

Title of Presentation: Aerocapture Technologies

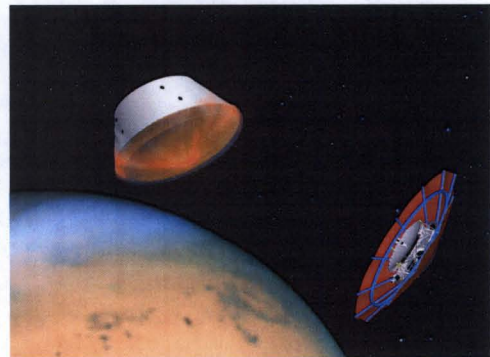
Primary Author: Andrew S. Keys

Organization of Primary Author: NASA/Marshall Space Flight Center

Phone: 256-544-8038

Email: Andrew.Keys@nasa.gov

Abstract: Aeroassist technology development is a vital part of the NASA In-Space Propulsion Technology (ISPT) Program. One of the main focus areas of ISPT is aeroassist technologies through the Aerocapture Technology (AT) Activity. Aeroassist is the general term given to various techniques to maneuver a space vehicle within an atmosphere, using aerodynamic forces in lieu of propulsive fuel. Techniques include aeroentry, aerobraking, aerocapture and aerogravity assist. Within the ISPT, the current aeroassist technology development focus is aerocapture. Aerocapture relies on the exchange of momentum with an atmosphere to achieve thrust, in this case a decelerating thrust leading to orbit capture. This technique is very attractive since it permits spacecraft to be launched from Earth at higher velocities, thus providing a shorter overall trip time. At the destination, the velocity is reduced by aerodynamic drag within the atmosphere. Without aerocapture, a substantial propulsion system would be needed on the spacecraft to perform the same reduction of velocity. This could cause reductions in the science payload delivered to the destination, increases in the size of the launch vehicle (to carry the additional fuel required for planetary capture) or could simply make the mission impossible due to additional propulsion requirements.



The AT is advancing each technology needed for the successful implementation of aerocapture in future missions. The technology development focuses on both rigid aeroshell systems as well as the development of inflatable aerocapture systems. Rigid aeroshell systems development includes new ablative and non-ablative thermal protection systems, advanced aeroshell performance sensors, lightweight structures and higher temperature adhesives. Inflatable systems such as tethered trailing ballutes (“balloon parachutes”), clamped ballutes, and inflatable aeroshells are also under development. Aerocapture-specific computational tools required to support future aerocapture missions are also an integral part of the ATP. Tools include: engineering reference atmosphere models, guidance and navigation, aerothermodynamic modeling, radiation modeling, and flight simulation.

Systems analysis plays a key role in the AT development process. The NASA in-house aerocapture systems analysis team has been tasked with multiple systems definition and concept studies to complement the technology development tasks. The team derives science requirements, develops guidance and navigation algorithms, as well as engineering reference atmosphere models and aeroheating specifications. The study team also creates designs for the overall mission spacecraft. A systems definition study of rigid aeroshell aerocapture at Saturn’s moon, Titan, was completed in 2002. Systems definition studies for aerocapture at Neptune, Venus, and Earth have also been completed. The AT is also funding multiple concept studies for aerocapture inflatable systems.

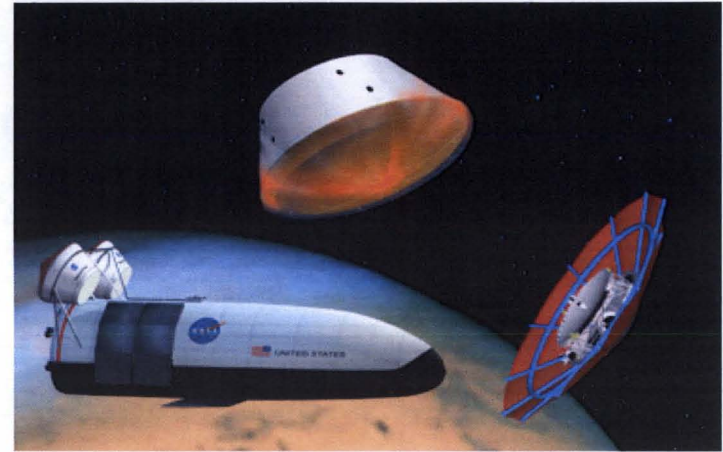


Aerocapture Technologies

Andrew Keys, NASA/Marshall Space Flight Center

Technology Description

- Aerocapture is a maneuver for orbital insertion of spacecraft around solar system bodies possessing atmospheres.
- Aerocapture relies on the exchange of momentum with an atmosphere to decelerate, resulting in orbital capture.
- Aerocapture permits spacecraft to employ higher trans-planetary velocities, carry less fuel mass and more payload mass.



Proposed aerocapture vehicles including high lift-to-drag bodies, rigid blunt body aeroshells, inflatable systems.

Approach

- Develop aerocapture systems for robotic exploration of the Solar System and validate those systems in relevant environments.
- Raise aerocapture propulsion to TRL 6 through the development of subsystems, operations tools, and system level validation and verification.
- Uncover all risk factors for Aerocapture infusion into science missions and mitigate each risk factor.
- Technical issues include: atmospheric modeling, GN&C, materials selection, aerothermodynamic heating, environmental effects.

Key Activities:

Applied Research Associates, NASA/LaRC - High-Temperature Structures: Instrumented, 70-degree sphere-cone structures.

Ball Aerospace - Ballute Development: Systems analysis/evaluation/test of inflatable concepts.

Lockheed Martin - Aeroshell Technology: 2-meter-diameter Carbon-Carbon rib-stiffened hot structure.

Lockheed Martin - Inflatable Aeroshell: Flexible TPS test plans and data for inflatable aeroshell.

NASA/ARC - Aeroshell Development: Aerothermal sensitivity analyses, documented TPS qualification plan.

NASA/ARC - Sensors: Thermal Heat Flux and Recession Sensors integrated with and validated in 2 TPS materials.

National Aeronautics and Space Administration



Aerocapture Technologies

*In-Space Propulsion Technology Project
NASA Marshall Space Flight Center
Dr. Andrew S. Keys
Earth Science Technology Conference 2006
June 27-29, 2006*

In-Space Propulsion Technology Program Priorities 2002 to 2006



High Priority	Medium Priority	Low Priority	High Payoff High Risk
Aerocapture 	Adv. Chem. 		1 g/m2 S. Sails
Next Gen. Ion 	SEP <50 kW 	Solar Thermal 	MXER Tethers
Solar Sails 	SEP Hall 100kW 		Plasma Sails

ISP Priorities 2002

- Flagship mission propulsion needs
 - Outer planet destinations
 - Cross Agency needs
- Low level technology push

ISP Priorities 2006

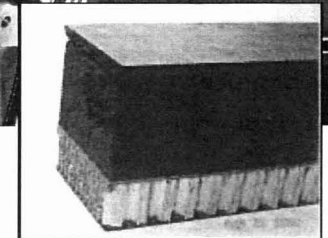
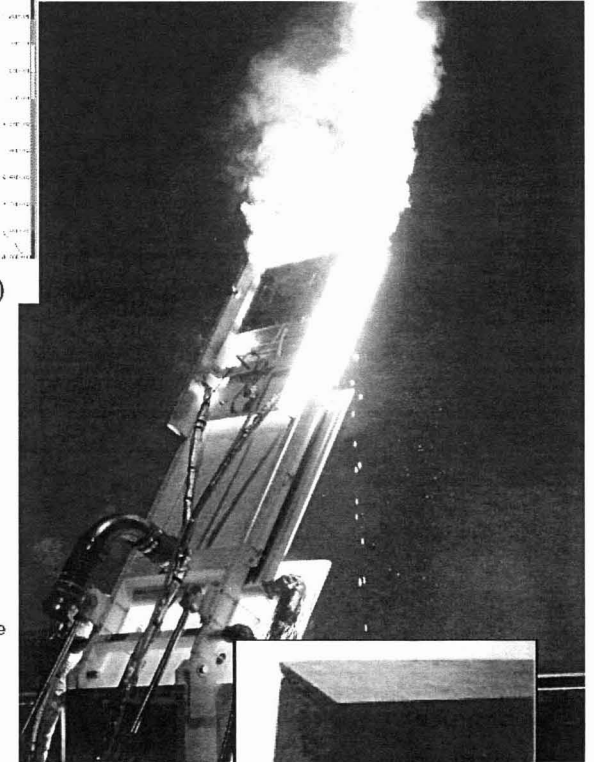
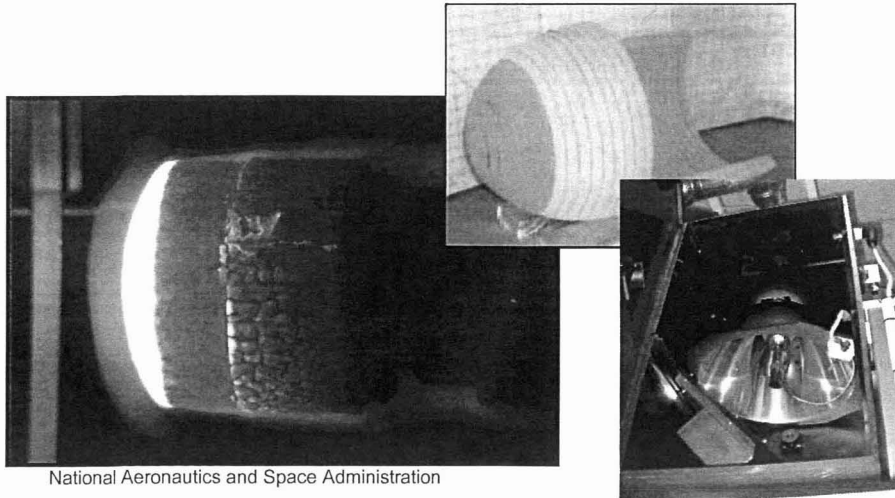
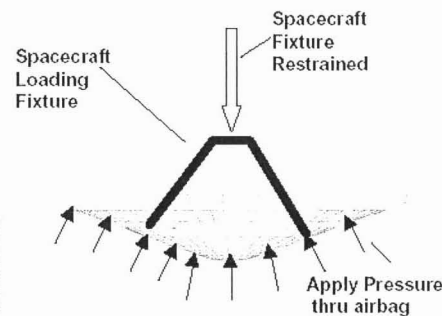
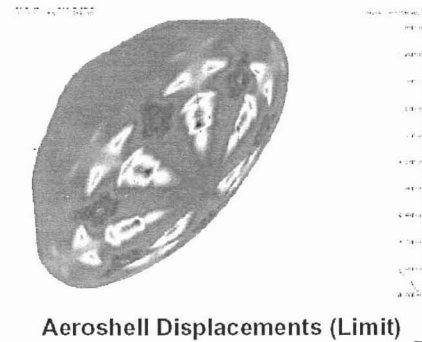
- Focus on Near term deliverables for SMD
- GOALS: - to enhance/enable science missions - to lower cost
 - reduce risk to end user
- Technologies linked to SMD mission pull

High Priority	Medium Priority	Low Priority	High Payoff High Risk
Aerocapture 	Adv. Chem. 		
Solar Electric 			
Solar Sails 			

Aerocapture Project Project Approach



- Raise aerocapture propulsion to TRL 6 through the development of subsystems, operations tools, and system level validation and verification.
- Uncover all risk factors for Aerocapture infusion into science missions and mitigate each risk factor
- **Technical issues**
 - Atmospheric modeling
 - GN&C
 - Materials selection
 - Aerothermodynamic heating
 - Environmental effects





Aerocapture Benefits

- The benefits of aerocapture as a method of orbital deceleration and capture are quantified through various cost/mass/benefit studies.

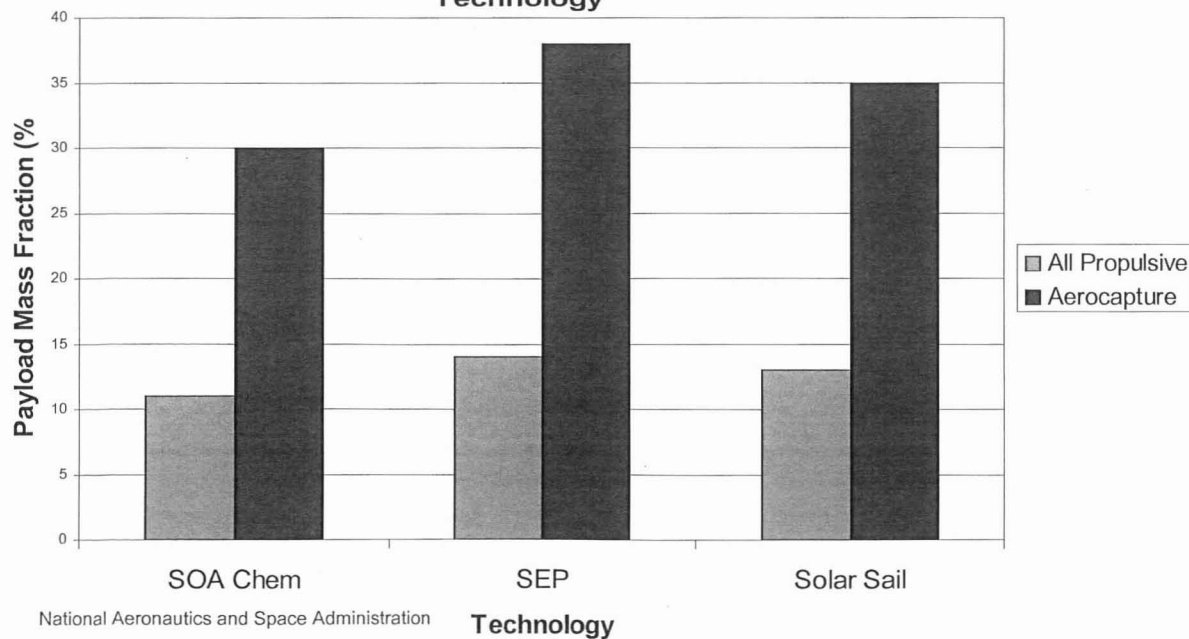
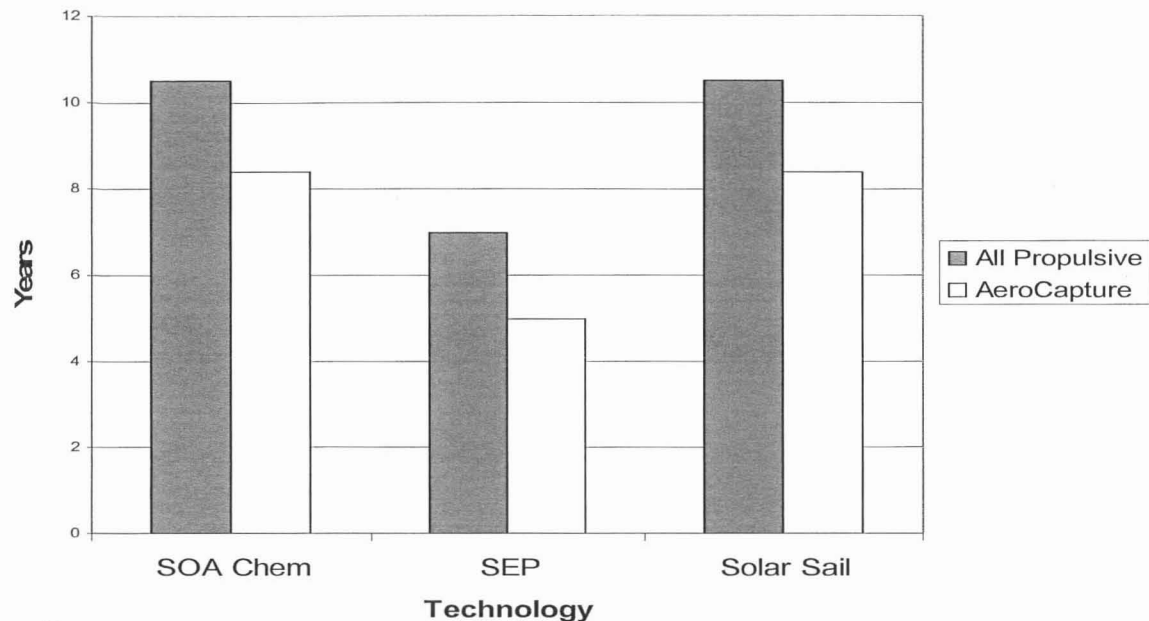
Comparison of Payload Mass Increase Using Aerocapture vs. Best Non-Aerocapture Method for Various Mission Scenarios*

Destination	Working Orbit (km)	Nominal Inertial Entry Speed (km/s)	Orbit Insertion, ΔV (km/s)	Delivered Payload Mass Increase
Venus	300 (circular)	11.7	4.6	79%
Venus	8,500 x 300 (elliptical)	11.7	3.3	43%
Mars	300 (circular)	5.9	2.4	15%
Mars	37,000 x 300 (elliptical)	5.9	1.2	5%
Jupiter	2000 (circular)	59.0	17.0	Mission Enabling
Jupiter	1,880,000 x 1,000 (elliptical)	59.0	1.4	-51%
Saturn	120,000 (circular)	35.0	8.0	Mission Enabling
Titan	1,700 (circular)	5.9	4.4	280%
Uranus	450,000 x 4,000 (elliptical)	24.0	4.5	218%
Neptune	430,000 x 4,000 (elliptical)	29.0	6.0	832%

* J.L. Hall, M. A. Noca, and R.W. Baily, "Cost-Benefit Analysis of the Aerocapture Mission Set," *Journal of Spacecraft and Rockets*, Vol. 42, No. 2, Mar-Apr 2005.



Titan Aerocapture Benefits



Aerocapture provides significant benefits in Trip Times and Payload Mass Fraction for Titan Exploration

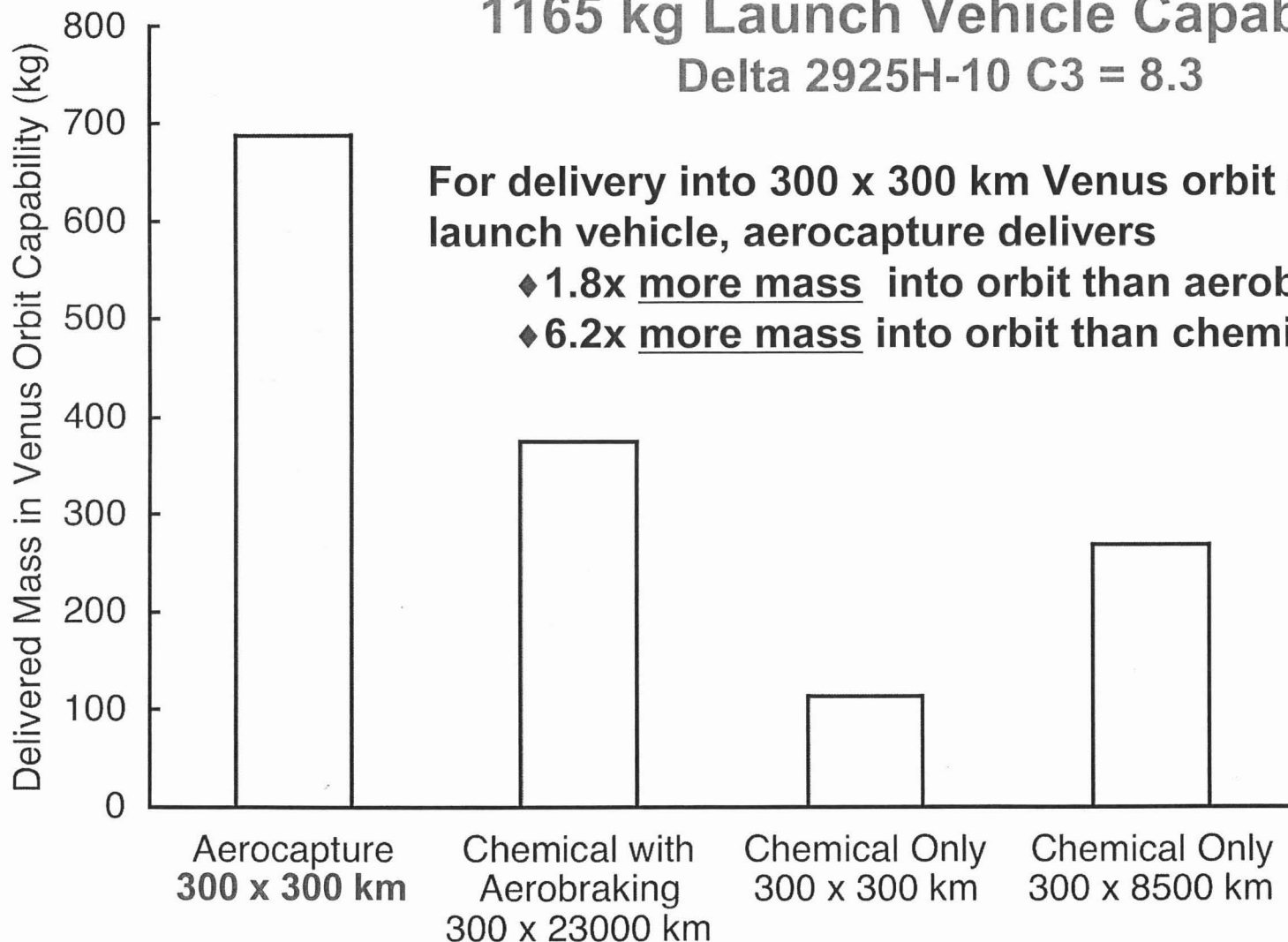
Venus Aerocapture Benefits



1165 kg Launch Vehicle Capability
Delta 2925H-10 C3 = 8.3

For delivery into 300 x 300 km Venus orbit on same launch vehicle, aerocapture delivers

- ◆ **1.8x more mass into orbit than aerobraking**
- ◆ **6.2x more mass into orbit than chemical only**

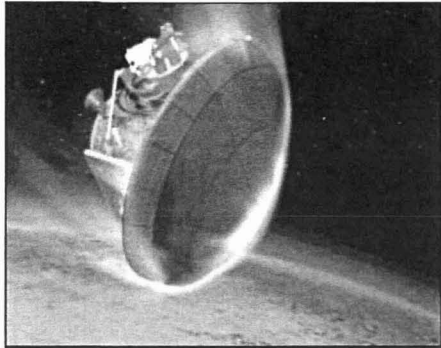


Aerocapture Technology Specific Architectures



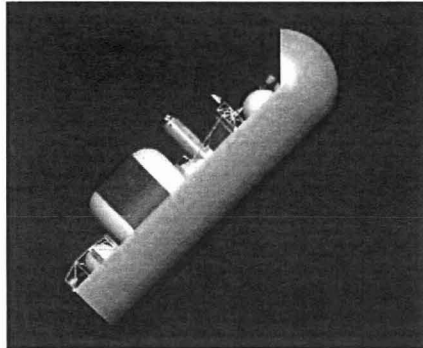
Higher TRL

Blunt Body Designs



- Moderate to high maturity for small bodies; low to moderate maturity for other planets
- Provides modest tolerance for nav and atmospheric uncertainties

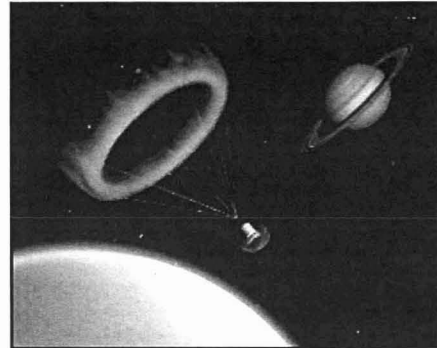
Slender Body Designs



- Low to moderate maturity
- Provides increased tolerance for nav and atmos. uncertainties
- Design originally for human missions to Mars. Preliminary studies indicate that Slender Body Designs may be required for Neptune.
- Provides increased volume and improved packaging advantages for larger spacecraft.

Lower TRL

Trailing Ballutes



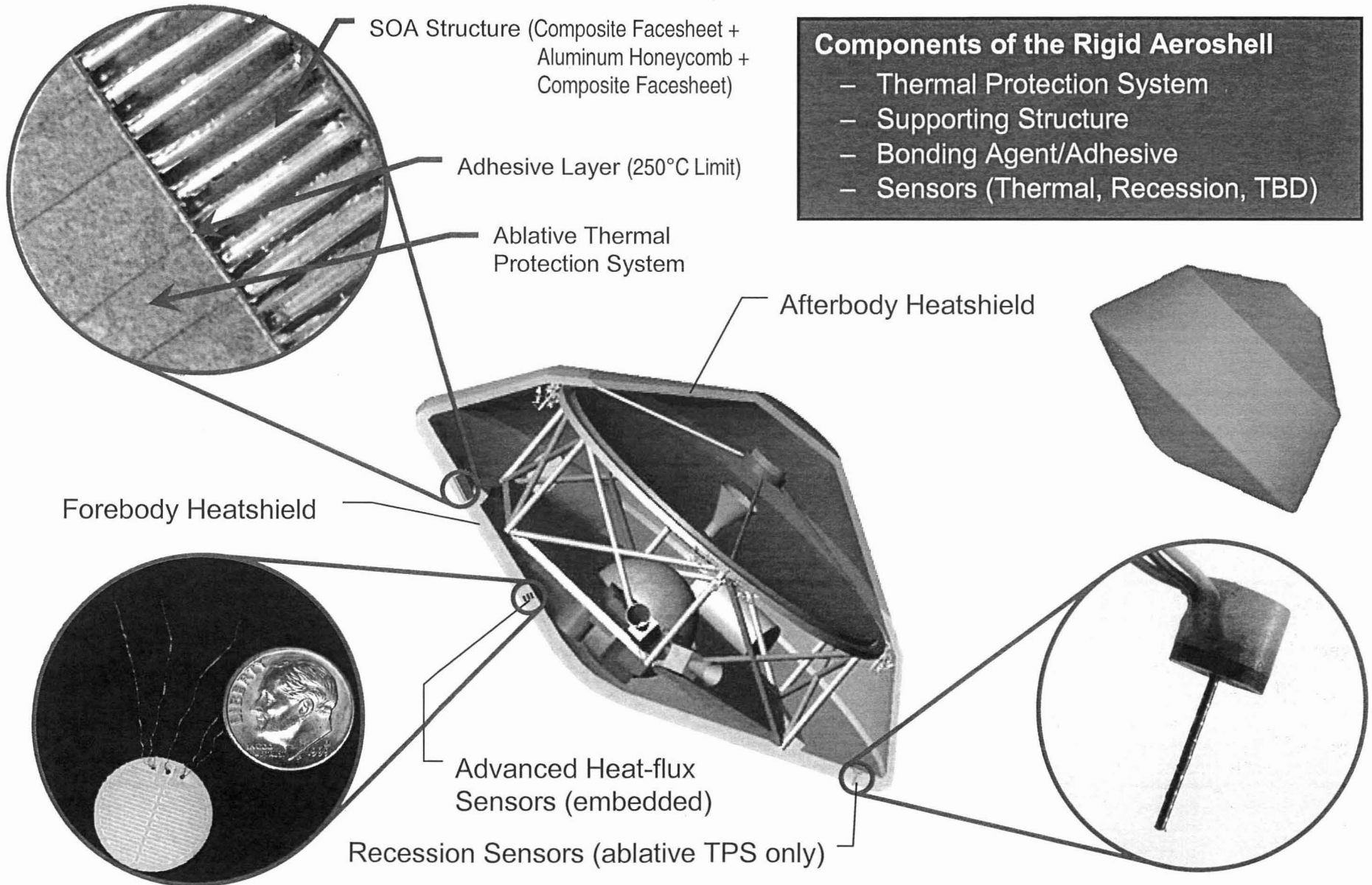
- Low maturity
- Applicable to all size and shape payloads
- May have performance advantages over Blunt Body, such as not having the payload enclosed during interplanetary cruise

Attached Ballutes



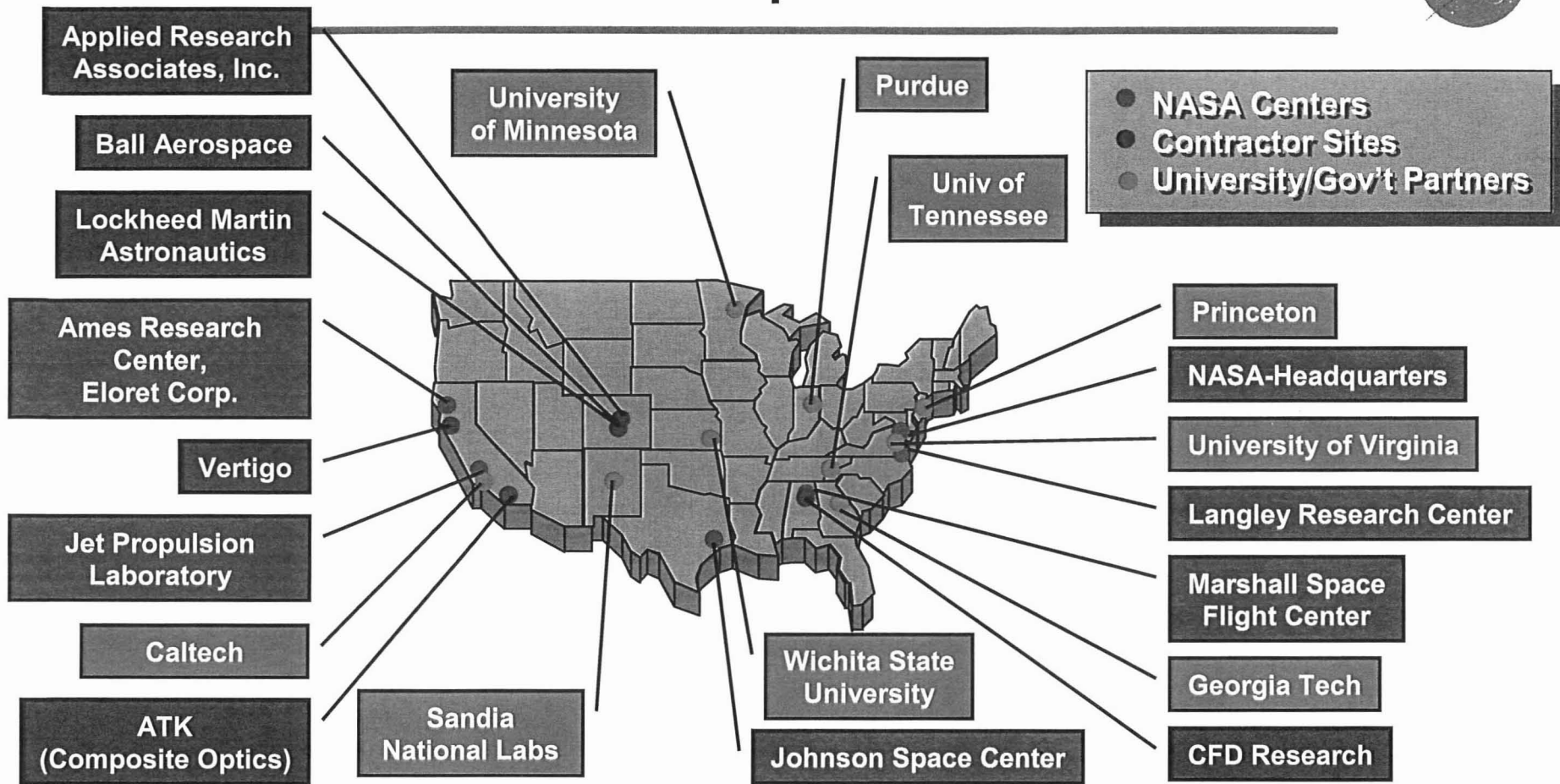
- Low to moderate maturity for Earth and Mars
- Developed and launched in 1996 by Soviet Union as part of Mars penetrator mission. Launch vehicle failure.
- Investigating feasibility of using aerodynamic lift for precision trajectory control
- Has potential volume and packaging advantage for larger spacecraft

The Rigid Aeroshell System

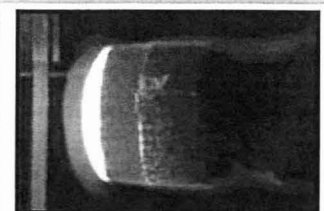




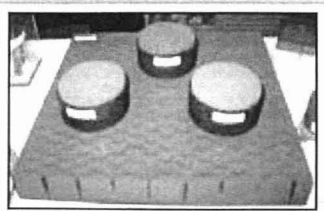
ISPT Aerocapture Team



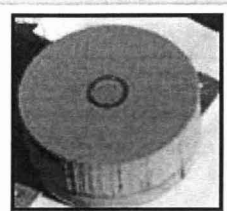
The ISPT Aerocapture Team is distributed across the United States



NASA ARC Arcjet



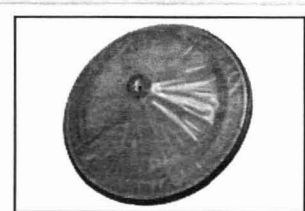
ARA, Inc.



LMA



NASA ARC Sensors



Ball

Current Competed Aerocapture Tasks



	Title	Lead Organization	Major Products
Rigid Aeroshell Related Tasks	1) Aeroshell Development for Aerocapture	NASA-ARC	<ul style="list-style-type: none"> Fully characterized TPS materials and response models for Titan TPS concepts and heating predictions for other small-body destinations
	2) Microsensor & Instrumentation Technology for Aerocapture	NASA-ARC	<ul style="list-style-type: none"> Heat flux and recession microsensors for use in Titan and other small body aerocapture environments Fully integrated aeroshell instrumentation system
	3) Advanced Ablator Families for Aero-assist Missions	Applied Research Associates	<ul style="list-style-type: none"> Fully tested and characterized ablator options utilizing low-cost manufacturing techniques Tests of integrated low-mass structures and ablators
	4) High-Temp 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 4 (1-meter) rigid aeroshell test articles
	5) Aerocapture Technologies	Lockheed Martin Astronautics	<ul style="list-style-type: none"> Development of 3 structural/TPS concepts using traditional and advanced materials and manufacturing techniques (1 SLA, 2 C-C) 1 (2-meter) rigid aeroshell test article
Inflatable-Related Tasks	6) 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
	7) Clamped Afterbody Decelerator (Cycle 2)	Ball Aerospace	<ul style="list-style-type: none"> Design, fabrication and test of inflatable afterbody ballute deceleration system Builds on previous work with Gossamer Program
	8) Inflatable Forebody Aerocapture Concepts (Cycle 2)	Lockheed Martin Astronautics	<ul style="list-style-type: none"> Design, fabrication and test of inflatable aeroshell system Builds on previous work for Mars Program



TASK 1: Aeroshell Development for Aerocapture

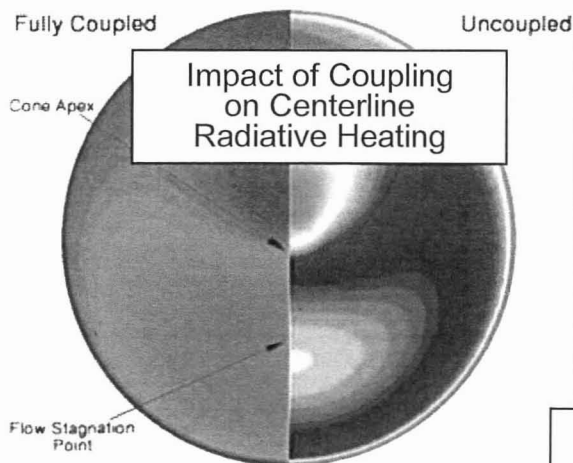
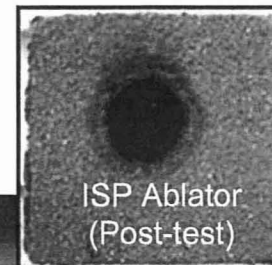
➤ **Summary** - NASA ARC is focusing on reducing uncertainties in aeroshell design for a Titan aerocapture mission. This involves evaluating the aerothermal environment & candidate TPS materials.

➤ **Accomplishments:**

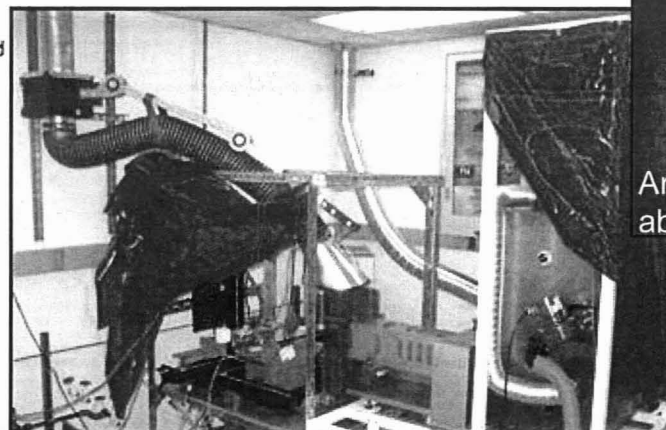
- Completed tests in the EAST shock tunnel to measure shock layer radiation in a simulated Titan atmosphere at relevant conditions
- Completed tests in the Caltech T5 facility to measure turbulent convective heating in a simulated Titan atmosphere at relevant conditions
- Completed arc jet screening tests in a nitrogen atmosphere of candidate TPS materials for Titan aerocapture
- Demonstrated that coupling the convective and radiative heating solutions reduces the radiant heating in comparison to uncoupled solutions
- Completed testing candidate Titan TPS materials in ISP-funded Radiative Lamp Facility

➤ **Plans:**

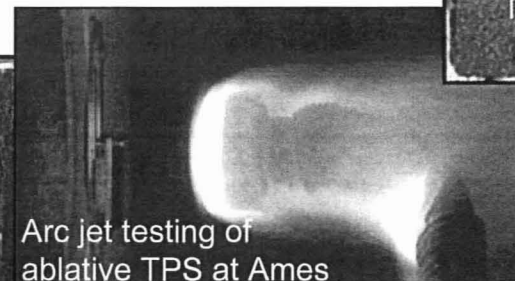
- Complete aerothermal modeling



National Aeronautics and Space Administration



ISPT-Funded Radiant Lamp Test Facility at ARC



Arc jet testing of ablative TPS at Ames

Contact: Bernie Laub
blaub@mail.arc.nasa.gov
M/S 234-1 NASA ARC
Moffet Field, CA 94035
650.604.5017

TASK 2:

Microsensor & Instrumentation Technology for Aerocapture



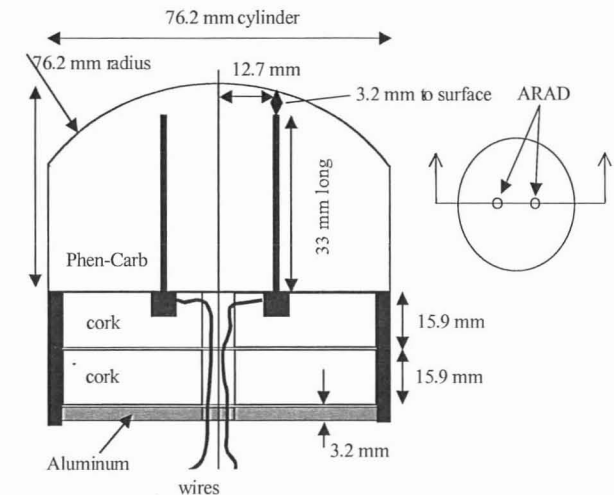
➤ **Summary** - ARC is developing heat flux and recession sensors for rigid aeroshells. Data from these sensors will be used to optimize design of future aeroshells for aerocapture and direct entry missions.

➤ **Accomplishments:**

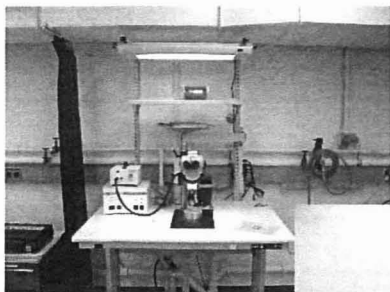
- Initial sensor design and fabrication is complete
- Arcjet testing of heat flux and recession sensors has begun
- Integration of sensors into ISPT TPS materials has begun
- Laboratory arcjet has been complete and is operational

➤ **Plans:**

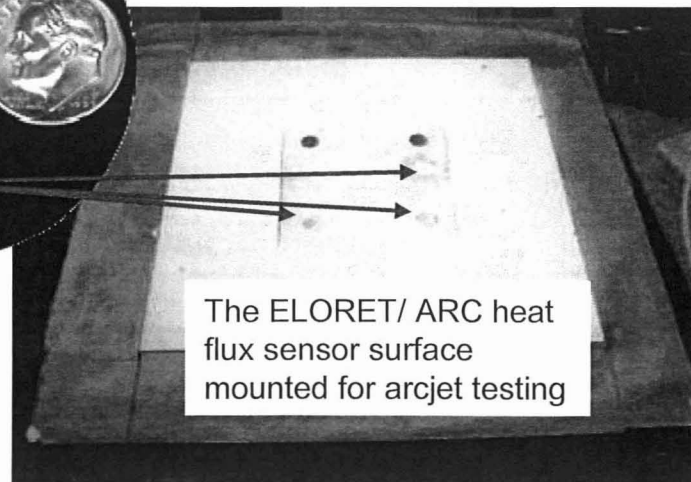
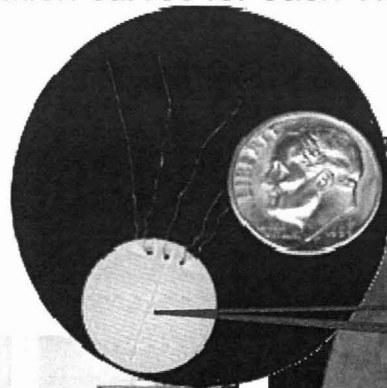
- Continue with calibration efforts
- Complete laboratory arcjet calibration and begin sensor screening tests
- Perform full-scale arcjet testing on integrated TPS/sensor samples and develop calibration curves for each TPS material



ELORET/ ARC recession sensors integrated into ISP ablator for initial arcjet screening



The ELORET/ ARC lab and sensor fabrication equipment



The ELORET/ ARC heat flux sensor surface mounted for arcjet testing

Contact: Ed Martinez
ed.martinez@nasa.gov
Ames Research Center
M/S 229-4 NASA Ames
Moffet Field, 94035
650.604.2544

TASK 3:

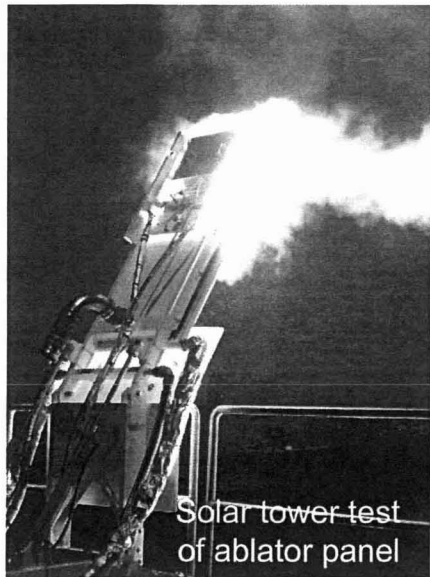
Advanced Ablator Families for Aeroassist Missions



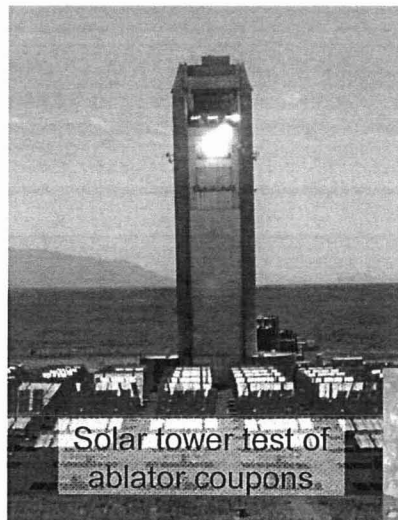
- **Summary** - ARA is developing and testing candidate ablator materials for aerocapture TPS. Test samples are formulated at the ARA facility in Denver & tested at various facilities that simulate the aerocapture environment.
- **Accomplishments:**
 - ❑ Completed convective heating tests at the Ames Research Center Arcjet Facility
 - ❑ Completed radiative screening of TPS coupons at Sandia Solar Tower
 - ❑ Completed proof-of-concept manufacturing of large-cell honeycomb and honeycomb-packed TPS
 - ❑ Updated TPS thermal response models
- **Plans:**
 - ❑ Return to Sandia Solar Tower to conduct TPS/Structure panel testing
 - ❑ Manufacture three 1m aeroshells for thermal testing at Sandia Solar Tower
 - ❑ Update TPS thermal response models



Ablator arcjet coupons, post test



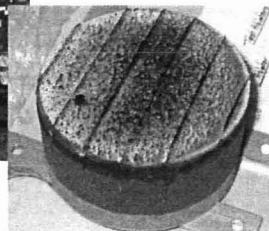
Solar tower test of ablator panel



Solar tower test of ablator coupons



PhenCarb-28 (150W/cm² for 200 sec)



Ablator solar tower coupon, post test

Contact: Bill Congdon
bcongdon@msn.com
ARA, Ablatives Laboratory
14824 E. Hinsdale Ave.
Unit C
Centennial, CO 80121
303.699.7737



TASK 4: High-Temp Structures for Reduced Aeroshell Mass

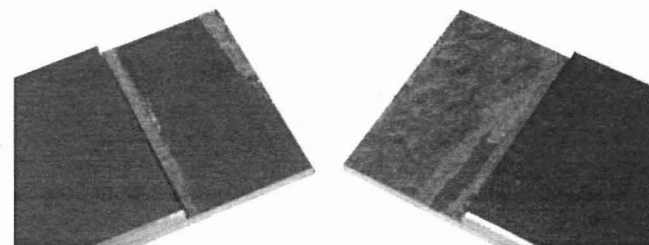
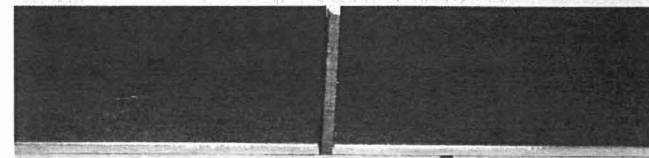
➤ **Summary** – LaRC is selecting candidate adhesives for attaching the TPS to the structure of the aerocapture heat shield. They are also investigating new high-temperature resins to be used in the manufacture of the structure. They plan to conduct screening tests to determine the relative strength of these adhesives at aerocapture-like temperatures.

➤ **Accomplishments:**

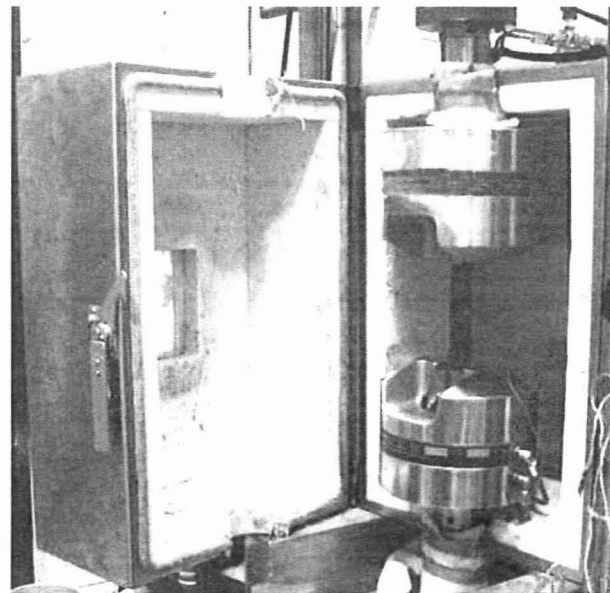
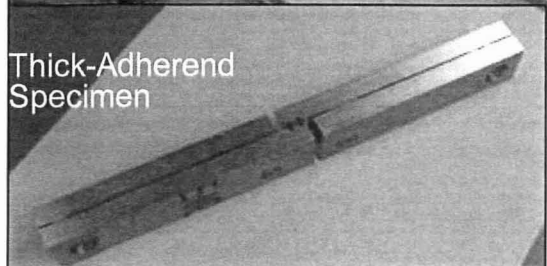
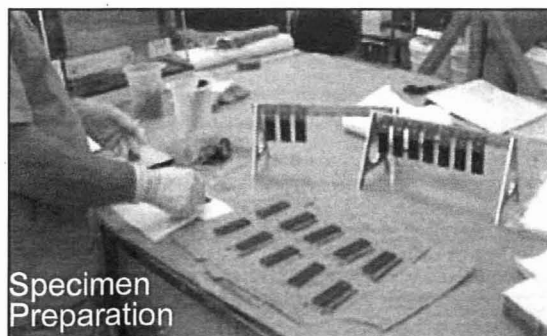
- 15 adhesives procured for testing
- ASTM laboratory test plans in place and coupons manufactured for thin-adherent and thick-adherent testing

➤ **Plans:**

- Complete TPS integration and mass properties analysis for Titan
- Complete composite materials testing (using new resins)
- Down select adhesives for coupon fabrication



Thin-adherent specimen,
Pre- and post-test



Test Specimen in Oven

Contact: Tim Collins
t.j.collins@LaRC.nasa.gov
M/S 190 NASA LaRC
Hampton, VA 23861
757.864.3113

TASK 5: Aerocapture Technologies



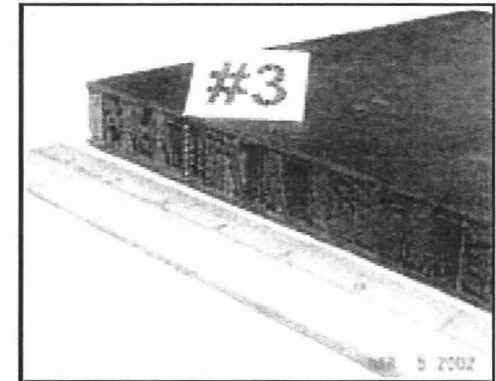
➤ **Summary** - Lockheed Martin Astronautics is developing composite “warm” & “hot” structure materials for rigid aeroshells. The “warm” structure is capable of higher-temperature performance, requiring less TPS than traditional aluminum structure. The “hot” structure is able to handle the intense heat of aerocapture or direct entry without the use of TPS, and has much higher temperature capabilities than traditional ablative TPS. Lockheed is also investigating alternate techniques for the manufacture of aeroshells.

➤ **Accomplishments:**

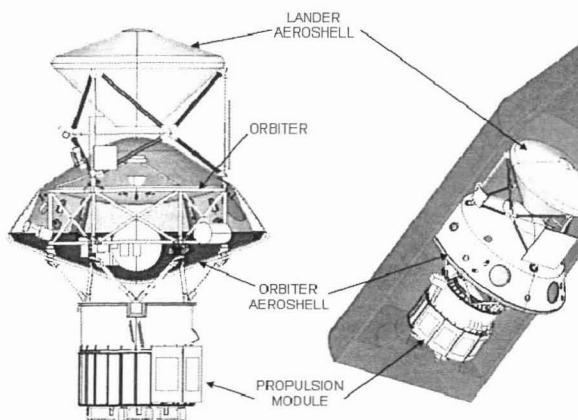
- Completed a preliminary conceptual design of a rigid aeroshell for Titan aerocapture. Key technologies have been identified and verified and models have been created. Lander, propulsion module, backshell, and orbiter separation modes have been examined and preliminary designs have been completed.
- Completed arcjet testing at NASA ARC for traditional TPS and warm structure coupons
- Completed radiative lamp testing on warm and hot structure coupons
- Completed mechanical testing on hot structure coupons
- Manufacture and perform mechanical-load testing of a 2-m hot structure rigid aeroshell

➤ **Plans:**

- Continue arcjet testing of hot structure coupons at NASA ARC

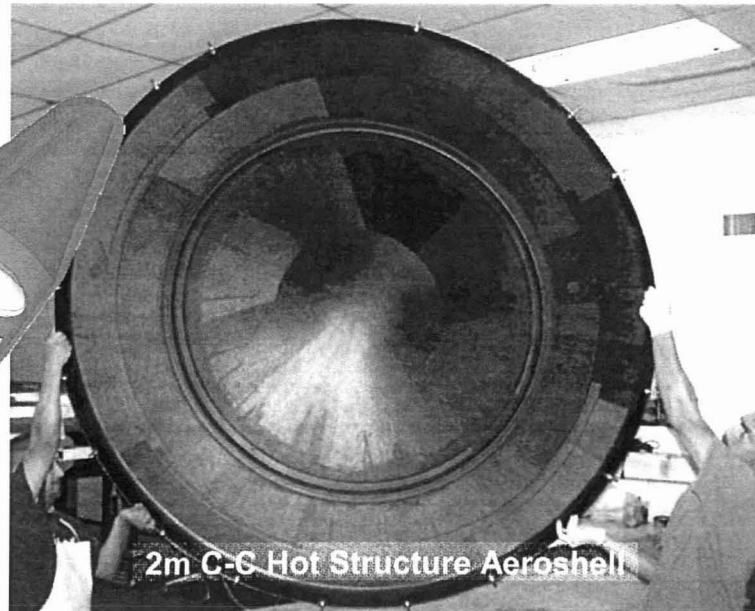


LMA warm structure



LMA Titan aerocapture design

National Aeronautics and Space Administration



2m C-C Hot Structure Aeroshell

Contact: Bill Willcockson
william.h.willcockson@lmco.com
LMA
P.O. Box 179
Denver, CO 80201
303.977.5094

TASK 6 and 7: Technology Development of Ballute Aerocapture and Clamped afterbody Decelerator



➤ **Summary** – Under Cycle 1, Ball Aerospace is performing critical initial trades for an aerocapture concept that utilizes a towed inflatable toroid. Trade studies include analysis of aspect ratio for optimal toroidal shape, tether dynamics for optimizing the number of tethers required, separation algorithms to optimize guidance and control, aerothermodynamics and heating for selection of materials and determination of material thickness. Algorithms now developed for timing of ballute separation from spacecraft. Preliminary aeroheating analyses show no radiative heating issues for Titan aerocapture as were encountered with the rigid aeroshell case. Under Cycle 2, Ball is completing Design, fabrication and test of inflatable afterbody ballute deceleration system which builds on previous work with the Gossamer Spacecraft Exploratory Research and Technology Program

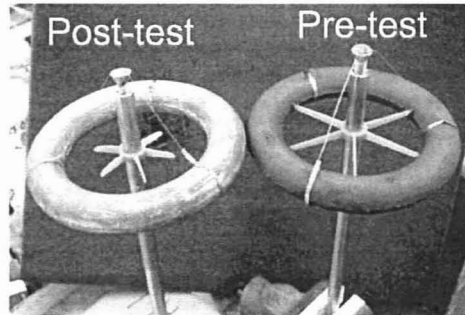
➤ **Accomplishments:**

- ❑ Multiple candidate ballute and tether materials identified, procured, and high-temperature and strength testing underway
- ❑ Guidance and control algorithms developed and successfully demonstrated in Monte Carlo simulations
- ❑ Initial system design for Titan complete

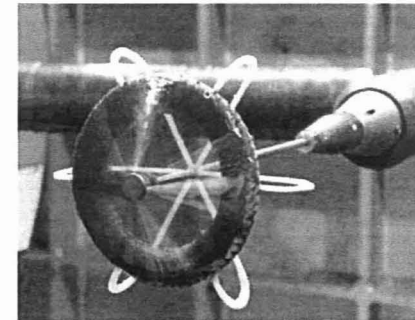
➤ **Plans:**

- ❑ Development of scale inflatable assemblies for test verification
- ❑ Completion of hypersonic validation tests
- ❑ Continued material tests and seaming development
- ❑ Develop earth flight validation concept

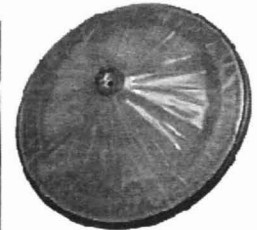
Hypersonic tunnel testing of Trailing and Clamped Ballutes



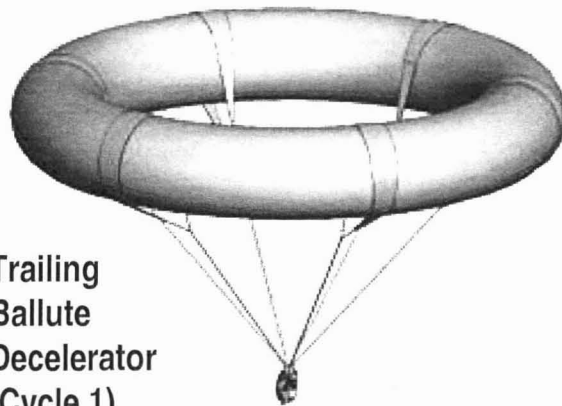
Trailing Ballute Model



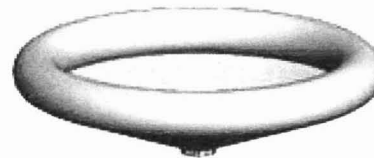
Clamped Ballute Model on Sting Arm



Clamped Ballute post-test



Trailing Ballute Decelerator (Cycle 1)



Clamped Ballute Decelerator (Cycle 2)

Contact:

Kevin Miller (Cycle 1)
 klmiller@ball.com
 1600 Commerce St
 Boulder, CO
 303.939.6550

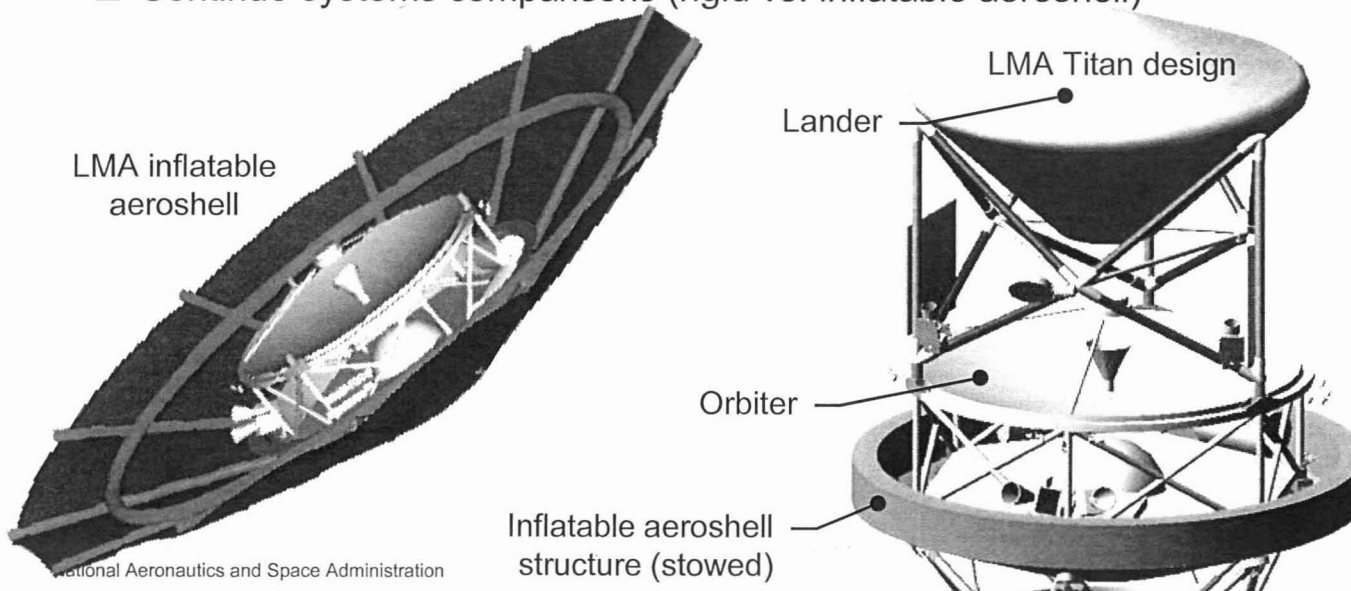
Jim Masciarelli (Cycle 2)
 jmasciar@ball.com
 303.939.5416

TASK 8:

Inflatable Forebody Aerocapture Concepts

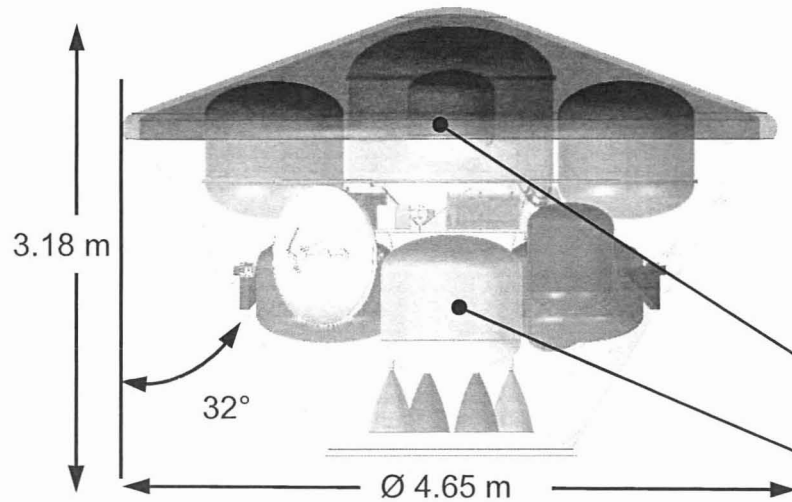


- **Summary** – Under Cycle 2, Lockheed Martin Astronautics is under contract to design, fabricate and test an inflatable aeroshell system. This aeroshell could be lighter than a rigid aeroshell allowing more science or a smaller launch vehicle. Spacecraft designers will be able to more fully utilize the volume inside the launch shroud because they are not constrained by a rigid aeroshell.
- **Accomplishments:**
 - ❑ Established a Titan point of departure (POD) design
 - ❑ Conducted preliminary trades for each program element
 - ❑ Completed initial systems comparisons (rigid vs. inflatable aeroshell)
- **Plans:**
 - ❑ Complete mass determination for POD
 - ❑ Perform trade studies for alternate shapes and sizes and internal configurations
 - ❑ Perform structural analysis to determine strength, stiffness, and stability
 - ❑ Continue systems comparisons (rigid vs. inflatable aeroshell)



Contact: Rich Hund
richard.a.hund@lmco.com
LMA
P.O. Box 179 M/S 8350
Denver, CO 80201
303.977.1471

AEROCAPTURE STUDY TASKS: Mars Aerocapture Systems Study (MASS)



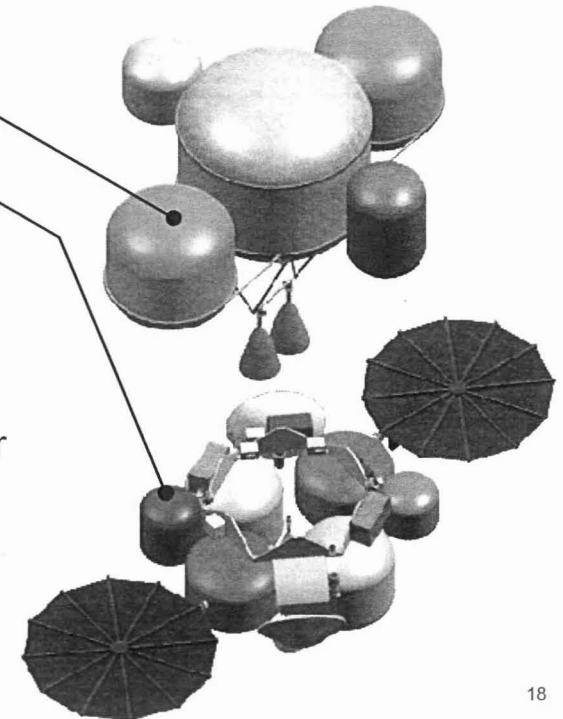
Notional Configuration, Launch Orientation
No primary structure shown

Element	Dry Mass CBE (kg)	Dry Mass w/Contingency (kg)	Propellant Mass (kg)	Total Wet Mass w/Contingency (kg)
Earth Return Vehicle, Total	678	882	2120	3002
Propulsion Stage	672	874	2950	3824
Mid-Truss Stage	201	261		261
Aeroshell/Backshell	917			1192
Cruise Stage	386	502	260	762
Total Launch Mass				9041
		Launch Vehicle C3 (km ² /s ²)	Delta 4050H-19	10.3
		Launch Vehicle Capability		7760
		Launch Vehicle Margin (kg)		-1281
		Launch Vehicle Margin (%)		-16.5%

Propulsion Stage

ERV

- ◆ Study kicked off on April 13
- ◆ LaRC/Henry Wright is leading study with participants from ARC, JPL, JSC, MSFC
- ◆ The primary objective is to perform a high fidelity aerocapture systems definition study for a large Mars robotic mission (MSR, 2013 Launch)
- ◆ Three stage vehicle: Aeroshell + ERV + Propulsion Stage
 - Forebody and Backshell separate immediately after aerocapture maneuver
 - Propulsion Stage separates after Mars apoapsis raise maneuver
 - ERV conducts trans-Earth injection and Deep Space Maneuvers
- ◆ Challenges: Requires packing density 18% higher than MER (226 kg/m³); negative launch vehicle margin.



AEROCAPTURE STUDY TASKS: Other Previous System Study Efforts



- The In-Space Propulsion Technology (ISPT) Project has commissioned other system studies to develop aerocapture missions to Solar System destinations possessing significant atmospheres:



System Analysis for a Mars Aerocapture Mission

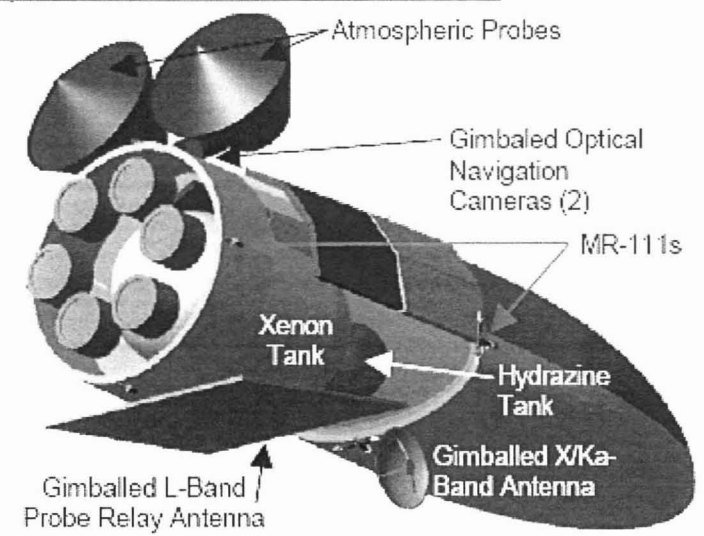
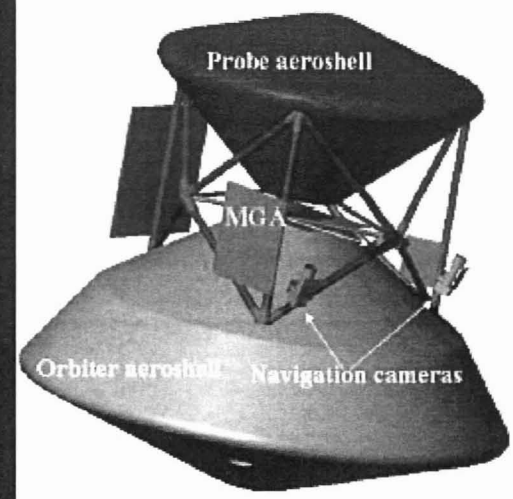
91

URL: <http://hdl.handle.net/2002/16212>

Aerocapture Systems Analysis for a Neptune Mission

NASA TM-2006-214300

URL: <http://hdl.handle.net/2002/16221>



<http://hdl.handle.net/2002/16166>

AEROCAPTURE STUDY TASKS:

Aerocapture Probabilistic Risk Assessment



- **Aerocapture PRA**
 - Completed in February 2005, recently modified to include aerocapture technology validation flight as a risk reducer.
 - Compares relative risks of capture techniques to quantify current assumptions about the nature of aerocapture
 - The current assumptions that the inherent risk of aerocapture makes it less appealing for interplanetary missions than aerobraking or propulsive capture are being put to the test with quantitative assessment.
 - This study will lend credibility to risk-benefit analyses and can establish aerocapture as a more viable technology if results show risk to be at least comparable with other capture techniques.

Future Developments/Plans/Tests

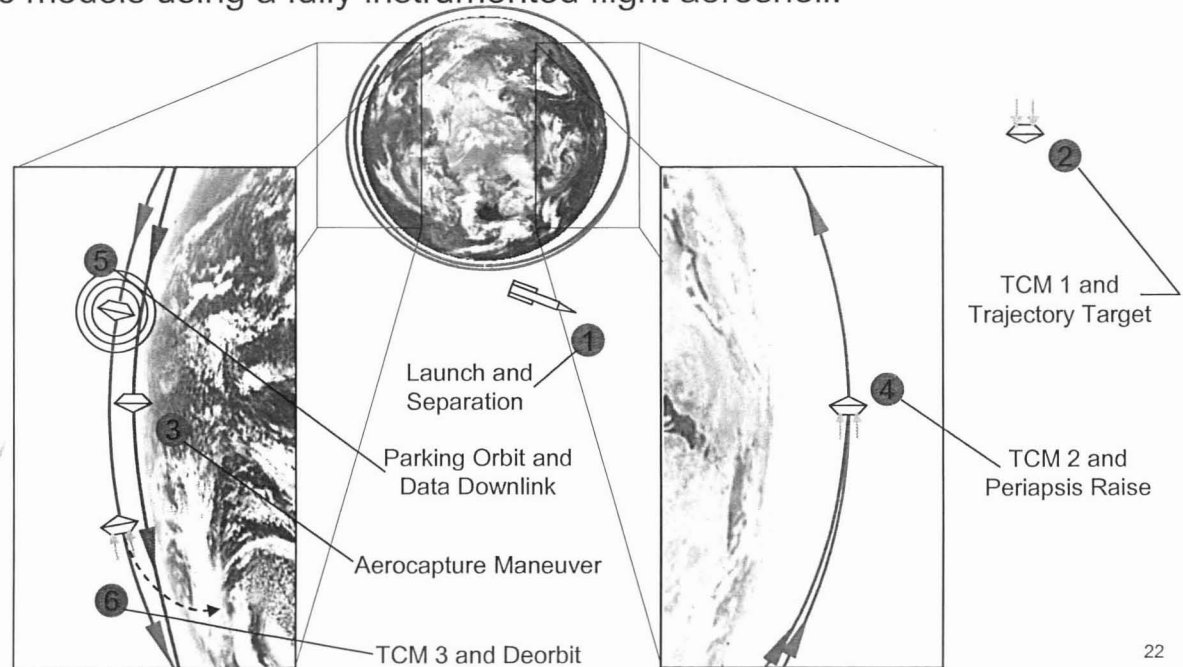
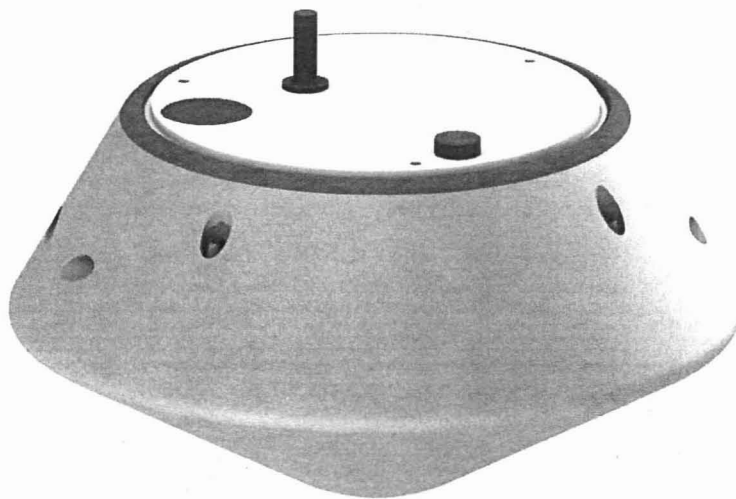


- **Flight validate the aerocapture maneuver aboard NMP's ST9.**
- **Develop other partnering opportunities for proposed missions (i.e. Discovery/New Frontiers/Mars Scout) employing aerocapture technologies (TPS, instrumented aeroshells, GN&C, etc.).**
- **Upcoming Testing**
 - Solar Tower Testing at Sandia
 - July through August – Solar Tower test series of 24" square full-up panels.
 - September/October/November – Solar Tower testing of 1m aeroshells.
 - Lockheed Martin TPS screening tests in ARC arcjet in June-July.
 - Aerocapture Sensor Testing in ARC Arcjet facility in 3rd Quarter FY06.
- **Upcoming Conferences**
 - **4th International Planetary Probe Workshop**, Pasadena, CA 27-30 June 2006.
 - **42nd AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit**, Sacramento, CA, 09-12 July 2006.

New Millennium Program's Space Technology 9 Aerocapture Flight Validation Proposal



- The NASA's New Millennium Program is currently sponsoring five competing system technologies for potential flight aboard the Space Technology 9 mission.
- Aerocapture System Technology for Planetary Missions is one of the five competitors.
- If aerocapture is the system technology selected for flight, the ST9 mission will flight validate:
 - Aerocapture as a system technology for immediate use in future missions to Solar System destinations possessing significant atmospheres,
 - New, advanced technologies:
 - Guidance Navigation and Control System
 - Thermal Protection Systems, and
 - Aerothermal and aerodynamic models using a fully instrumented flight aeroshell.



Contact Information



For additional information on the Aerocapture Technologies task area within the In-Space Propulsion Technology Program, please contact:

Ms. Bonnie James
Aerocapture Technology Area Manager
Phone: 256-544-6985
bonnie.f.james@nasa.gov

Ms. Michelle Munk
Aerocapture Lead Systems Engineer
Phone: 256-544-6544
michelle.m.munk@nasa.gov

Dr. Andrew Keys
Aeroshell Subsystem Manager for ST9
Phone: 256-544-8038
andrew.s.keys@nasa.gov





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