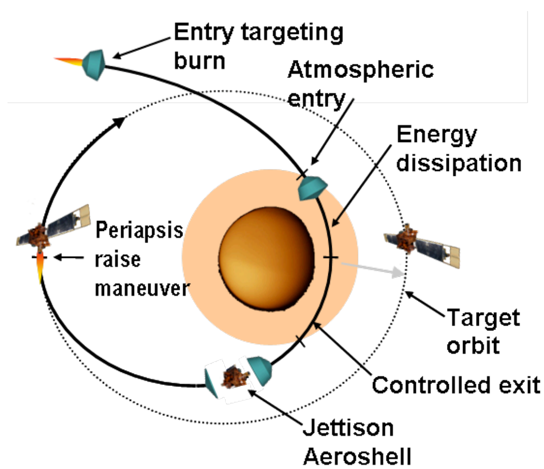

Figure 1. Illustration of the aerocapture maneuver.

The technical community of entry systems experts believes that the maneuver is very manageable from a risk perspective, and in fact could be far less risky than a planetary lander. First and foremost, the aerocapture is accomplished within the hypersonic flight regime only, so the complicated aerodynamics and stability characteristics of a vehicle traveling through several flight regimes is not applicable. Hypersonic flight through an atmosphere is accomplished routinely by the Space Shuttle, and has been demonstrated by a series of planetary entry vehicles starting with Mercury, Gemini, and Apollo and continuing most recently to the landings of the Mars Exploration Rovers on the Red Planet. The required aerocapture autonomous guidance algorithm to accomplish the maneuver is operating in a hardware-in-the-loop ground testbed, ready to be applied to a scientific mission. All aspects of the maneuver are simulated thousands of times in a Monte Carlo fashion, with realistic perturbations for the actual mission applied. This ensures that the vehicle has sufficient performance to handle even the most challenging entry environments.

2.0 Development Status and Availability

Since 2002, NASA's Science Mission Directorate, through the In-Space Propulsion Technology (ISPT) Program, has invested in analysis, technology development, and ground-based testing to advance aerocapture readiness and efficiency. Efforts in aerocapture-related technologies have included development of:

- Families of low & medium density (14 - 36 lb/ft^3) thermal protection systems (TPS) and the related sensors,
- Development of a carbon-carbon rib-stiffened rigid aeroshell, and higher temperature honeycomb structures and adhesives.

In addition, significant progress has been made through improvement of:

- Models for atmospheres, aerothermal effects, and
- Algorithms and testing of a guidance, navigation and control (GN&C) system.

The majority of ISPT investment in aerocapture technology has occurred in furthering the TRL and the efficiency of the rigid aeroshell systems. A family of low-density TPS materials carrying the identifier "SRAM" (silicone, reinforced carbon ablator) have been developed under a competitively awarded contract with Advanced Research Associates (ARA). These have a density range between 14 lb/ft^3 and 24 lb/ft^3 with the variable performance achieved by adjusting the ratios of constituent elements. These are applicable for heating rates up to 150 W/cm^2 and 500 W/cm^2 respectively and could eventually be used on missions with destinations to small bodies such Titan and Mars. The SRAM family of ablators has been tested both in arcjet (convective) and solar tower (radiative) facilities at the coupon level; 1 ft and 2 ft square flat panels, and on a 1-meter blunt body aeroshell structure, shown in figure 2. Another ARA family of low- to medium- density TPS systems (PhenCarb) is phenolic-based, ranges in density between 20 and 36 lb/ft^3, and is applicable for heating rates between 200 and 1,300 W/cm^2. Table 1 summarizes the materials and their heat rates of applicability (the number in each material name is the density in lb/ft^3; the table gives densities in g/cm^3, as well).

Thermal Protection Material	Density (g/cm^3)	Heat Rate of Applicability (W/cm2)
SRAM-14	0.22	90 -140
SRAM-17	0.27	120 - 220
SRAM-20	0.32	150 - 300
SRAM-24	0.38	180 - 380
PhenCarb-20	0.32	200 - 500
PhenCarb-24	0.38	300 - 700
PhenCarb-28	0.45	400 - 900
PhenCarb-32	0.51	500 – 1,100
PhenCarb-36	0.58	600 – 1,300

Table 1. ARA's TPS material densities and performance regimes

In support of the rigid TPS system, ISPT has funded testing of higher temperature adhesives and development of higher temperature structures effectively increasing the allowable bond-line temperature from 250˚C to 325˚ or 400˚C depending on the adhesive and composite construction. These improvements can yield 15-30% lower aeroshell system masses than conventional systems. ISPT is currently nearing completion on a 2.65-meter diameter, 70-degree sphere cone constructed of this high-temperature structure (400˚C bondline) with SRAM-20 ablator applied. The manufacturing demonstration unit will validate and document the processes for future mission customers. Also included are sensors that measure recession with an accuracy of hundredths of millimeters. The recession sensors were developed by NASA-Ames with ISPT funding, and are currently integrated for use on the Mars Science Laboratory (MSL) mission. Instrumenting entry systems to gather flight data is of primary importance to better understanding the environments and resulting vehicle requirements for future missions. These measurements can also provide scientific data to missions with such an objective.

Models that predict the entry thermal environments to which the aeroshell systems will be exposed, have been developed and enhanced. In some cases, previous heating estimates have been overly conservative because of the lack of resources available to produce validation data or to develop more complicated analysis methods. Coupled models updated with the most current Cassini data reveal, for example, that aerocapture at Titan will load the TPS system at less than 20 W/cm^2 verses prior predictions of 150-200 W/cm^2.

Through multiple years of concentrated effort that includes ground validation testing, researchers funded by ISPT have been able to make modeling improvements that will benefit all future entry missions. ISPT has also updated the atmospheric models for all primary aerocapture destinations except Earth, which is being updated by the Constellation Program. These atmosphere models are based on detailed Global Circulation Models and ground and space observations, and have been captured in subroutines that are utilized by the detailed flight dynamics simulations.

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

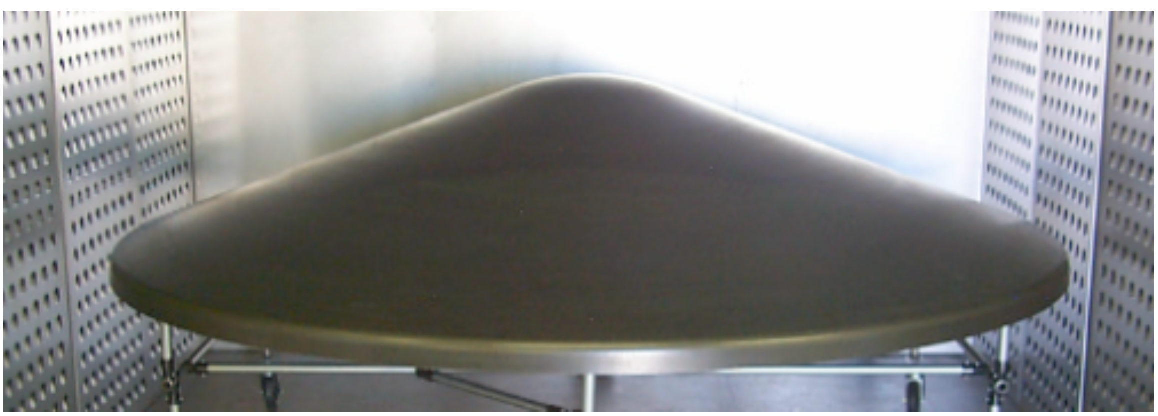

Figure 3. 2.65-meter aeroshell structure, to be outfitted with ARA's SRAM-20 TPS material

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

3.0 Mission Benefits

The use of aerocapture has been studied extensively, most notably for use at Titan, Neptune, Venus and Mars. Anticipated increases in delivered mass are shown in figure 4. The largest mass benefit from aerocapture was observed for Neptune, low Jupiter orbits, followed by Titan, Uranus, Venus, and then only marginal gains for Mars (the mass benefit is directly correlated to the amount of velocity change required for each mission). Detailed mission assessment results can be found in references [1 and 5-10].

Even though the mission mass benefits to Mars are only expected to be on the order of 5-15%, these benefits can be enabling, especially if the mission is constrained by cost or mass to a particular launch vehicle. Detailed mission and cost analyses have been conducted for various Mars opportunities by a multi-center team from ARC, JPL, JSC, LaRC, and MSFC. An opposition class sample return mission can be enabled through the use of aerocapture. Aerocapture is significantly enhancing for conjunction-class sample-return missions, and in general for large Mars orbiters. Also, no technology gaps have been identified that would delay aerocapture implementation on such a mission. The use of autonomous hypersonic maneuvering on the Mars Science Laboratory mission, to be launched in 2011, is an important step towards utilizing aerocapture on future missions.

Venus has also been studied extensively to identify any needs for TPS, guidance, atmospheric or heating models. Detailed analyses also evaluated the potential for aerocapture for a Venus Discovery class mission. Aerocapture was shown to deliver more than 80% additional mass over aerobraking and more than 600% from a chemical insertion. This could allow both a probe/lander and orbiter to be accommodated in one launch vehicle, for significantly more science benefit. Aerocapture also offers a reduction of over 120 days of Deep Space Network (DSN) time. Some aerothermodynamics and thermal protection system work would have to be done at Venus, to ensure the qualification of a carbon phenolic heatshield, or to show that other, more readily-available materials (such as PICA, phenolic-impregnated carbon ablator) could be used. No other critical technology gaps have been identified for aerocapture at Venus.

Mission - Science Orbit	Nominal Orbit Insertion ΔV, km/s	Best A/C Mass, kg	Best non-A/C Mass, kg	A/C % Increase	Best non-A/C Option
Venus V1 - 300 km circ	4.6	5078	2834	79	All-SEP
Venus V2 - 8500 x 300 km	3.3	5078	3542	43	All-SEP
Mars M1 - 300 km circ	2.4	5232	4556	15	Aerobraking
Mars M2 - ~1 Sol ellipse	1.2	5232	4983	5	Chem370
Jupiter J1 - 2000 km circ	17.0	2262	<0	Infinite	N/A
Jupiter J2 - Callisto ellipse	1.4	2262	4628	-51	Chem370
Saturn S1 - 120,000 km circ	8.0	494	<0	Infinite	N/A
Titan T1 - 1700 km circ	4.4	2630	691	280	Chem370
Uranus U1 - Titania ellipse	4.5	1966	618	218	Chem370
Neptune N1 - Triton ellipse	6.0	1680	180	832	Chem370

Figure 4. Aerocapture benefits for various targets.

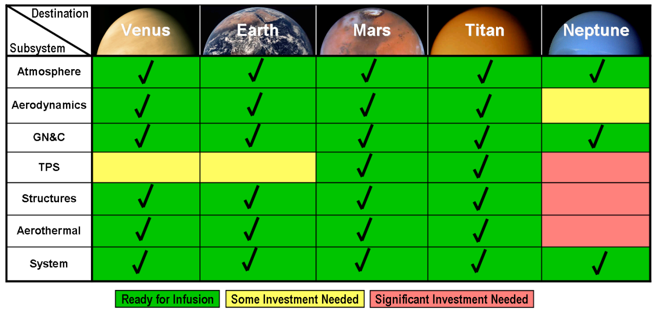

Figure 5. Aerocapture readiness for various targets.

Titan has been of considerable scientific interest following the success of Cassini/Huygens. Because of its atmospheric conditions, it is an ideal candidate for aerocapture. The Titan flagship study sponsored by NASA did consider aerocapture within the baseline mission concept since aerocapture has the capability to delivery more than double the mass of the chemical alternative.

Aerocapture has been repeatedly found to be an enabling technology for several atmospheric targets of interest. The ISPT project has continued to develop aerocapture technologies in preparation for a flight demonstration. Rapid aerocapture analysis tools are being developed and made available. The TPS materials developed through ISPT can also enhance a wide range of missions by reducing the mass of entry vehicles. Figure 5 illustrates the remaining gaps required for technology infusion. The Earth application for TPS, although showing some investment needed, has received heavy investment for the Constellation Program's Orion vehicle so only some aerocapture-specific work is likely necessary. In general, the Aerocapture technology is currently at or is funded to reach TRL6 within the year, for multiple targets and applications of interest.

4.0 NASA Entry Systems Expertise

Aerocapture and entry systems design and development is a multi-disciplinary specialty that is not widely available within the space industry. NASA (including the Jet Propulsion Laboratory) has a unique capability in these areas; a community of about 100 engineers and researchers performs the design and analysis of every planetary entry vehicle that supports a NASA mission. Expertise in aerodynamics, aerothermodynamics, and atmospheric flight dynamics comes together to guide vehicle design. Much of this expertise resides at NASA's Ames Research Center and Langley Research Center. At NASA-Ames, aerothermal expertise for multiple destinations leads to thermal protection system materials knowledge, testing, and design. At NASA-Langley, aerodynamics database computation and testing are used in end-to-end high-fidelity entry simulations. The vast experience at these two centers can be easily brought to bear on new applications, a particular advantage when cost control is critical.

For more information about Aerocapture technology investments or to receive contact information for experts at NASA-Langley and NASA-Ames, please contact the In-Space Propulsion Technology Program Manager David J. Anderson, NASA-Glenn Research Center, 216-433-8709, David.J.Anderson@nasa.gov.

5.0 References

1. Jeffery L. Hall, Muriel A. Noca and Robert W. Bailey, "Cost-Benefit Analysis of the Aerocapture Mission Set", Journal of Spacecraft and Rockets, Vol. 42, No. 2, pp 309-320.
2. "Solar System Exploration Roadmap for NASA's Science Mission Directorate," JPL D-

35618, July 2006.
3. B. James and M. Munk, “Aerocapture Technology Development Within the NASA In-Space Propulsion Program”, AIAA-2003-4654, 39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Huntsville, Alabama, July 20-23, 2003.
4. Jeffery L. Hall, **“**An Overview of the Aerocapture Flight Test Experiment (AFTE)”, AIAA-2002-4621, August 2002.
5. Lockwood, M. K. “Titan Aerocapture Systems Analysis,” AIAA-2003-4799, July 2003.
6. Lockwood, et al, “Aerocapture Systems Analysis for a Titan Mission”, NASA/TM-2006-214273, March 2006.
7. Lockwood, M. K., “Neptune Aerocapture Systems Analysis,” AIAA Paper 2004-4951, August 2004.
8. Lockwood et al, “Aerocapture Systems Analysis for a Neptune Mission,” NASA/TM-2006-214300, May 2006.
9. Lockwood, et al, “Systems Analysis for a Venus Aerocapture Mission”, NASA/TM-2006-214291, April 2006.
10. Wright, H., et al, “Mars Aerocapture Systems Study,” NASA/TM-2006-214522, November 2006.
11. Munk, M., and Moon, S., “Aerocapture Technology Development Overview,” IEEE Aerospace Conference Paper #1147, Big Sky, Montana, March 2008.