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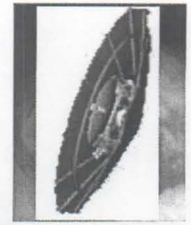


In-Space Propulsion

Aerocapture Inflatable Decelerator (AID)

Lockheed Martin Inflatable Aeroshell

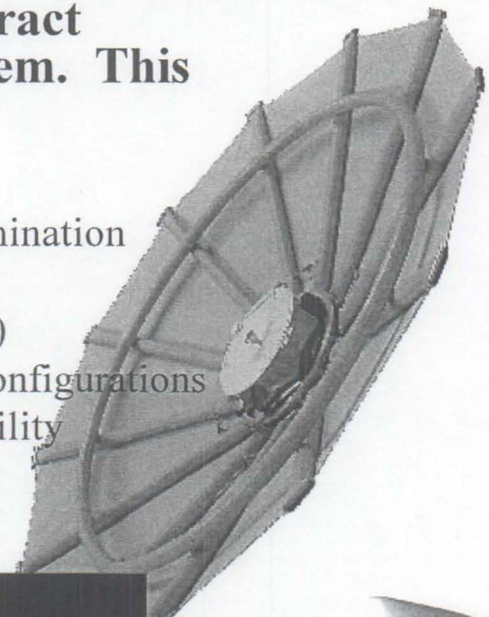
19th AIAA Aerodynamic Decelerator Systems Technology Conference

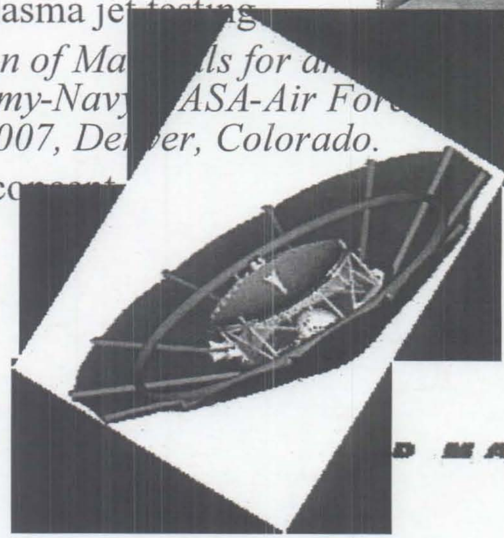
Sajjad Reza
Lockheed Martin Space Systems
23 May 2007

AID Team

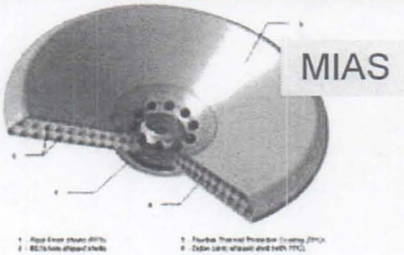
- Key Personnel
  - NASA MSFC Project Manager - Bonnie James
  - AID Program Manager – Rich Hund
  - Systems Analysis –Sajjad Reza / Dick Foss
  - Configuration – Kevin Makowski / Ken Romeo
  - Inflatable analysis – Glen Brown **(Vertigo Inc)**
  - Materials Analysis & Selection – Frank Kustas
  - Aeroelastic Analysis – Jarvis Songer / Michel Lesoinne **(CU)**
  - Thermal analysis – Chuck Rasbach / Greg Estrel
  - Aerothermal Analysis – Bill Willcockson / Jarvis Songer

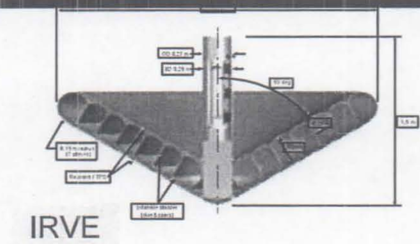
- **Lockheed Martin Astronautics was under an AID contract to design, fabricate and test an inflatable aeroshell system. This includes sizing, heat rates, loads analysis, etc.**
- Accomplishments:
  - Established a Titan point of departure (POD) design and mass determination
  - Conducted preliminary trades for each program element
  - Completed initial systems comparisons (rigid vs. inflatable aeroshell)
  - Completed trade studies for alternate shapes and sizes and internal configurations
  - Performed structural analysis to determine strength, stiffness, & stability
  - Completed Guidance Accuracy, Aeroelastic and Packaging analyses
  - Constructed scaled model for manufacturing process development
  - Completed inflatable aeroshell TPS material plasma je
    - *Kustas, F, et al, "Testing and Evaluation of Ma ls for a re Inflatable Decelerator (AID)," Joint Army-Nav ASA-Air Fo NAF) 54th Propulsion Meeting, May 14-17, 2007, De er, Colorado.*
  - Completed Assessment of inflatable aeroshell c for Mars direct entry





Traded Options





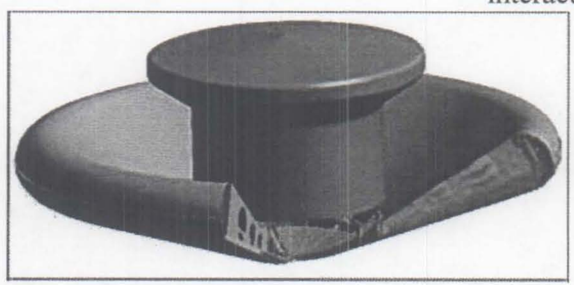
Multiple Stacked Tori

Pros:

- Good structural stability.

Cons:

- Poor use of inflation gas.
- Difficult interfaces
  - tube-tube
  - inflation
- MIAS: poor heat transfer
- IRVE: poor shear stiffness



Ribbed Double Surface

Pros:

- Good surface control
- Streamwise smooth
- Efficient material use

Cons:

- Manufacturing issues
  - Joining/seaming
  - Structural reinforcement
- Cross-flow wavy

Single Surface (Hypercone)

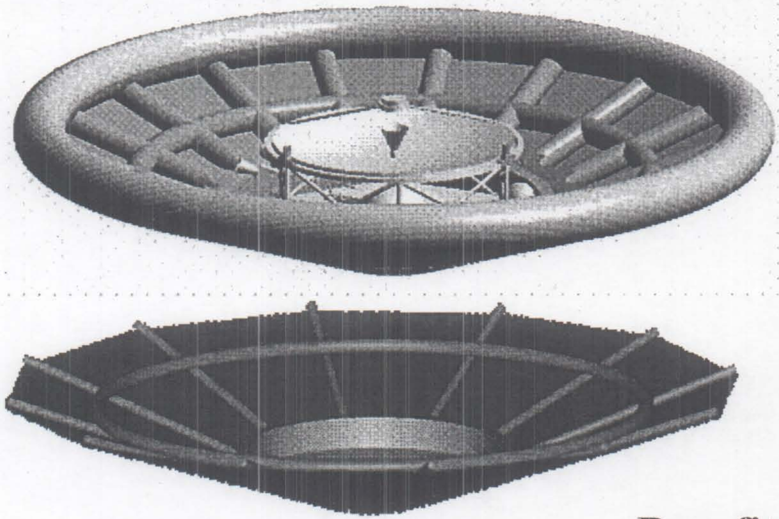
Pros:

- Lightest weight structure
- Efficient use of inflation gas
- Good heat transfer

Cons:

- Concave shape causes adverse shock interaction and high local heating.

Selected Option - Spar with Rims



Pros:

- Efficient structure
- Efficient gas usage
- Good heat transfer
- Potential for shape-morphing
- Known, scalable manufacturing technology
- Inflatable Components Thermally Protected

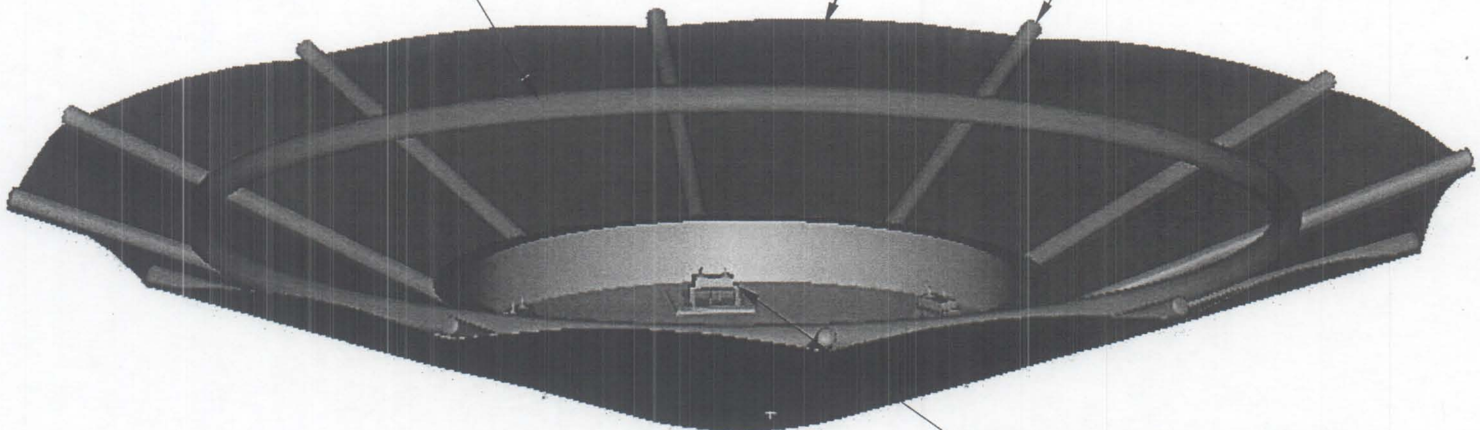
Cons:

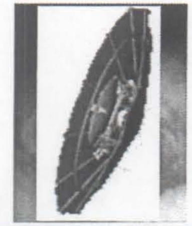
- Surface deflection – Assessed in Guidance Analysis - minimal
- Cross-flow wavy
  - Minimal impact

Benefits

- Back surface is efficient heat radiator
- Accommodates multiple material types
  - More efficient as material TRL improves
- Easily scalable
  - In terms of size/geometry, materials, etc.
    - High and low TRL options considered
      - High TRL = 7.5 m at Titan
      - Low TRL = 15 m at Titan

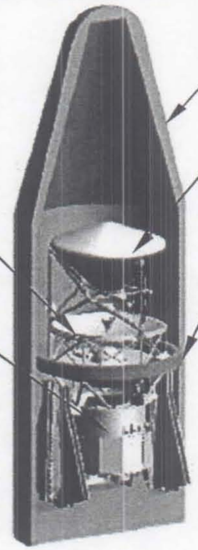
Inflatable Aeroshell Features



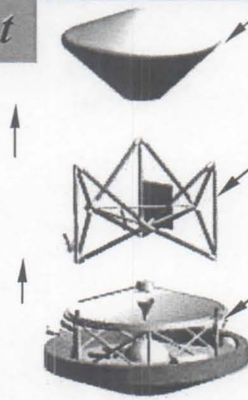


Titan Aerodecelerator Features

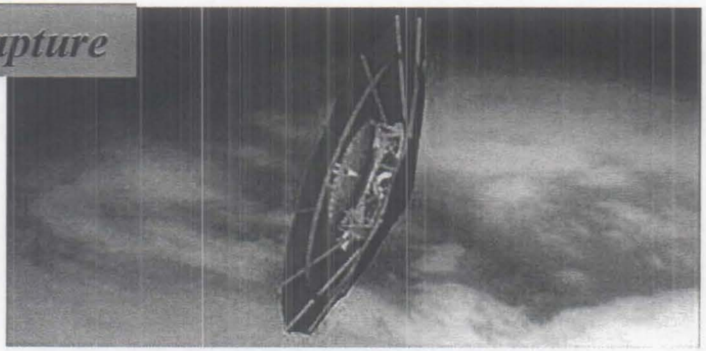
Launch



Deployment



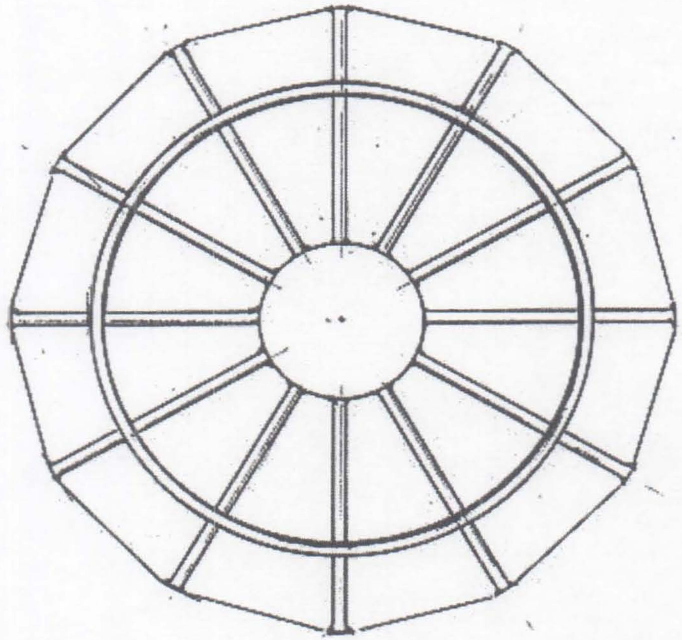
Aerocapture



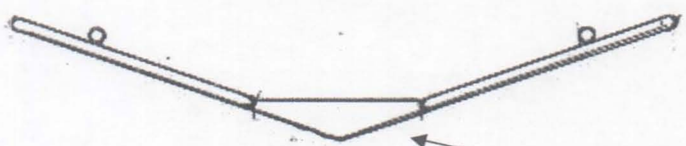
Payload CG offset and roll control via thrusters for corridor control

Spacecraft Release

Inflatable Structure



Feature		Unit
Spacecraft Diameter	3.75	m
Deployable Diameter	15	m
Length of Beam (spoke)	5.6	m
Axis-Beam Angle	70	deg



Rigid nosepiece

- interface location, TPS

Inflatable Design Integration

- Design Integration Provides
  - Stiffness Tailoring
  - Deflection Reduction
- Extensive Vertigo Heritage
  - Grounded with Tests
- Table for 15m High TRL Design

Pressure Required		
d_beam=	10	in
d_torus=	14	in
P_beam=	10.5	psi
P_torus=	10.8	psi

Slenderness	
L/d_beam=	22.1
πD/d_torus=	109.1

Bending Stiffness - Beam		
Fbrkmin=	845	lbf
Fbrkuse=	3382	lbf
ɛbrk=	3.0%	
EI=	1.41E+06	lbf-in^2

Bending Stiffness - Torus		
Fbrkmin=	1657	lbf
Fbrkuse=	6628	lbf
ɛbrk=	3.0%	
EI=	1.97E+10	lbf-in^2
Eimin=	3.26E+07	
EI/Eimin=	605	

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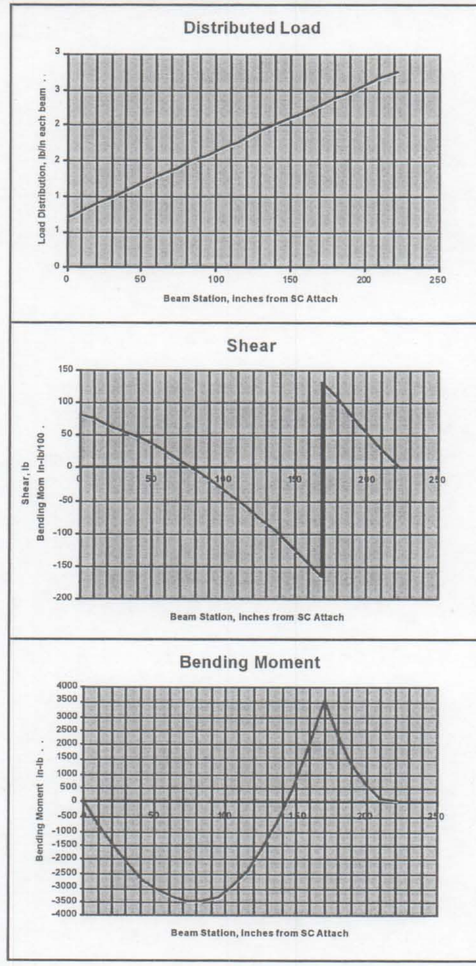
Inflatable Component Design

- Beam Design Based Upon
  - System Requirements
  - Vertigo Heritage
    - Shear and Moment

Beam Loading Uniform Pressure on Surface		
Total Axial Force (2.2g on 1,000 kg)	4840	lbf
Average Pressure	0.018	psi
Axial Force on AID (uniform pressure)	4537.5	lbf
Number of Beams	12	
Force on each beam	378	lbf

- Torus Design
  - System Requirements
  - Vertigo Heritage
  - L/3 & Optimization
    - V,M, Length

Estimated Optimum Torus Diameter and Loads		
Torus Attachment Beam Station	169.3	In
Torus Diameter	486.2	
Torus Vertical Reaction	296.3	lbf
Compression in Torus	224.5	lbf

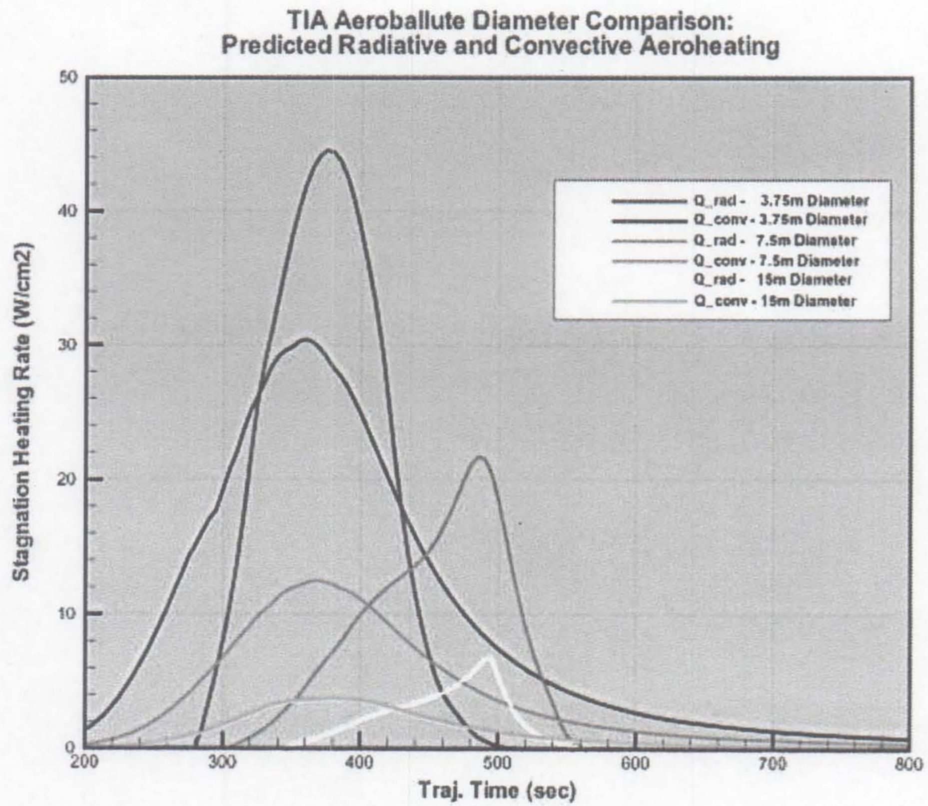


Aerothermal Objectives

- Establish the range of aerothermal environments expected for an Inflatable Aroshell aerocapture mission.
- Target Titan as a destination.
- Designate a single P.O.D. design to proceed with for initial sizing.
- Perform more extensive aerothermal analysis of P.O.D. ballute
- Iterate design if needed based on refined aerothermal environments and material/structural capabilities

Titan Inflatable Aeroshell Environments

- **Preliminary environments**
  - **3.75m, 7.5m and 15m diameters examined.**
  - **Convective heating analyzed using a combination of CFD and engineering tools.**
  - **Radiative heating predictions made by scaling methods using data from the ISP-1 rigid aeroshell mission. (Full explanation to follow.)**
  - **Radiative heating dominates as expected from previous experience.**

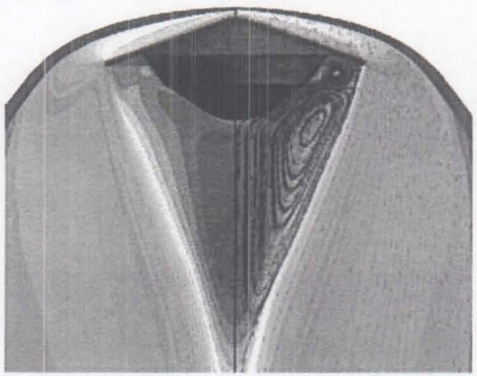


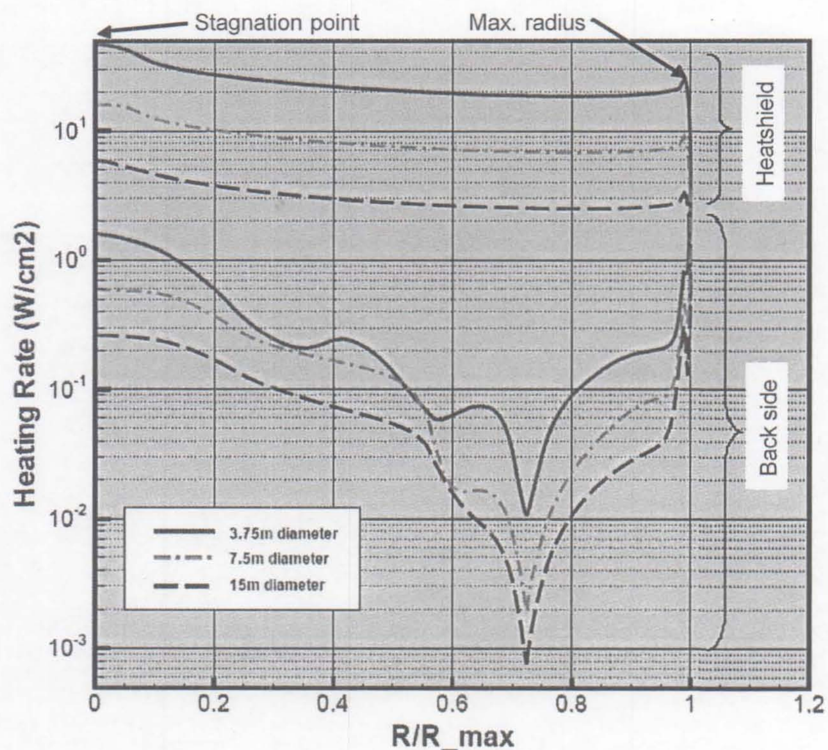
Titan Radiation Environment

- **Analysis of radiation heating at Titan presents significant challenges.**
  - **Radiation is highly coupled to flowfield, dictating the need for coupled CFD solutions or empirical correction factors to produce accurate estimates of heating.**
  - **Radiation heating is a strong function of methane concentration – still relatively uncertain for Titan.**
  - **Radiation predictions for preliminary analysis extrapolated from existing ISP1 data, using 3.75m diameter as a common reference point.**
  - **ISP1 values derived from data published by NASA ARC and LaRC (AIAA 2004-0484 & AIAA 2003-4953)**
  - **Scaling factors for larger diameters derived using LMA tool results and 3.75m ISP1 results.**

Afterbody Heating

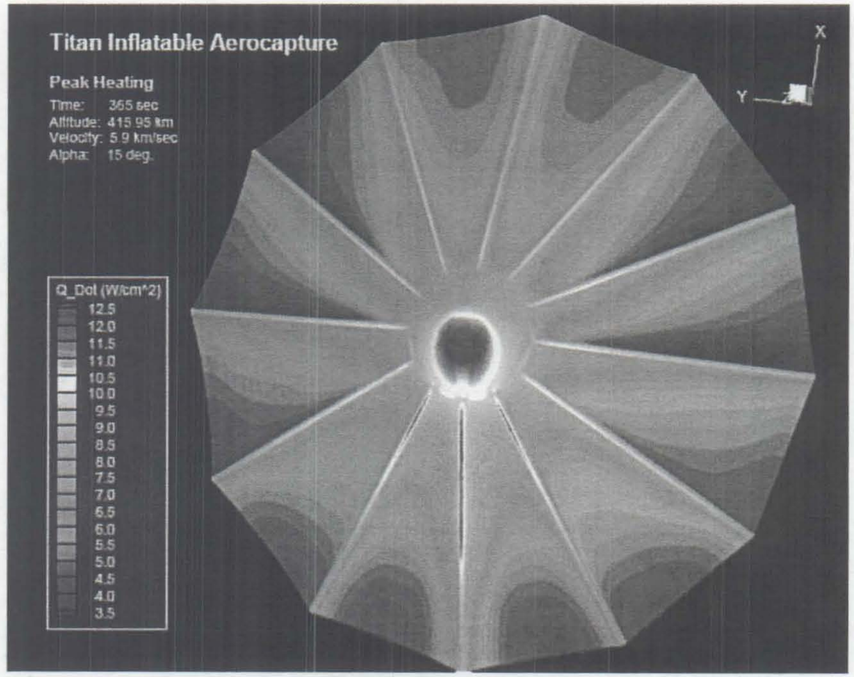
- Simplified vehicle geometry w/ assumed spacecraft envelope
- 0° AoA (provides most conservative heating
  - Three diameters analyzed to provide parametric data
  - Corner radius matched to inflatable spar thickness
- Backshell not required for P.O.D. ballute - thermal blankets provide adequate thermal isolation





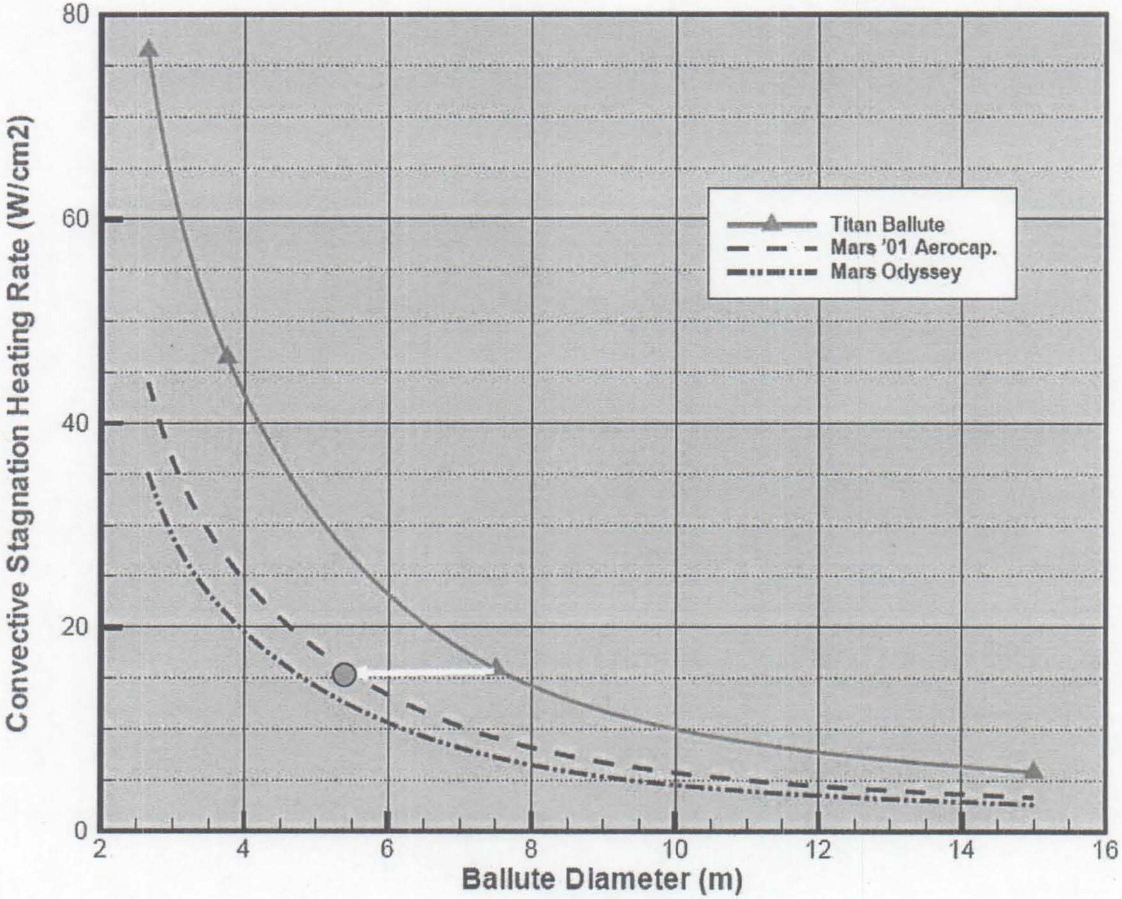
Forebody Convective Heating

- Deformation of forebody results in "ridged" surface
- Local heating accentuation expected at spar locations
- CFD analysis of aero-loaded forebody performed using LAURA
  - 18 species Titan atmosphere
  - Laminar flow
  - 0°, 5°, and 15° cases
- Local heating increase on spars ~50% compared to surrounding areas
- Spar heating is bounded by stagnation point heating in all cases



Scaling (with heat rate)

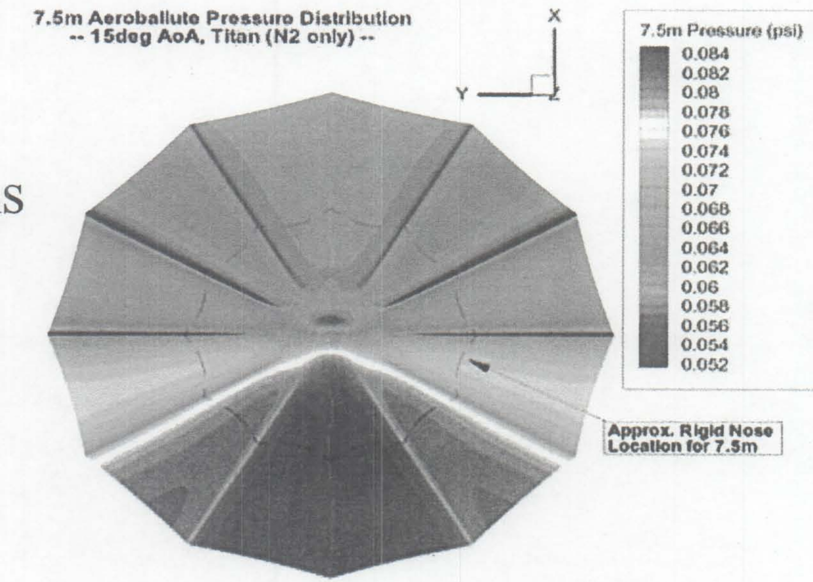
Differing environments can translate into a reduced ballute diameter



Surface Pressure

- 7.5m Pressure Distribution

- Used as input to detemine Spar and membrane deflections



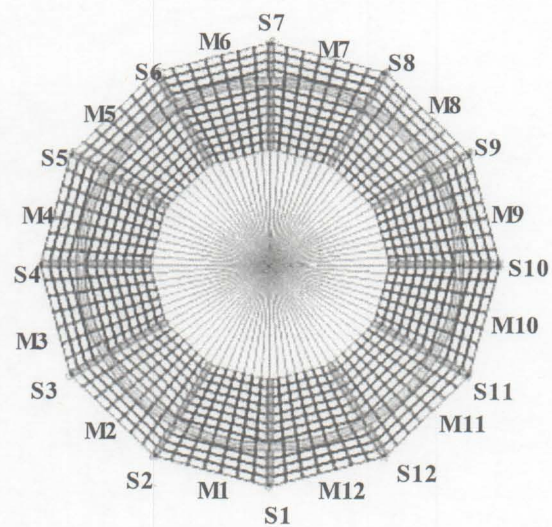
Worst Case Deflections

- Edge Deflections for 15 deg AoA
- Max delfection at membrane = 6.42”
- Max deflection at spar = 2.77”

Edge Displacements of Deployable

Membrane	R Disp in.	Z Displ in.	Spar	R Disp in.	Z Displ in.
M1	-2.774	6.420	S1	-1.142	2.772
M2	-2.774	6.421	S2	-1.040	2.745
M3	-2.704	6.278	S3	-0.973	2.574
M4	-2.529	5.917	S4	-0.891	2.367
M5	-2.384	5.613	S5	-0.815	2.173
M6	-2.517	5.259	S6	-0.777	2.074
M7	-2.517	5.259	S7	-0.782	2.088
M8	-2.384	5.613	S8	-0.777	2.074
M9	-2.529	5.917	S9	-0.815	2.173
M10	-2.704	6.278	S10	-0.891	2.367
M11	-2.774	6.421	S11	-0.973	2.574
M12	-2.774	6.420	S12	-1.040	2.745

Displacements at end of Spars (Si)
And outer edge midpoint of Membrane (Mi)



Accuracy Initial Conditions

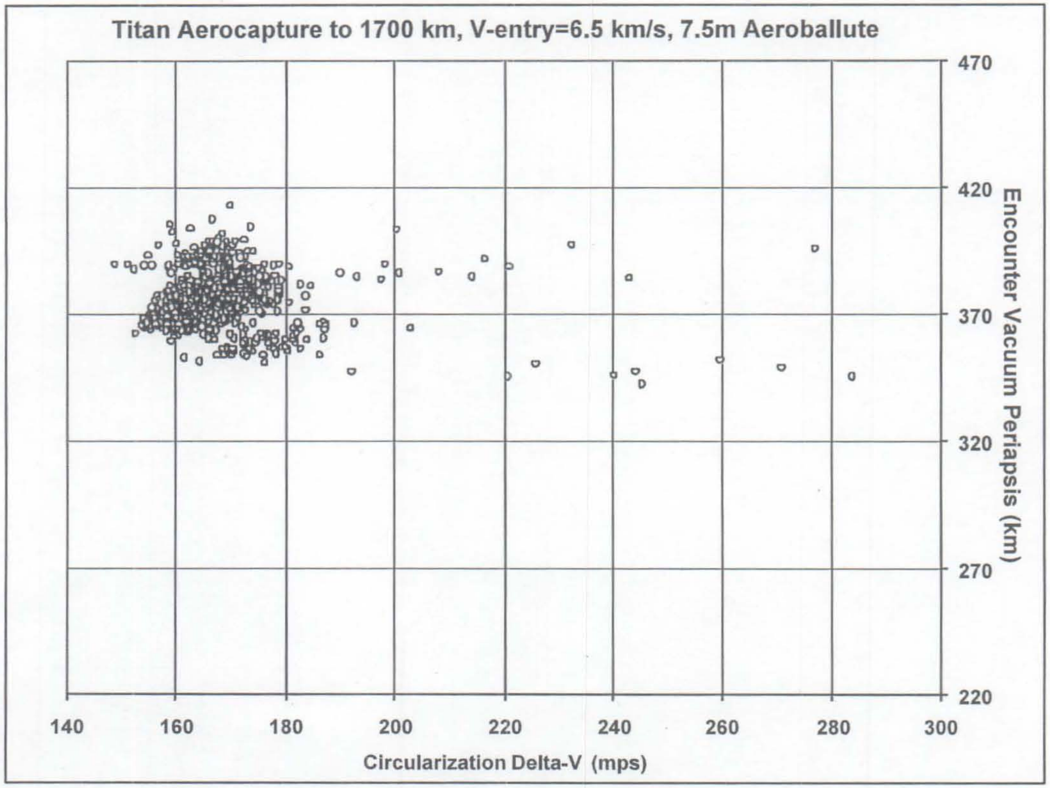
- Closed-loop aeroassist simulation (CLAAS)
- Utilized bank angle control of the positive lift vehicle in the presence of navigation and atmospheric errors

1) 1200 kg entry mass
2) 7.5 m diameter
3) 1700 km exit orbit apoapsis target (same as rigid study)
4) 375 km Encounter periapsis (required to satisfy Items 1, 2, and 3) – this is in contrast to the 296 km used for the smaller (3.65 m) rigid aeroshell
5) 2% Area change due to deflected shape
6) 0.7 deg angle of attack shift due to deflected shape
7) Aerodynamic coefficient change (Cd & Cl) due to 2.7 deg change in deflected average cone angle
8) 5% overall aerodynamics uncertainty (vs. 2.5% used for rigids)
9) 25% reduction in roll angular acceleration due to assumed reduction in torsional stiffness

Monte Carlo Results

1) Apoapsis error had a standard deviation of 176 km. This is in contrast to a value of 97 km for the rigid vehicle.

2) Circularization trim delta-V requirements (fixing both apoapsis and periapsis errors) had a 99% maximum magnitude of 240 mps. The corresponding value for the rigid aeroshell was 238 mps.



Guidance Summary

- An orbit-insertion accuracy analysis based on deflected shapes of the down-selected AID inflatable aeroshell configuration, and concepts for membrane shape control/steering was completed.
- Results from the orbit-insertion accuracy analysis reveal:

1. Highly efficient lift vector control guidance is feasible and attractive for our inflatable concept,
2. Deflections associated with loads on the inflatable structure are relatively small and have minimum impact on guidance and control,
3. Aerocapture injection accuracy is similar to that of a rigid aeroshell,
4. Several promising concepts to achieve effective center of gravity (CG) offset are possible, and
5. Lift vector control is effective for aerocapture as well as entry scenarios.
6. Conventional control and stability methods can be used to control the inflatable aeroshell during aerocapture or planetary entry

Aerocapture Inflatable Decelerator

Rigid vs. Inflatable Aeroshell

RIGID AEROSHELL

- Requires a Separate Cruise Stage which includes Solar Power Systems, Star Trackers, ACS, Propulsion, and Radiators for heat rejection. (Internal for Spacecraft and External for Cruise)
- External Radiators likely necessary to Dissipate Heat generated within enclosed Aeroshell.
- Spacecraft Packaging is not optimized because it must be constrained to fit within the Aeroshell (Backshell and Heatshield) Shape.
- Less Flexibility to Tailor Spacecraft Mass Properties
- Limited Access to Spacecraft late in Integration flow

INFLATABLE AEROSHELL

- Inflatable Aeroshell is stowed during cruise, and no Backshell is required, therefore Spacecraft Navigation, ACS, Propulsion Systems can potentially be utilized Eliminating the need for an Independent Cruise Stage.
- Spacecraft has Clear view to Space Simplifying Heat Rejection
- Ability to Optimize Spacecraft Packaging within Launch Vehicle Payload Fairing
- More Flexibility to Tailor Spacecraft Mass Properties
- Allows for Spacecraft Access late in Integration Flow
- Low Mass Fraction

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Titan Rigid/Inflatable MEL

Rigid		Higher TRL Inflatable		Lower TRL Inflatable	
Component	mass (kg)	Component	mass (kg)	Component	mass (kg)
Heatshield	**194.2**	**Rigid Nosecone**	**107.3**	**Rigid Nosecone**	**102.3**
Honeycomb structure	45.47	Structure with ring	58.2	Structure with ring	58.2
Perimeter ring filler	12.71	TPS	17.9	TPS	12.9
SLA5612V TPS	94.92	S/C interface fittings	31.2	S/C interface fittings	31.2
TPS film adhesive	4.9	**Other Aeroshell**	**40.9**	**Other Aeroshell**	**31.6**
Seals	0.53	Torus	4.0	Torus	7.0
Kapton blanket	0.83	Membrane film,	21.6	Membrane film,	3.6
Backshell sep fittings	3.62	Membrane barrier,	3.5		
S/C prop module sep ftgs	31.19	Axial straps	1.4	Axial straps	1.4
Backshell	**92.5**	Zirconia insulation	2.7		
Honeycomb structure	47.04	Spars	5.2	Spars	17.1
SLA5612S TPS	21.41	Spar K1100	1.9	Spar K1100	1.9
Thrusters & fittings	14.16	Beam ends	0.7	Beam ends	0.7
Vents (2)	1.61	**Miscellaneous**	**3.1**	**Miscellaneous**	**3.1**
Radiators (2)	6.82	Gas inflation system	1.4	Gas inflation system	1.4
Probe sep seals (3)	1.46	Gas	0.9	Gas	0.9
Total rigid structure	**286.7**	Container	0.8	Container	0.8
		Total	**151.3**	**Total**	**137.0**
		Total w/ 30% contingency	**196.7**	**Total w/ 30% contingency**	**178.1**

Inflatable Aeroshell Applicability to Mars Entry

Mars Direct Entry

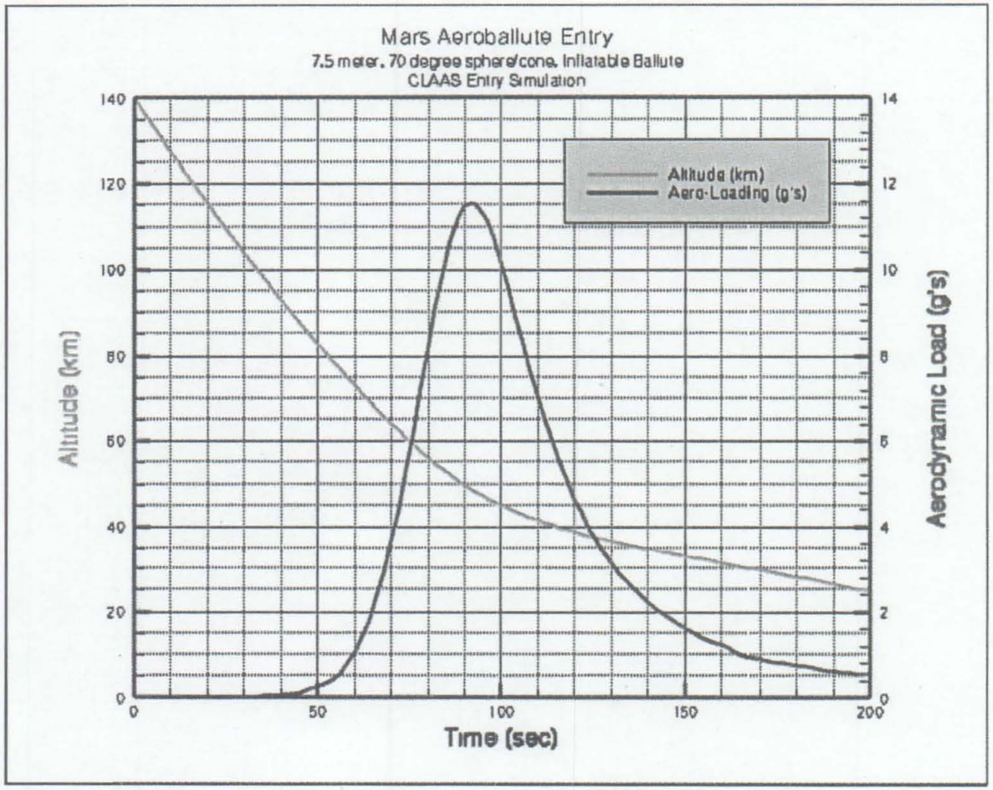
- Initial Conditions similar to Mars Scout Phoenix Mission

	Inflatable Aeroshell	PHX-Rigid Aeroshell
Total Mass	500 kg	600 kg
Entry AoA Flight Path Angle	15.5 deg -13 deg	0 deg -13 deg
Entry Altitude	125 km	125 km
Ballistic Coefficient	7.7	66
Aeroshell Diameter	7.5m	2.65m

Altitude and Load for Mars Entry

- Altitude vs Load for Inflatable Mars Entry

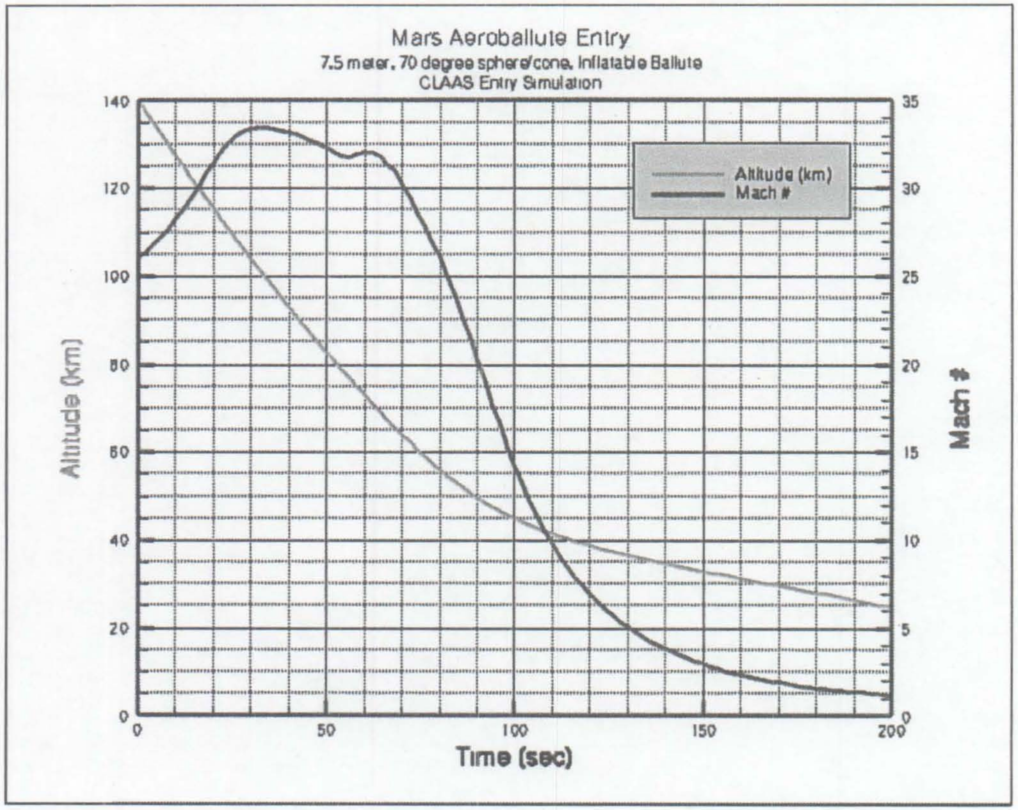
- Max load 11.5 g's



Altitude and Mach

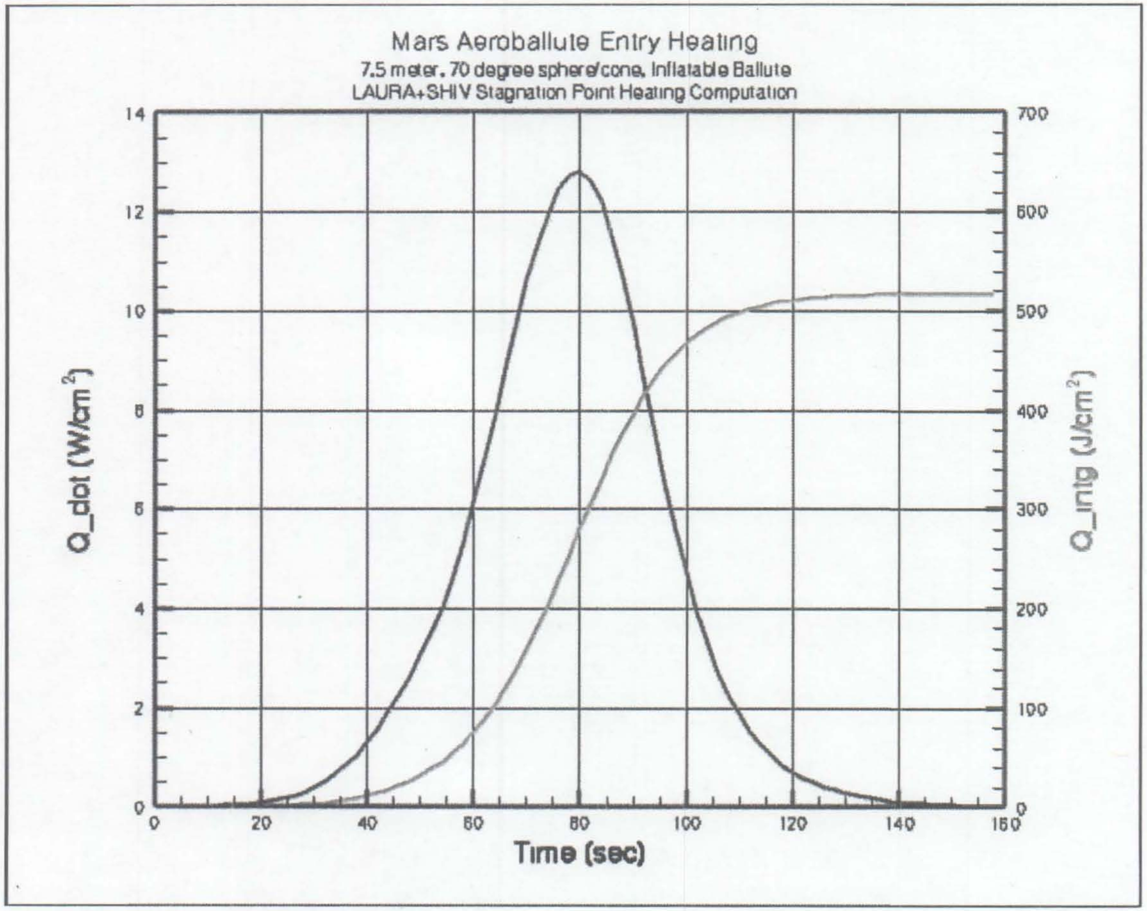
- The inflatable aeroshell allows the spacecraft to decelerate earlier during entry and at a higher altitude

- Mach 1.5 at 27km Alt



Mars Entry Heat Rates

- Max heat rate 12.8 w/cm2 and integrated head load of 518 J/cm2 within inflatable material limits



Summary

•Inflatable Aeroshell allows deployment of Parachute at much higher altitudes than is possible with rigid aeroshells.

•Parachute deployment at high Mach #'s (>3) is inefficient

	Inflatable	**PHX Rigid**
Max Heat Rate	12.8 W/cm2	56.0 W/cm2
Max g Loads	11.5	<10 Nom
Parachute Deploy Alt	27.5 km	10 km
Parachute Deploy Mach	<1.5	~2.0

Aerocapture Inflatable Decelerator (AID) for Atmospheric Entry

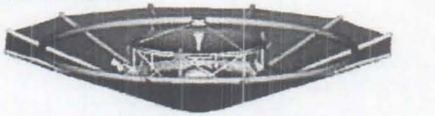
R. Hund, S. Reza, F. Kustas, K. Makowski, W. Willcockson, J. Songer, K. Romeo; Lockheed Martin Space Systems—Civil Space; Denver, CO
G. Brown; Vertigo Inc.; Lake Elsinore, CA M. Lesoinne; University of Colorado; Boulder, CO

Background:

- Entry into planetary atmospheres results in significant heating and aerodynamic pressures which stress thermal protection system materials to their useful limits.
- Decelerators with increased surface-area footprints reduce heat flux, induced temperatures and are stowable in a compact space in the spacecraft.
- LMSSC, Vertigo Inc., and the University of Colorado, developed a conceptual inflatable aeroshell design, performed Computation Fluid Dynamics (CFD) and thermal analyses, and tested candidate Thermal Protection System (TPS) articles.

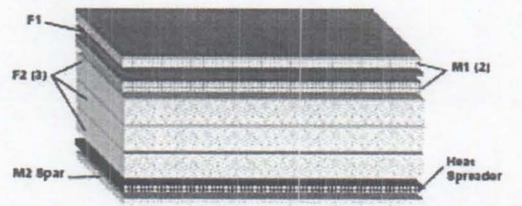
Inflatable Aeroshell Design Trade Study:

- Designs for an inflatable aeroshell were traded. Concepts included: 1) multiple stacked tori, 2) single-surface hypercone, 3) ribbed double surface, and 4) spar-supported membrane (selected)
- Benefits of selection: 1) membrane back surface as a thermal radiator, 2) ability to insert higher Technology Readiness Level (TRL) materials, 3) scalable to larger sizes for other missions, and 4) extremely low mass fraction.
- Deflections associated with our inflatable structure are relatively small therefore existing guidance and control methods can be used.



Membrane/Spar Concept for 7.5-m AID

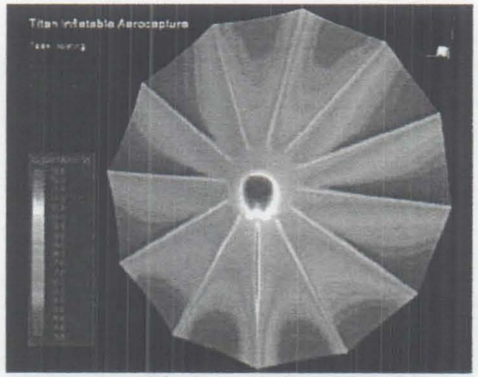
- Baseline AID configuration lay-up consists of high TRL TPS materials.



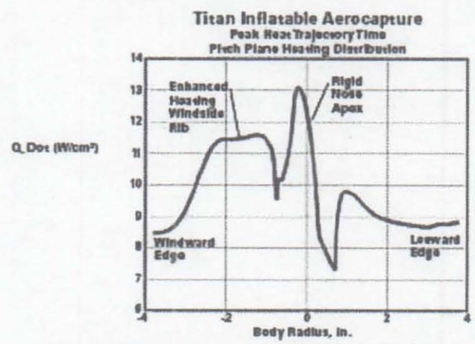
AID Materials Configuration Across Membrane-to-Spar

Analytical Modeling; CFD, Thermal:

- CFD were performed on membrane/spar configuration to provide heat flux and pressure distributions.
- Thermal model (figure on bottom right) developed to calculate temperature distributions from peak heating predicted from CFD.
  - Multilayer configuration with TPS material layers separating membrane and inflated spar is effective at reducing temperature on the spar material.



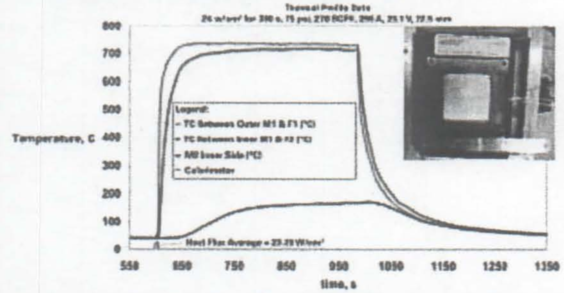
Heat Flux for 7.5-m AID Concept, Showing Localized Areas of Higher Heat Flux



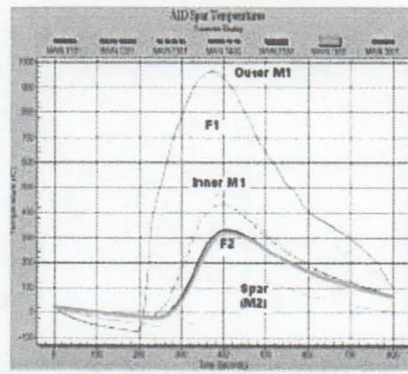
Relative Heating Rate as Function of Position

Thermal Testing:

- Plasma jet (PJ) testing conducted on test articles in LMSSC-Materials Technology Laboratory (MTL), to measure in-depth temperatures and validate materials survivability.
- Systematic series of tests with increasing heat flux to achieve predicted temperature (900-1000°C) during entry into Titan.
- Heat flux of ~32W/cm² required for M1 outer material temperature of 900-1000°C in Earth atmosphere. Maximum spar temperature measured ~215°C.
- Multilayered TPS materials survived multiple (5) PJ exposures during heat flux-temperature calibration experiments.



Plasma Jet Test Results: Measured Temperatures Showing Attainment of >700°C beneath outer M1 for Heat Flux of ~24W/cm² and <200°C on Spar (M2)



Temperature Distributions Predicted for Various Locations Across AID Membrane/Spar Multilayer

AID Conclusions

- Inflatable aeroshell offers mass savings over rigid
  - Flight-proven materials exist
  - More advanced materials allow additional mass savings
- Backshell elimination possible
  - Even with modest forebody diameters
  - Use existing orbiter subsystems during cruise
- Inflatables allow for flexibility
  - Tailor forebody diameter (associated heat rate)
  - Material options
- "Hot spots" are manageable
- Global and Local flutter minimal
- Packaging and deployment efficiency
- Manufacturable
- Scalable to multiple destinations
- Potential cost savings (recurring cost)
- Inflatable Aeroshell is applicable to Mars EDLS
  - Parachute deployment at high altitudes

Model of 15m Inflatable Aeroshell