A Survey of Ballute Technology for Aerocapture

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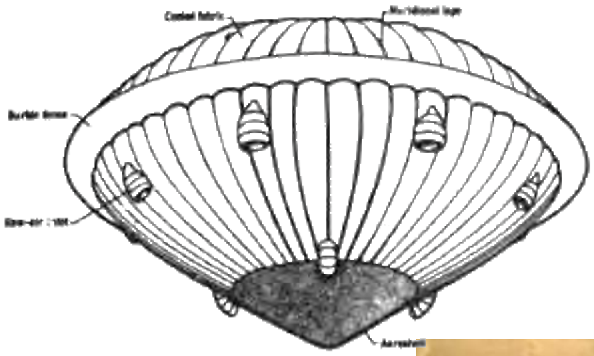
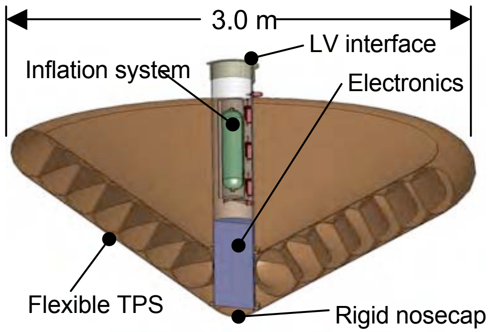
Outline

- Introduction
  - Aerocapture
  - Ballute configurations
- Ballutes background
- Thin-film ballutes
- Trajectory analysis
- Structural analysis
- Hypersonic aerothermodynamics
- Coupled analysis
- Flight tests
- Advancing ballute technology
- Summary



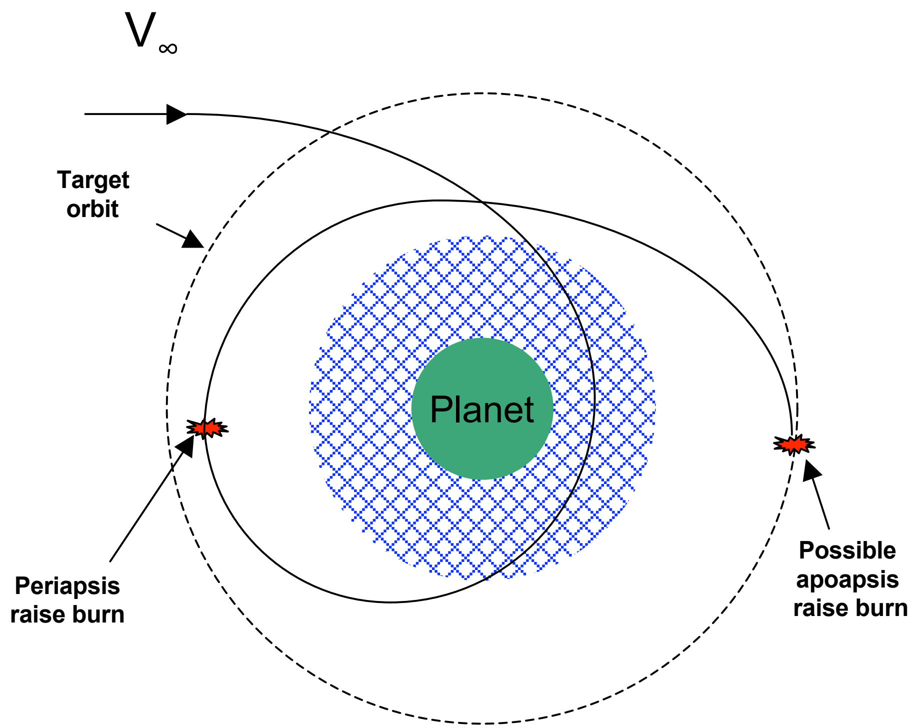


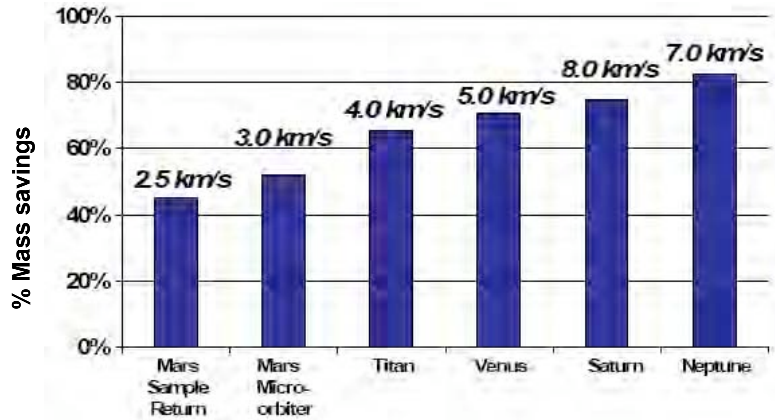
Introduction - Aerocapture

- Aerocapture
  - Hyperbolic orbit to elliptic
  - Single drag pass
  - Small propulsive requirements

- Traditional aerocapture
  - Rigid aeroshell
  - Lift modulation to control energy dissipated
  - High heat rates due to small nose radius
  - Difficult packaging

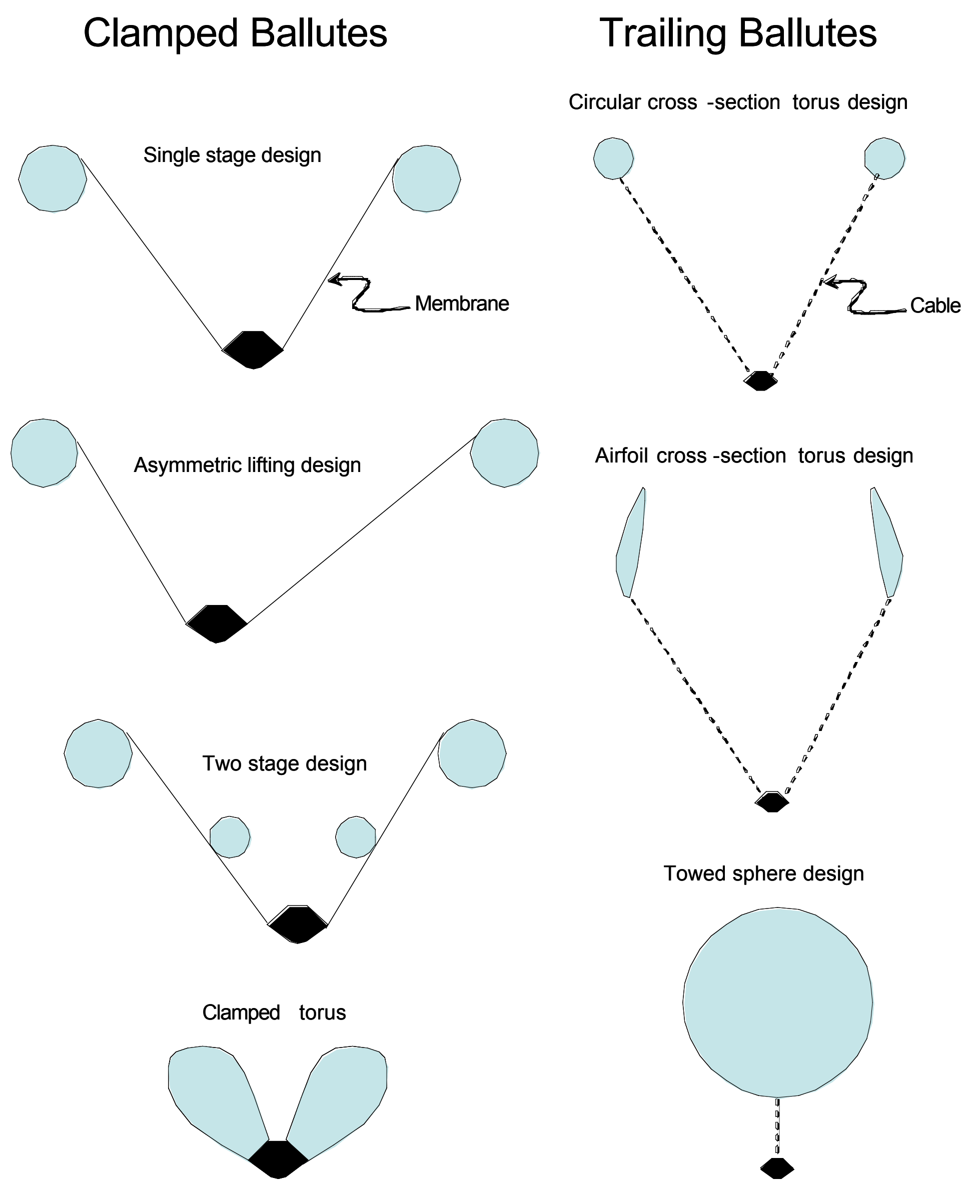
- Significant mass savings over propulsive orbit insertion





Introduction – Ballute Configurations

- Clamped ballute
  - Extends aeroshell with inflatable structure
  - Easy separation
- Trailing ballute
  - Various geometries towed behind a spacecraft
  - Connected with tethers
  - Easy separation
- Cocoon ballute
  - Difficult to package
  - Difficult to separate
- Materials
  - Coated fabrics
  - Polymer membranes
  - Metal fabrics

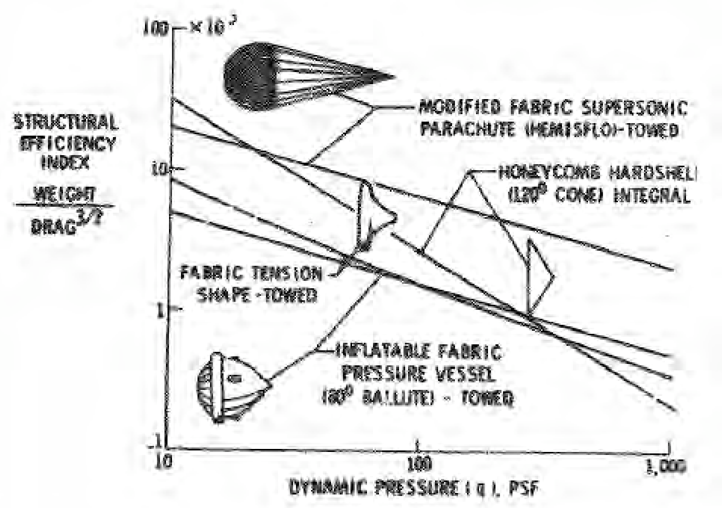


Ballute Background

- Originally developed in the 1960's as a better supersonic parachute
  - Early testing by McShera, Charczenko, and Keyes (1961-1963)
  - Demonstrated better stability and higher drag than supersonic parachutes

- Used for payload stabilization and recovery
  - MK-82 bomb
  - Gemini escape system

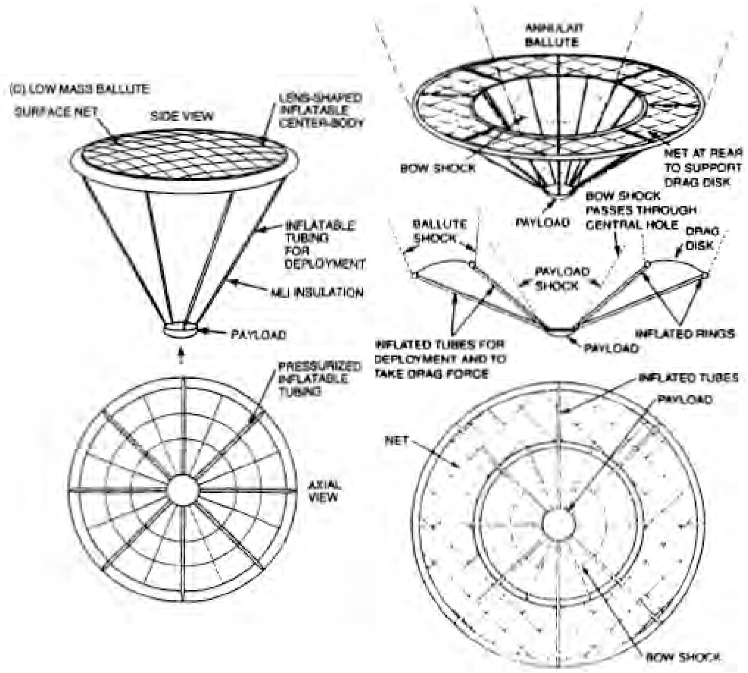
- Mars entry supersonic decelerator
  - Deployment from Mach 3 to 5
  - Improved payload landed by > 15%



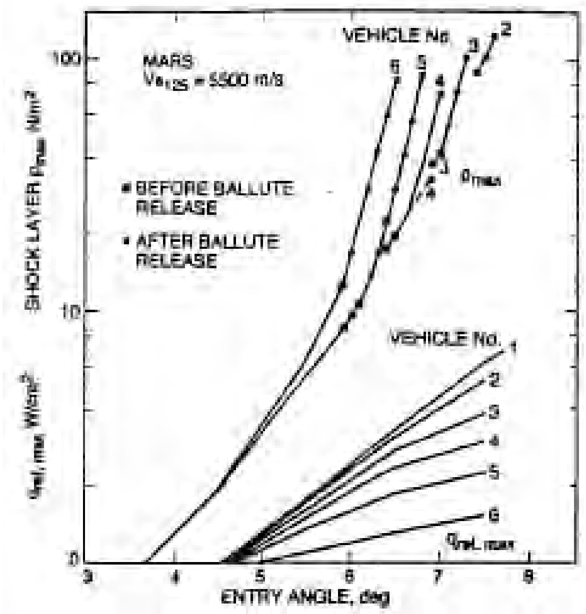
Comparison of propulsion and aerocapture mass on future missions.

	Mission Parameters			Orbit Insert Opt.	
	Entry speed	Orbit insert DV	Non-braking mass	Prop. mass fraction	Ballute mass fraction
	(km/s)	(km/s)	(kg)	(%)	(%)
Mars Comm/ Nav Sat	6.4	2.9	100	63	20
Venus Sample Ret.	11.6	4.5	2600	78	30
Titan Explorer	9.6	8.0	325	93	30
Saturn Ring Observer	26.1	8.0	250	93	40
Neptune Orbiter	28.9	5.9	230	86	40

Thin-Film Ballutes



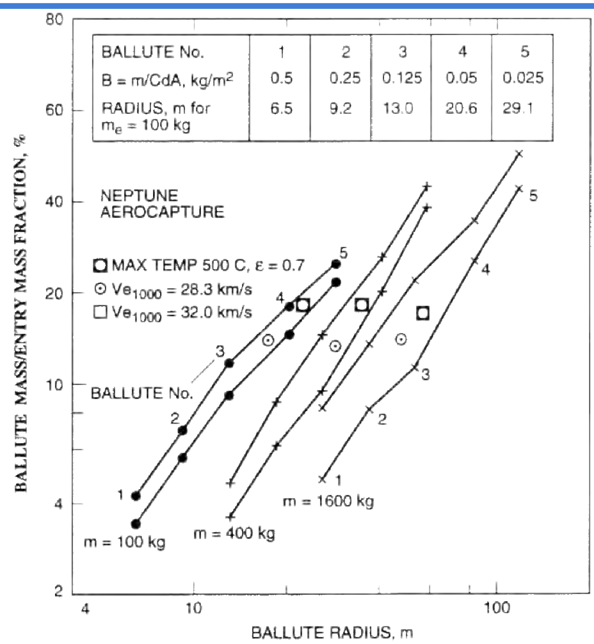
- Bigger is better
  - Lower the ballistic coefficient by using a larger ballute
  - This leads to:
    - Deceleration at higher altitude (low density)
    - Larger nose radius leads to lower convective heat rates



- Low heat rates
  - Typical rigid aeroshell
    - Heat rate = 40 W/cm^2
    - Ballistic coef. 90 kg/m^2
  - Typical thin-film ballute
    - Heat rate = 4 W/cm^2
    - Ballistic coef. 1.0 kg/m^2

Thin-Film Ballutes – Mass Savings

- Lower mass fraction than rigid aeroshells
  - ~15% compared to 35 to 45% for rigid aeroshells
  - Lower heat rate leads to lighter materials
  - Little or no TPS required



- Thin-film materials
  - Kapton
  - Mylar
  - PBO
  - PIBO

Property	Unit	Kapton	Aramid	PET	PEN	PBO
Density	g/cm³	1.420	1.500	1.395	1.355	1.54
Melting Temp	°C	none	none	263	272	none
Glass Transition Temp	°C	350	280	68	113	none
Young's Modulus	kg/mm²	300	1000-2000	500-850	650-1400	4900
Tensile Strength	kg/mm²	18	50	25	30	56-63
Tensile Elongation	%	70	60	150	95	1-2
Long-Term Heat Stability	°C	230	180	120	155	>300
Heat Shrinkage (200°C x % min)	%	0.1	0.1	5-10	1.5	<0.1
Coefficient of Thermal Expansion	ppm/°C	20	15	15	13	~ 2
Coefficient of Hygroscopic Expansion	ppm/%RH	20	18	10	10	0.8
Moisture Absorption	%	2.9	1.5	0.4	0.4	0.8

Technical Challenges

1) Determination of optimal ballute shape

Several ballute shapes have been proposed in the literature with various advantages. Issues include tether heating, system mass, and drag characteristics.

2) Survivability of the ballute material

Can thin-film membrane materials actually handle the heat produced? Expanded material testing is needed, and more accurate heat fluxes are needed to determine actual material temperature, including radiative heating.

3) Flow stability

Large scale flow instability, such as vortex shedding, can cause motion and orientation changes of the ballute/spacecraft system. Smaller scale instability has also been discovered due to shock-shock interaction. Preliminary results suggest that this can be avoided by using a toroid of proper geometry, but further studies are needed. So far studies have assumed ballutes are rigid, but aeroelastic phenomenon need to be explored.

4) Ballute system mass

Preliminary results indicate significant mass savings over both propulsive orbit insertion and rigid aeroshell aerocapture, but more detailed analysis is necessary. A change in ballute shape, size, or inflation pressure could have a significant impact on the system mass.

5) Trajectory robustness

Can an algorithm be designed to handle the uncertainties and still have a useable entry corridor? Better atmospheric uncertainties are need for some planets, and uncertainties need to be estimated for the ballute. Probabilistic methods need to be used in trajectory design to determine the chance of success.

6) Structural integrity

Even though dynamic pressure and heating is low compared to rigid aeroshells, the materials have become correspondingly more fragile to achieve mass benefits.

7) Tether design

Can tethers handle the high heat flux due to their small diameter relative to the ballute? Issues such as shock impingement from the spacecraft and attachment to the ballute need to be resolved.

8) Parent spacecraft protection

The ballutes have large nose radii to reduce heating, but the spacecraft is relatively small, so heat fluxes are higher. Does the spacecraft need thermal protection, and how do you protect deployables?

9) Deployment and inflation

Deployment technology can be borrowed from the Inflatable Antenna Experiment, but additional work needs to be done to avoid tether tangling. The inflation system also needs a mechanism to avoid overpressure as the gas expands during the atmospheric pass.

10) Experimental verification

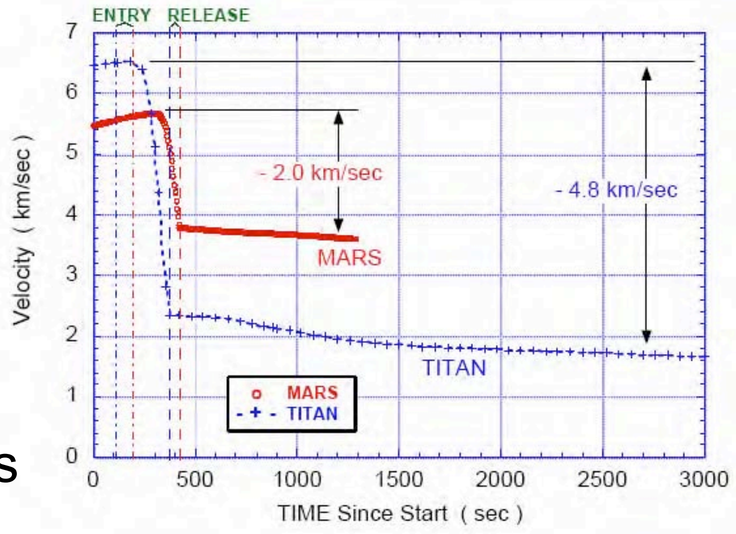
For planetary missions the complete aerothermodynamic environment cannot be reproduced on Earth. What combination of testing and analysis is sufficient to prove the concept? Can the appropriate scaling parameters be matched for testing?

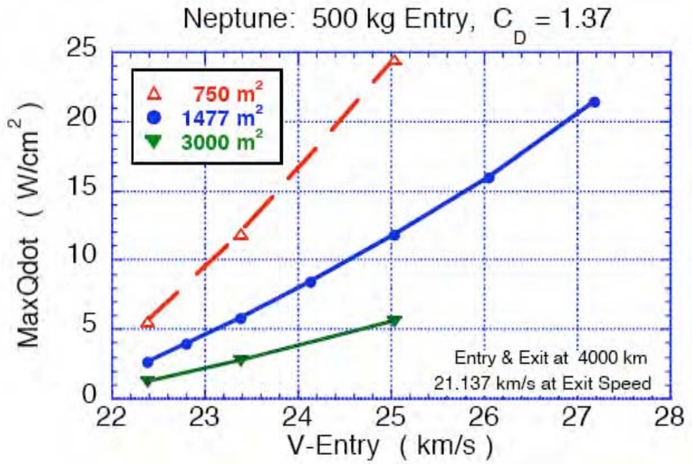
11) Is radiative heating a ballute killer? (Park, 1987)

Larger diameters increase shock standoff distance, and hence radiative heating.

Trajectory Analysis

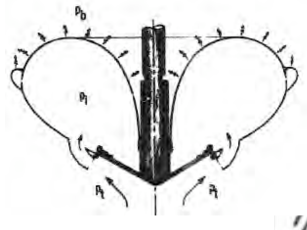
- Feasible corridors at Titan, Neptune, and Mars
  - Ballute release algorithms developed for Titan (2003-2004)
    - 3-sigma circularization DV = 285 m/s
    - Ballistic coefficient = 0.4 kg/m^2
  - Preliminary analysis at Neptune indicates feasibility (2004)
    - No uncertainties included
    - Trajectories targeted for exit without ballute release
    - Heat rate will be the limiting factor
    - Deceleration limited to 3.5 g's
  - Mars aerocapture possible with less than 3 g's (~2002)
    - Ballistic coefficient = 0.8 kg/m^2
    - Peak heat rate = 2 W/cm^2

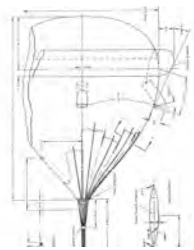


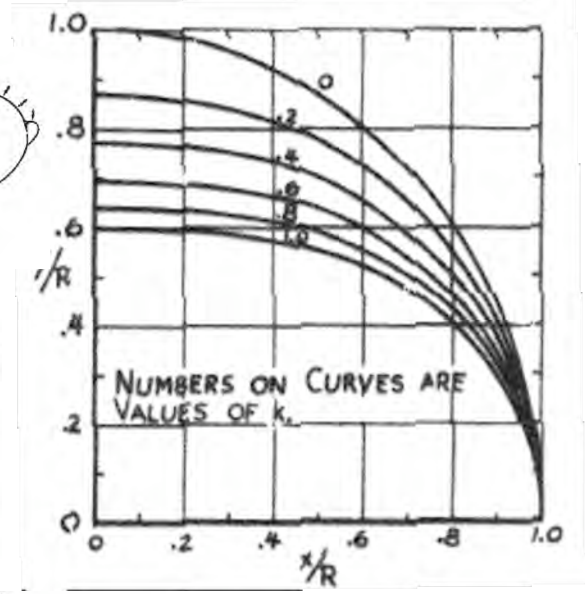


Structural Analysis – Shape Design

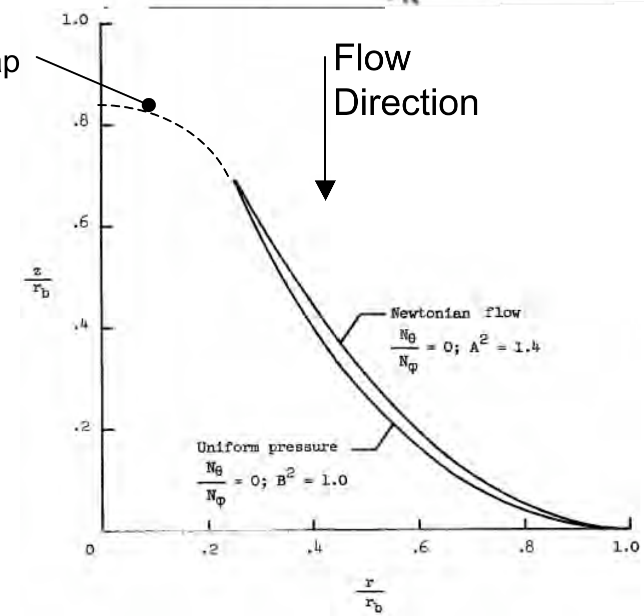
- Isotensoid design (1964)
  - Fabric with meridian tapes
  - Design considers internal and aerodynamic pressure
  - Determines number of meridian tapes and gore shapes





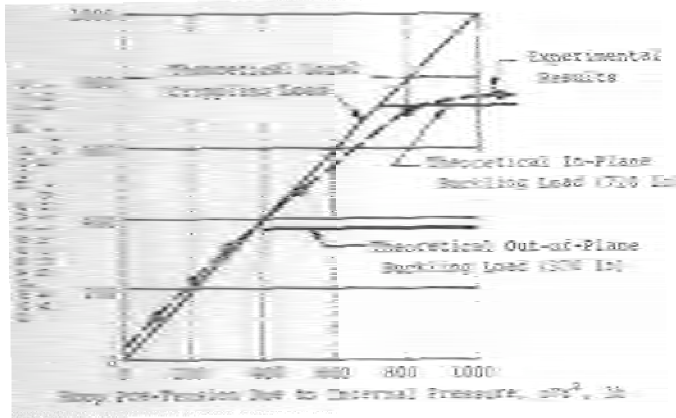


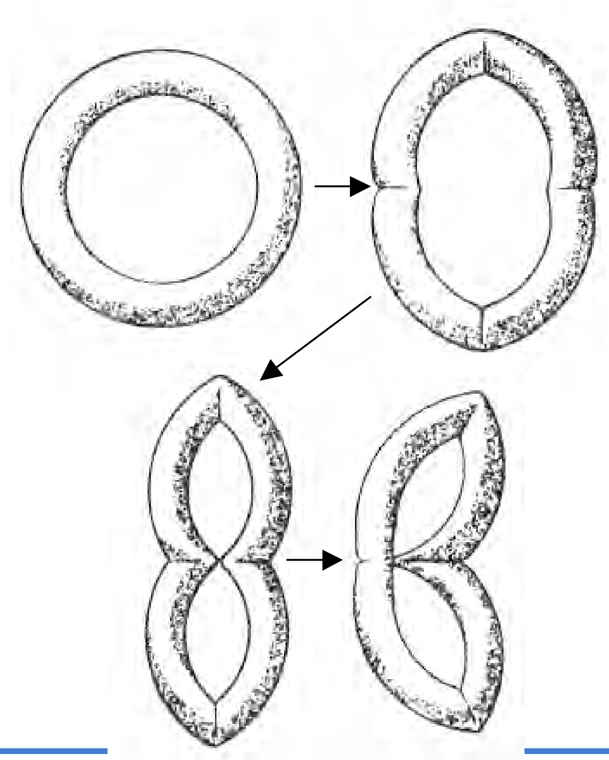
- Tension shells (1964)
  - Design for buckling is not efficient use of material
  - Limit compression to single member
  - Eliminates surface wrinkles
  - Lower mass than rigid aeroshells



Structural Analysis – Stability

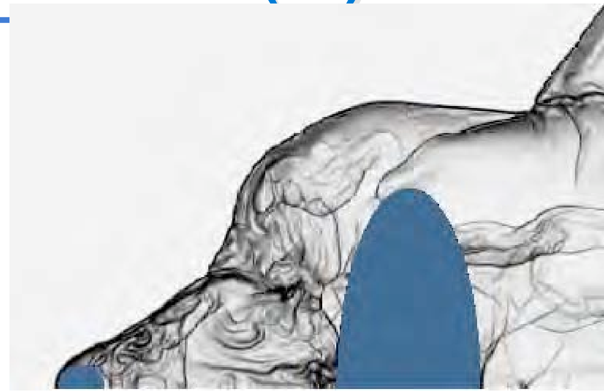
- Pressurized toroidal shell
  - Buckling equations developed in 1964 by Weeks
  - In-plane and out-of-plane modes identified
- Stability verified by test
  - Kyser verified the torus buckling equations for all modes in 1967
  - Good agreement with theory
  - Out-of-plane buckling does not cause loss of load carrying ability
  - Catastrophic failure when crippling load or in-plane buckling load reached

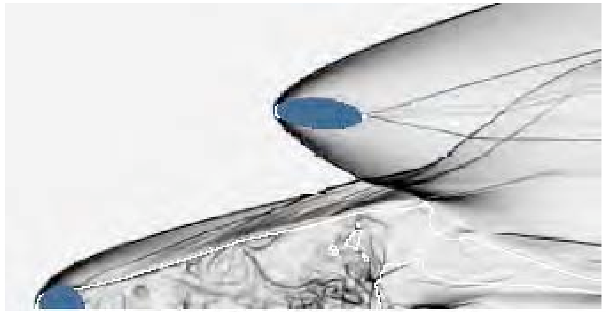


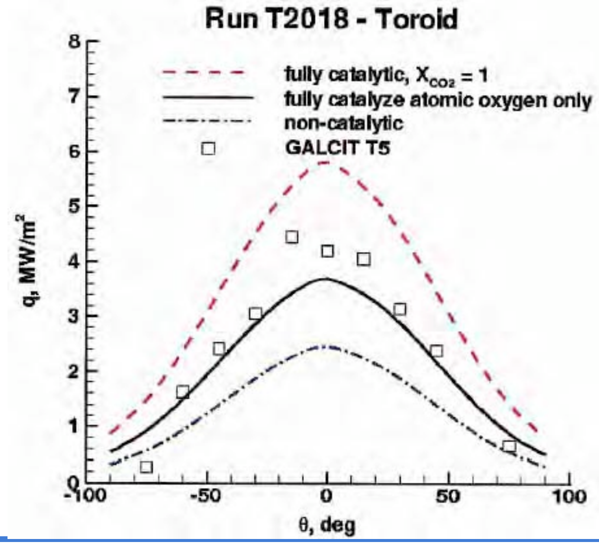


Hypersonic Aerothermodynamics (1)

- Shock tunnel tests (2001-2004)
  - Tests in GALCIT T5 shock tunnel and University of Queensland shock tube
  - Conditions were set to match flow enthalpy
  - Simply connected ballutes exhibited violently unsteady flow
  - Unsteady upstream flow was observed in the toroidal ballute
- Computational results (2002-2004)
  - Hornung simulated the flow using time-accurate, inviscid methods
    - Observed unsteady flow as seen in experiment
  - Gnoffo used the viscous solution in LAURA
    - discovered unsteadiness was dependent on Reynolds number
    - Matched heat rates from experiment well

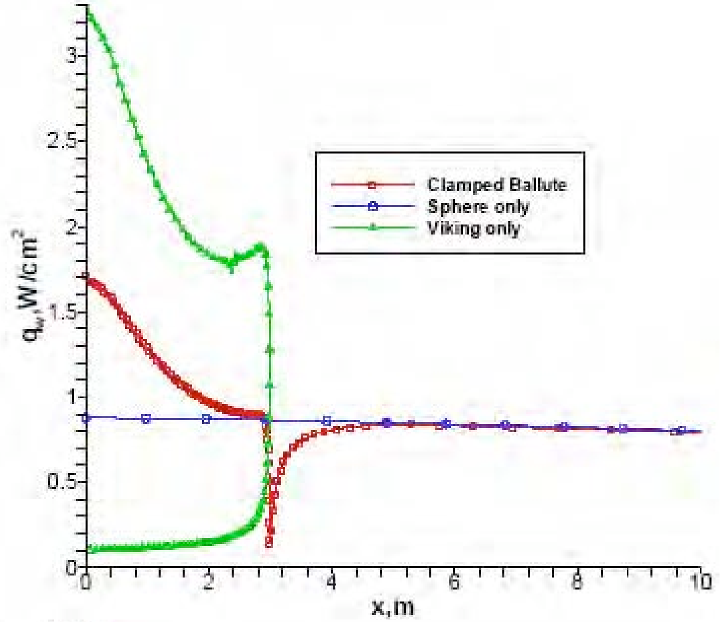


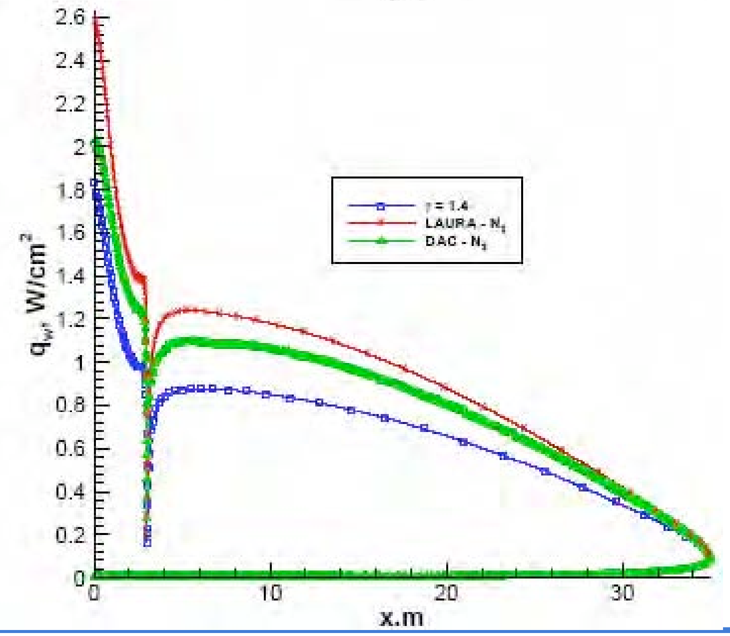




Computational Aerothermodynamics (2)

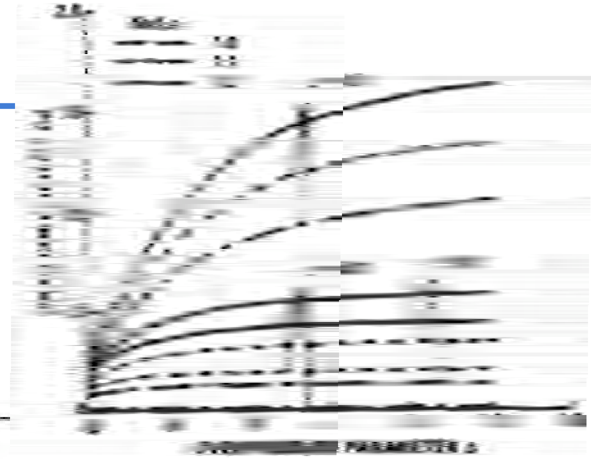
- Aerothermal configuration
  - Steady flow solutions found for toroids
  - Clamped ballute studies indicate lower heating on spacecraft and stability
- Rarefied effects (2004)
  - DAC used to model clamped ballute in transitional regime
  - Results compared to various chemistry models in LAURA
  - Continuum results bound the DSMC solutions (Kn ~= 0.05)

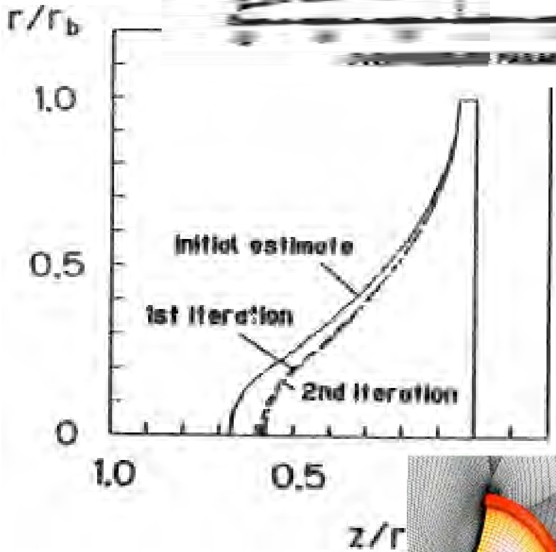


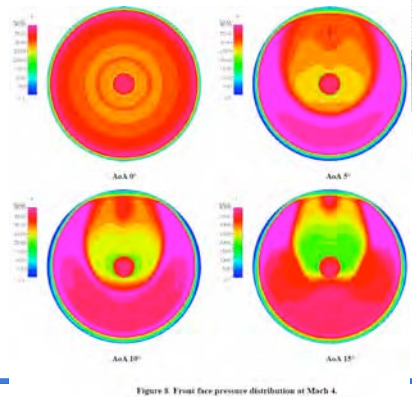


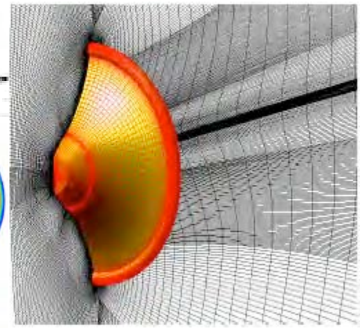
Coupled Analysis

- 2-D ballute in Newtonian flow
  - Demonstrated decreased stability due to deformation of inflatable
  - Ratio of internal pressure to elasticity must be of order 1 or greater to use variation in internal pressure to control drag
  - Park, 1986
- CFD coupling for tension shells
  - CFD pressure distribution significantly different than Newtonian
  - CFD solutions favored shorter vehicles than Newtonian pressure distribution
  - Abe, 1988
- CFD – CSD coupling
  - MONSTR code for supersonic analysis
  - Vertigo,AMA and CFDRC working on coupling in hypersonic continuum and rarefied regimes



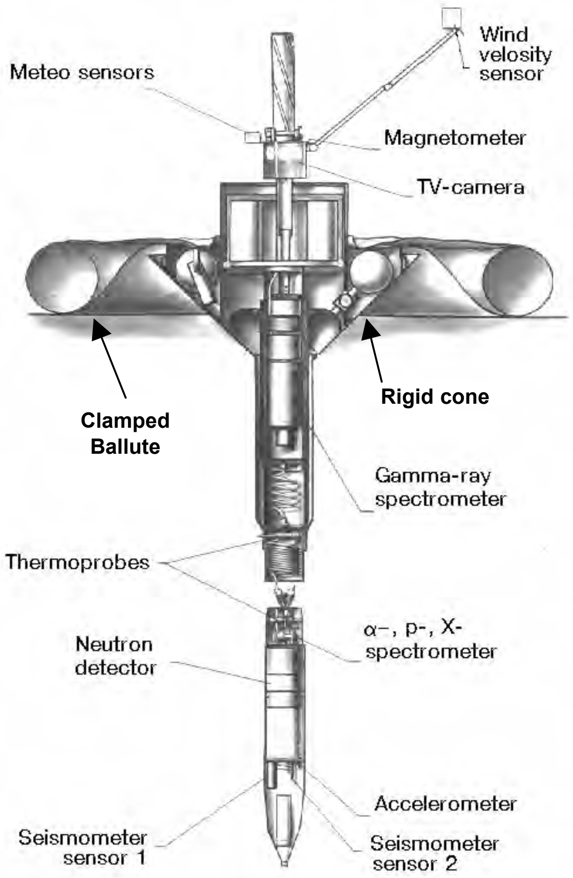




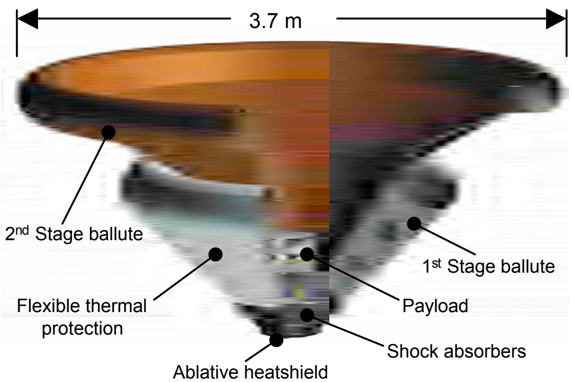


Flight Test

- MARS 96 penetrators
  - Clamped ballute
  - Controlled impact speed
  - Mission failed at launch

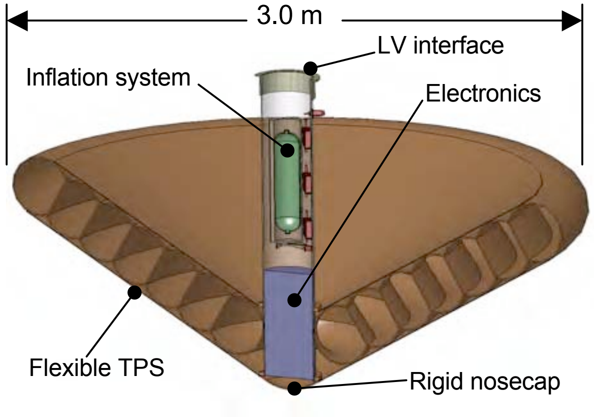


- IRDT project
  - 2-stage clamped fabric ballute
  - Flight test on Soyuz-Fregat test
    - flight resulted in destruction of inflatable
    - Suspected re-contact with upper stage after separation
  - Flight test on submarine launched missile failed to separate
  - Reflight scheduled for July 2005

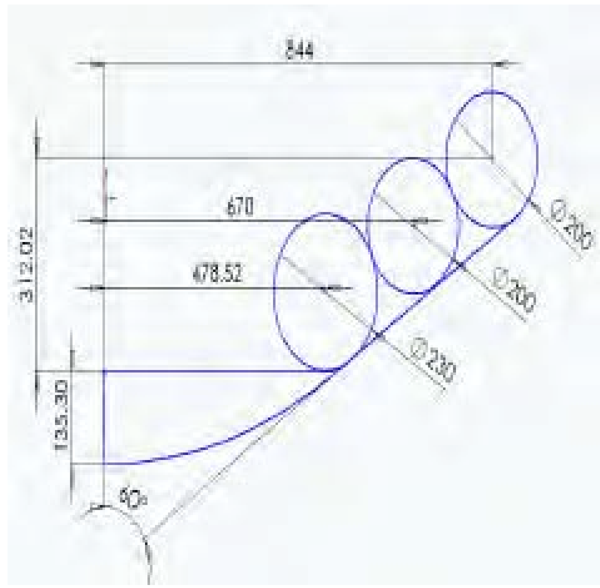


Current Studies – Flight Test

- Inflatable Reentry Vehicle Experiment (IRVE)
  - NASA Langley project to flight test clamped ballute
  - Sounding rocket used to simulate Earth entry
  - Launch scheduled for Dec. 2005



- 2nd Young Engineers' Satellite (YES2)
  - Clamped fabric ballute for to return small payload from orbit
  - Designed for 7 m/s impact speed
  - Launch scheduled for 2007



Current Studies – Systems Studies

- NASA In-Space Propulsion funding
  - Focus on Titan and Neptune aerocapture
  - System level design studies with focus on materials and coupled analysis
  - Includes wind tunnel testing to validate computational models
- NASA ESR&T funding
  - Focus on Lunar return with aerocapture to ISS orbit or direct entry
  - Additional applications in escape systems and Mars entry
  - Testing is scheduled in support of aeroelastic model validation
- Small Business funding
  - CFDRC: coupled hypersonic continuum and rarefied aeroelasticity
  - AMA: coupled analysis including dynamics
  - Vertigo: coupled supersonic analysis including dynamics

Summary

- Ballutes first theorized in the early 1960's as a "better supersonic parachute"
- Resurgence in ballute interest with the thin-film ballute concept by McRonald in 1999
  - Showed significant mass benefits over rigid aerocapture and propulsive orbit insertion
  - Improved materials made this possible
- Geometries that eliminate the flow stability problem have been found
- Aerothermal modeling predicts flow and convective heating well, but work is needed to determine radiative heating
- Trajectory work has shown feasibility at Titan and good corridors at Neptune and Mars
- Coupled modeling tools are under development and should be validated and ready for use within 2 years
- Current progress will lead to a successful flight test within 5 years

Questions?

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