Summary of Ultralightweight Ballute Technology Advances

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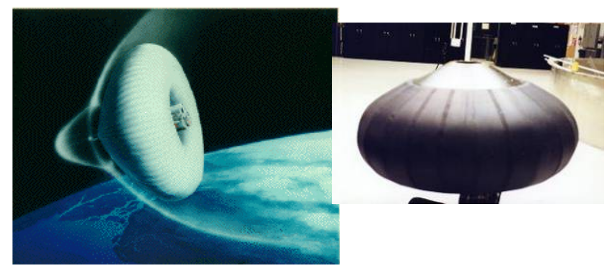
Ballute Development History & Applications

- Balloon + Parachute = Ballute
  - Deployable, inflatable drag device
  - Can provide aerodynamic deceleration for aerocapture or EDL
- Development in early 1960's under JPL contract to Goodyear to develop "Expandable Terminal Decelerators for Mars Atmosphere Entry"
  - Ballute flown on Gemini for high altitude crew escape (see following slide)
- Ballutes have been and are still used extensively as decelerators for military applications
- Low-level development activity for space applications into early 1980's
  - AOTV studies included ballutes for aerocapture & entry
  - Hampered by analytical and manufacturing limitations, but potential performance benefit maintained luster
- Inflatable entry system developed, flight qualified, and launched on Russian Mars 96 Mission
  - System would have been used for Mars landing, but mission was lost due to launch vehicle failure
  - Follow-on German/Russian development - Earth return from orbit (IRDT, 2000-2002) Illustrates key features of technology, including some of the performance benefit (both flights failed due to problems unrelated to the inflatable)

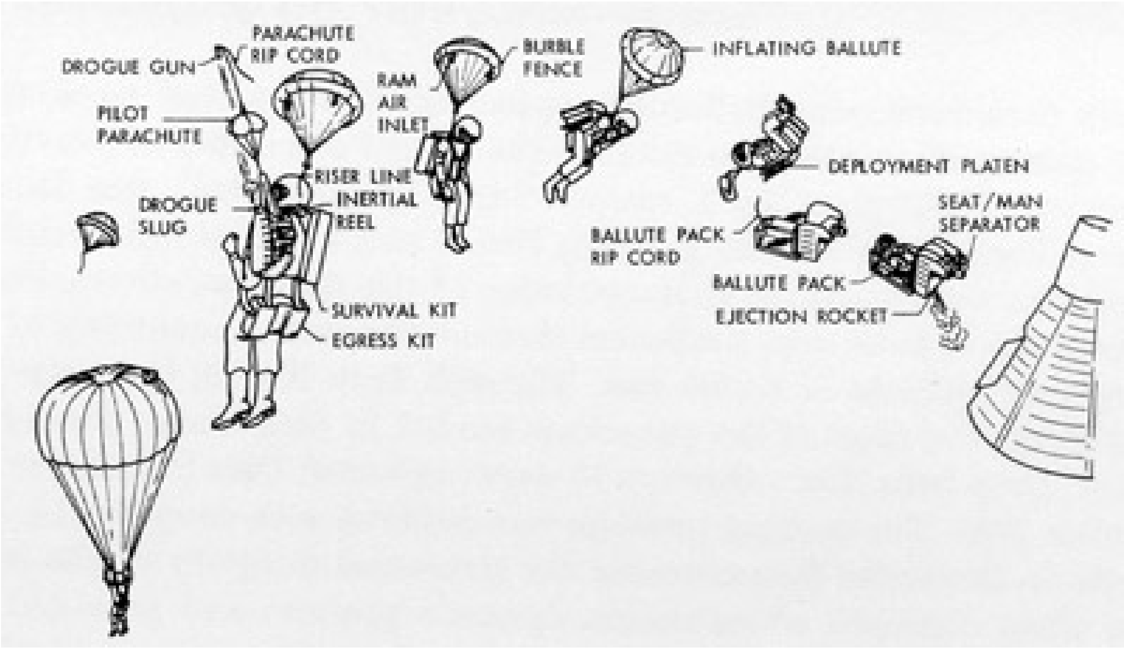
Ballutes for munitions deceleration



OTV with Ballute Aerocapture into LEO

IRDT-1, IRDT-2 Flight Systems

Gemini Crew Escape System

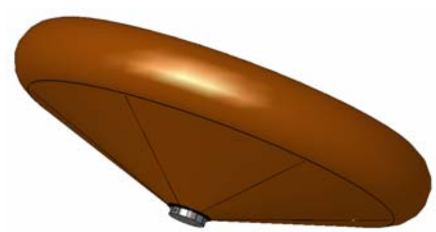


The ballute was certified for operation at Mach 4 and altitude of 80,000 ft.

Ultra Lightweight Ballutes (ULWB)

- "Fly Higher, Fly Lighter, Fly Cooler" Concept
  - Large drag area allows the spacecraft to decelerate at very low densities high in the atmosphere with relatively benign heating rates (comparable to that for aerobraking missions)
  - Lower heating rate experienced during atmospheric entry allows the use of light-weight construction techniques for the ballute, resulting in significant mass performance
- Packaging benefit enables aeroassist to be used where constraints imposed by structurally fixed aeroshells are prohibitive
  - Spacecraft component packaging not constrained by aeroshell structural envelope
  - CG does not have to be strictly controlled to maintain aerodynamic stability (large CG envelope)
  - Decelerator does not interfere with communications, instrument pointing, and spacecraft thermal control during interplanetary cruise because it is only deployed during entry

Trailing Ballute



Aft Attached, aka "Clamped" Ballute

Ball Development Efforts and Partners

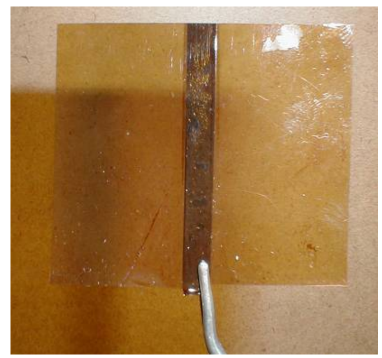
- Ballute Development Efforts
  - Mars Micromission (JPL) – Mars missions
  - Gossamer (JPL) – Mars missions
  - NASA In-Space Propulsion (ISP) Cycle 1 and Cycle 2 (MSFC) – Titan and Neptune missions
  - NASA ESR&T (Langley) – Return to Earth from the Moon
  - NASA NRA (Langley) – High mass Mars entry systems

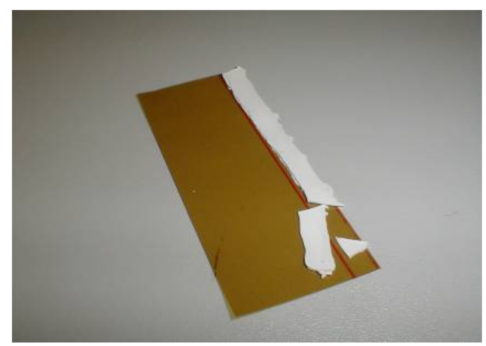
- Team Draws Expertise from Several Organizations with Applicable Experience
  - Ball Aerospace - Systems Engineering and Analyses
  - Vertigo – Materials, inflatable design, and fabrication
  - ILC Dover - Materials testing, inflatable design, and fabrication processes
  - Georgia Tech. - Aeroelastic modeling, integrated systems analysis tools
  - NASA Langley - Aerothermal analysis and test, aeroelastic analysis
  - NASA JSC - Guidance algorithm development
  - JPL - Mission and systems design, materials testing

- Technology Focus Areas:
  - Materials, Seaming, Construction
  - Flow Stability
  - Aeroelastic Modeling
  - Trajectory Control
  - Integrated Systems Analysis and Design

Materials Technology and Manufacturing

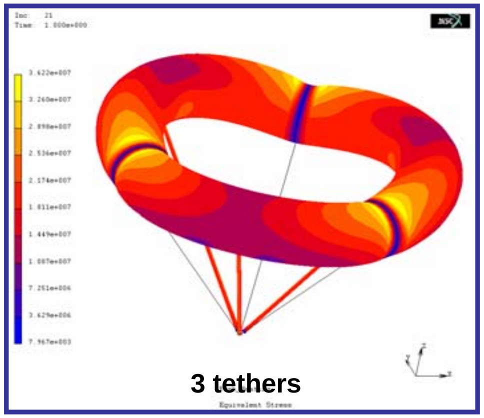
- Broad variety of lightweight films have been tested to develop properties at relevant temperatures
  - Testing of pristine & creased material samples at room and elevated temperatures
  - Key parameters include strength, flexibility, manufacturability, and mass
- An array of seaming adhesives and materials combinations have been evaluated
  - Testing of pristine & creased seamed samples at room and elevated temperatures
  - Flexibility, manufacturability, tear strength and tensile strength
  - Identified two combinations that meet goals
- Results
  - High strength solutions have been identified using Upilex and PBO films
  - Test results factored into nonlinear FEM and ballute structural design / sizing, as well as thermal analysis models

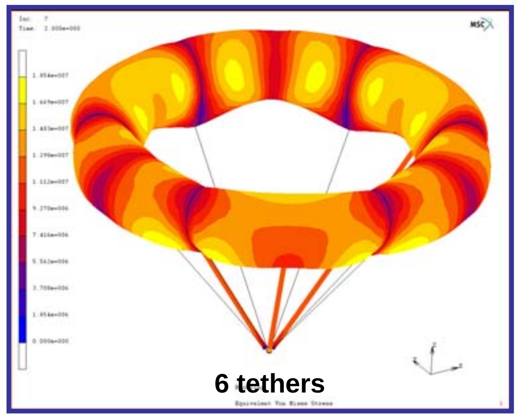


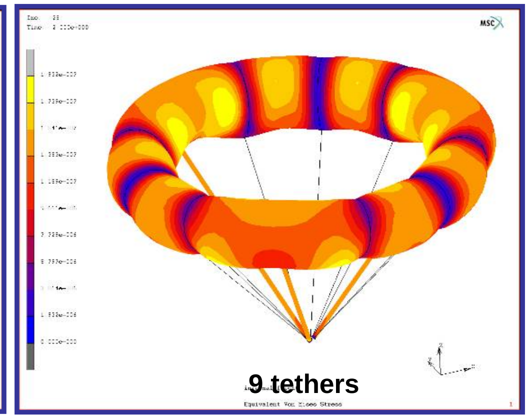


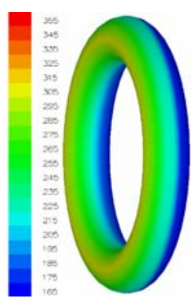
Ballute Structural and Thermal Design and Analysis Makes Use of Material Test Results

- Nonlinear structural analysis used to determine mode shapes, size ballute components, and perform structural configuration trades such as best number of tension tethers for trailing ballute.
- Structural analysis results (stress and deflections) were used to ensure ballute design has positive strength margins and can handle expected deflections.
- Thermal analysis was completed using 3-D models ensure positive margins vs. allowable peak temperature

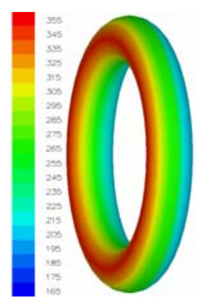




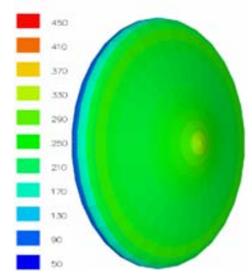




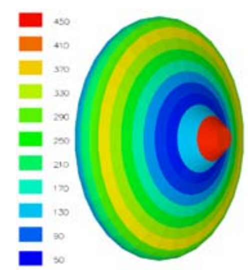
Peak Dynamic Pressure
Maximum Temperature 307°C



Peak Heating
Maximum Temperature 353°C



Peak Heating - Undeflected
Max Temperature = 308°C



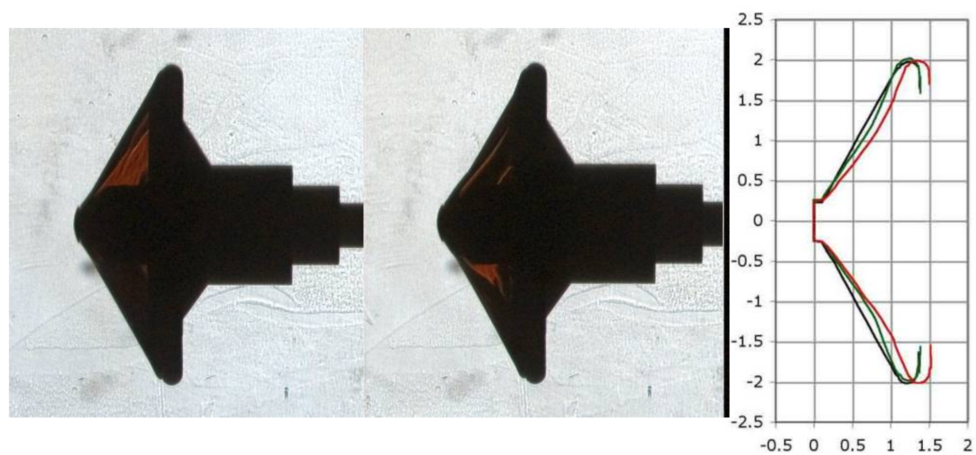
Peak Heating - Deflected
Max Temperature = 435°C

Flow Stability Validation in the Continuum Regime

- Wind tunnel models developed to capture response to hypersonic flow and heating
  - “Flight-like” film materials
  - Rotational and translational degrees of freedom
- Critical geometry evaluated parametrically to establish design limits
  - Varying trailing distance for trailing ballute
  - Different cone angles for clamped ballute
- Flow/ballute interaction captured for model validation

Flexible clamped ballute wind tunnel model

Several ballute wind tunnel models of various configurations were constructed and tested at NASA Langley.



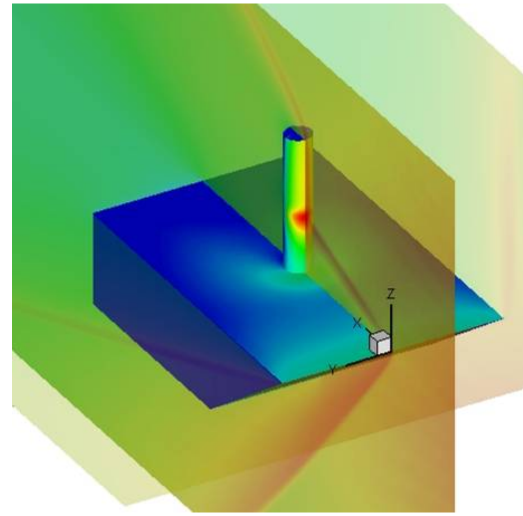
Aeroelastic deformation measured in hypersonic wind tunnel test

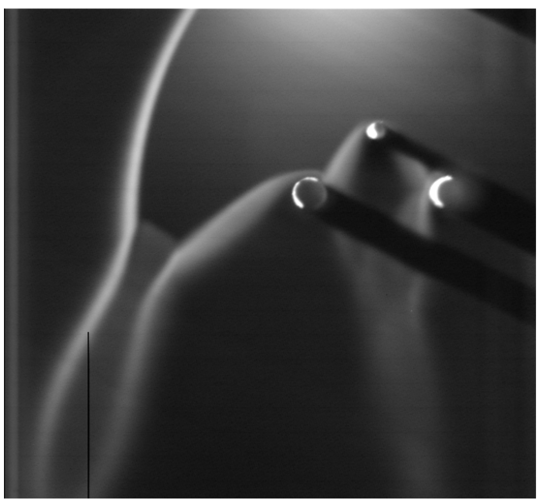
Hypersonic Test of Free Flying Clamped Ballute

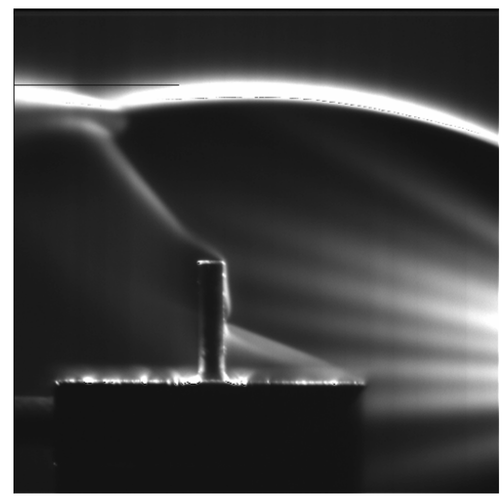
free_fly_run.avi

Flow Stability Validation in the Rarefied Regime

- Tests conducted at low density facility at University of Virginia provide good match for design Knudsen and Mach numbers
- Tests provide model validation on key facets of ballute design, including:
  - Validation cases with cylinder in cross flow,
  - Tether attachment point cases
  - Two body interaction cases

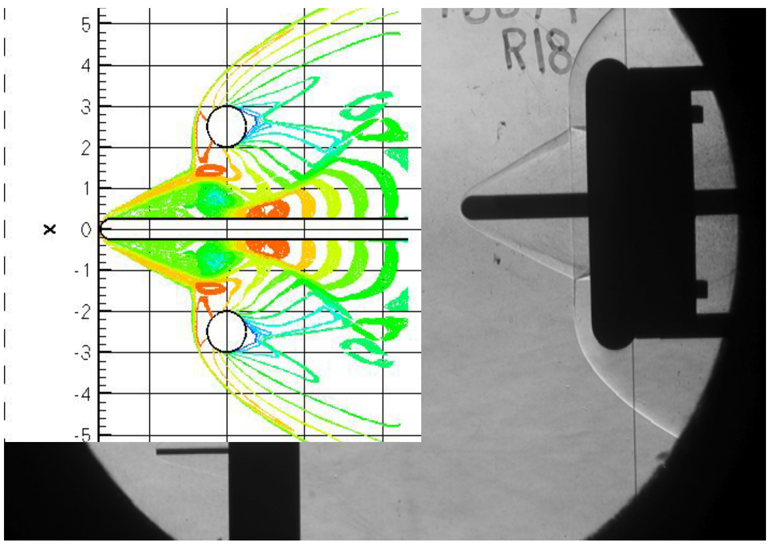




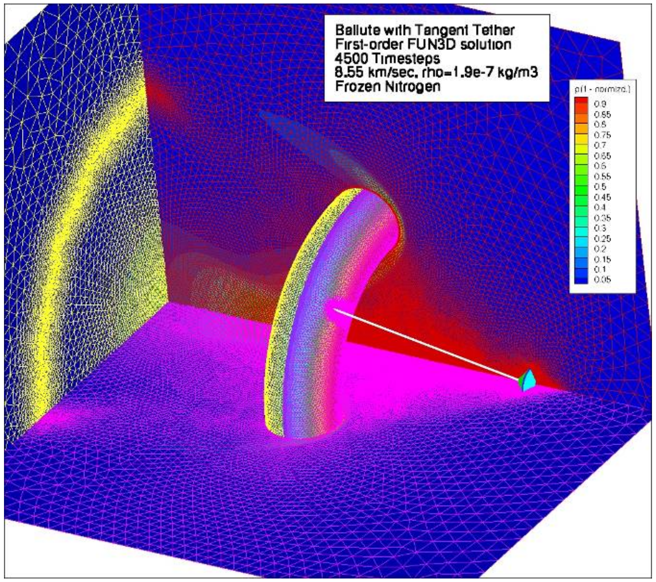


Hypersonic Analysis of Ballute Aerocapture

- CFD (LAURA and FUN3D) are used to compute drag efficiency, aerodynamic loads, aeroheating, and flow stability for candidate ballute configurations.
- Progress includes:
  - Simulations using CFD tools matches experiments performed in hypersonic wind tunnel
  - Confirmation that CFD tools can be used to predict steady or unsteady flow for the trailing ballute configuration through comparison with hypersonic test results
  - Unstructured grid used to accurately model widely variant feature sizes associated with ballute systems

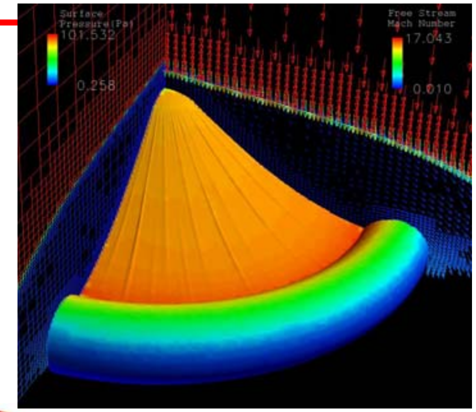


Experimental and computational images of trailing ballute. The computational results closely match experimental results, providing the first confirmation that CFD tools can be used to predict steady or unsteady flow for the trailing ballute configuration.

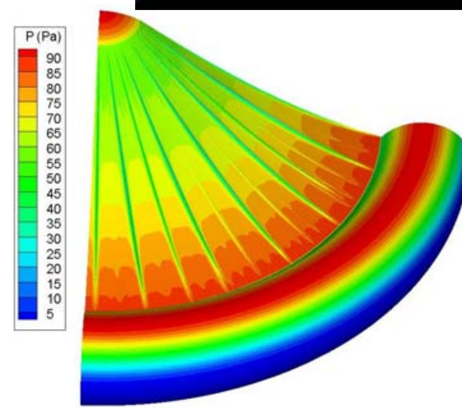


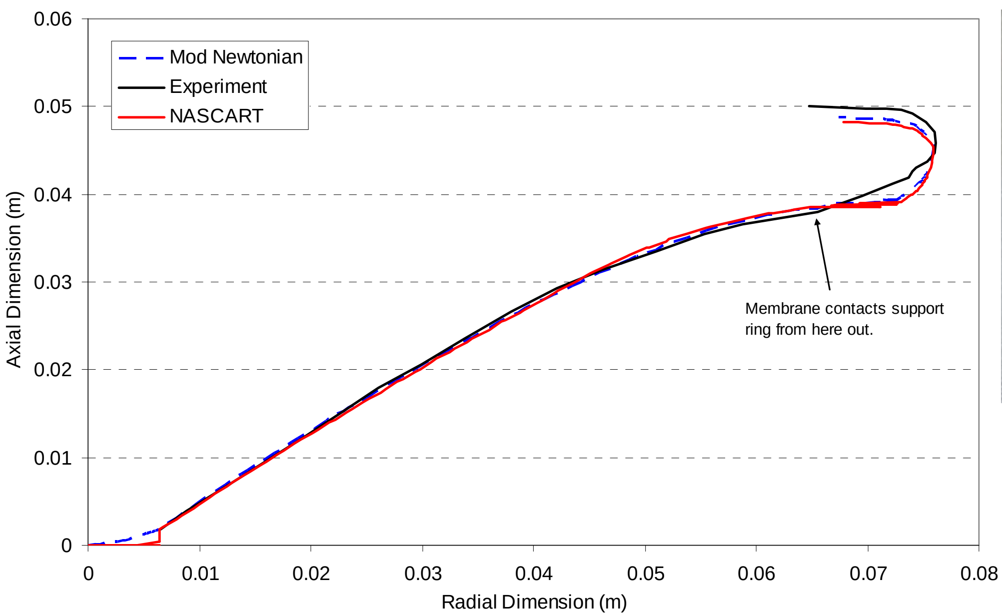
Simulation of spacecraft-tether-ballute interaction using unstructured flow solver FUN3D with hypersonic option

Aeroelastic Modeling and Analysis

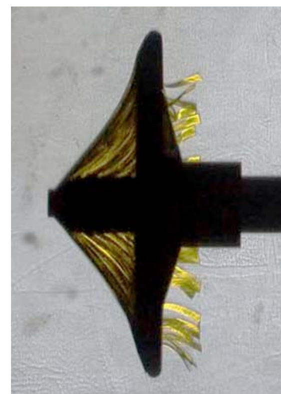


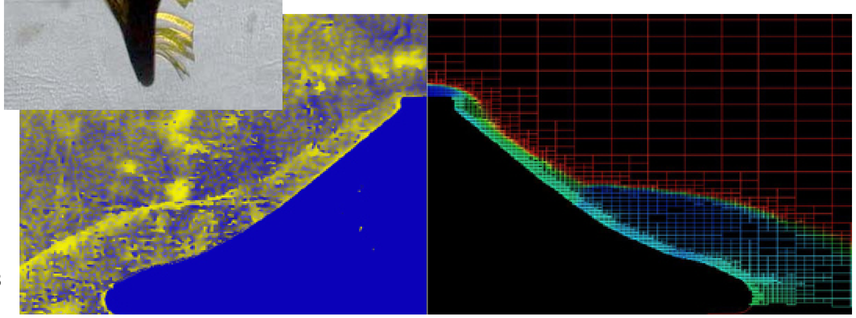
- Developed tool set for coupled aeroelastic response with non-linear structures in rarefied hypersonic flow
- Approach: Couple together validated tools for individual disciplines
  - Aero: NASA DSMC analysis code and NASCART-GT
  - Structural: (LS-DYNA)
- Results:
  - Coupled analysis tools able to obtain solutions.
  - Comparison with test data shows good agreement





Good agreeement is obtained between experiment and computation.

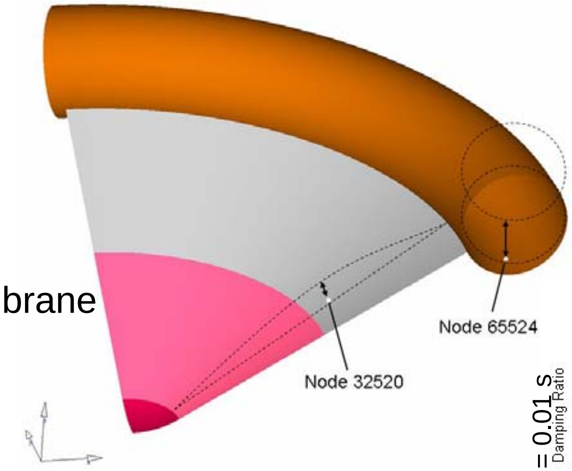


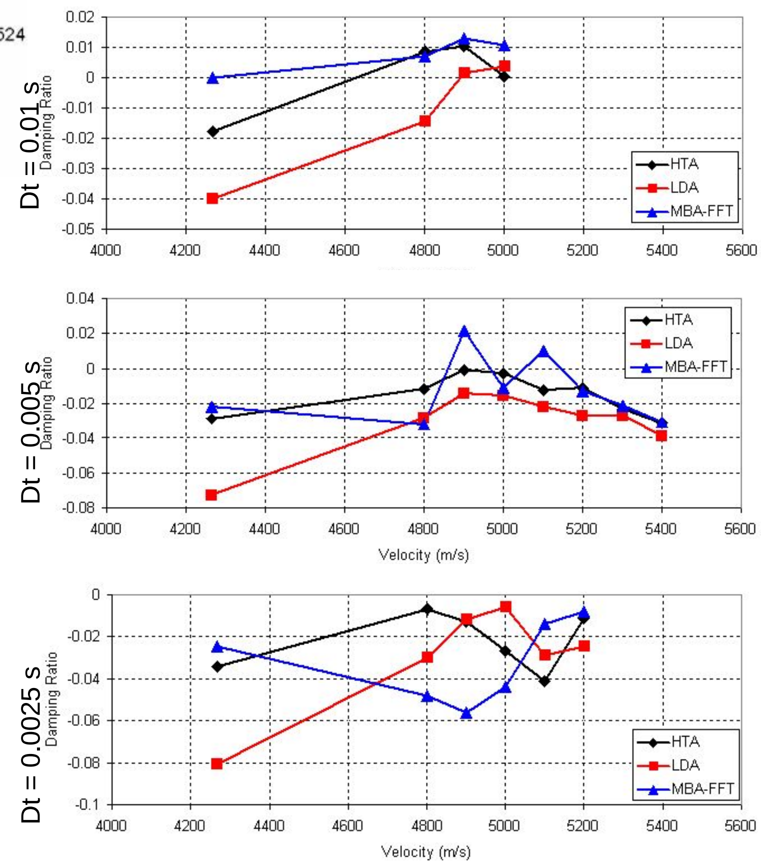


Shock structure is predicted accurately.

Dynamic Simulations

- 1^{st} mode
  - Axial motion of torus
  - ~1.75 Hz
  - Node 65524
- 2^{nd} mode
  - Flapping of conic membrane
  - ~6.5 Hz
  - Node 32520



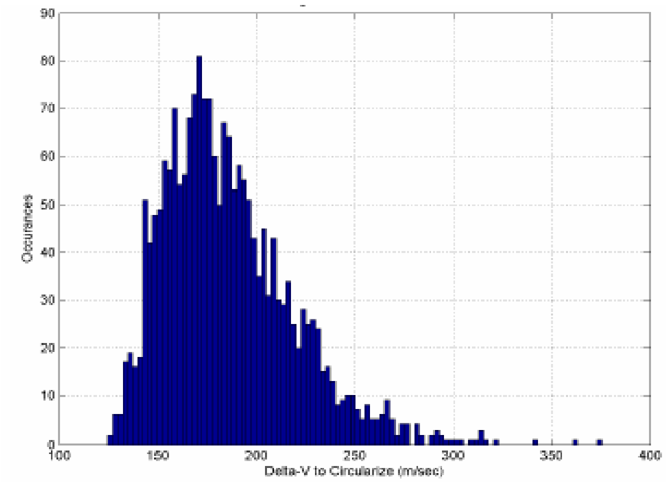


- Results are not converged WRT time step size
  - LS-DYNA limits the simulation time
- The MBA method found negative damping at V=4,900 and 5,100 m/s
- Decreasing time step size increases damping
- All modes explored were damped for 1^{st} and 2^{nd} modes

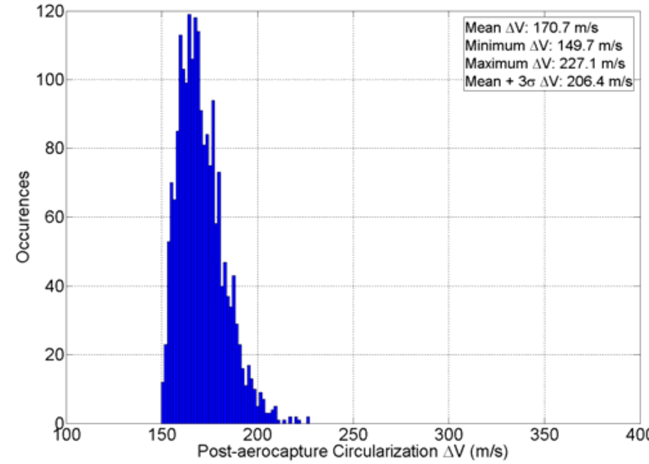
NASA Ball ILC DOVER JPL VERTIGO INC. Georgia Institute of Technology UNIVERSITY of VIRGINIA

Ballute Separation Algorithm for Aerocapture

Ball Monte Carlo Results



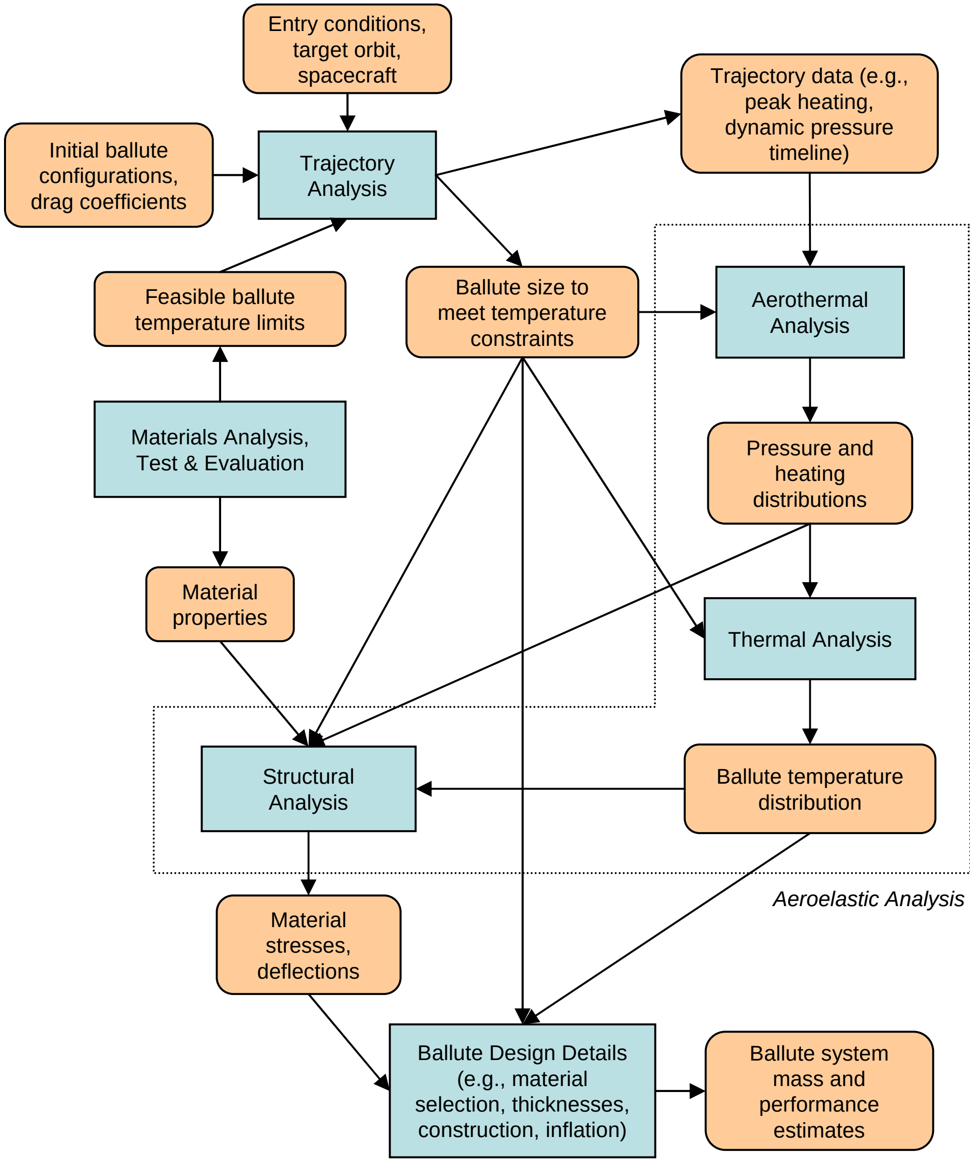
JSC Monte Carlo Results



- Objective: Evaluate effectiveness of aerocapture with drag-only trajectory modulation, which relies on critical timing of the ballute separation to accommodate navigation, atmospheric and design uncertainties.
- Ball-developed predictor-corrector algorithm provides excellent performance, with 100% successful capture in Monte Carlo simulations
- NASA JSC independently coded and tested the ballute separation algorithm based on the technical description of the algorithm provided by Ball
- JSC verified the Monte Carlo trajectory simulation results previously obtained by Ball
- After further tuning, JSC was able to improve upon the original Ball results, showing post-aerocapture delta-V requirements that are equal to that required for aerocapture with a rigid aeroshell and lift modulation

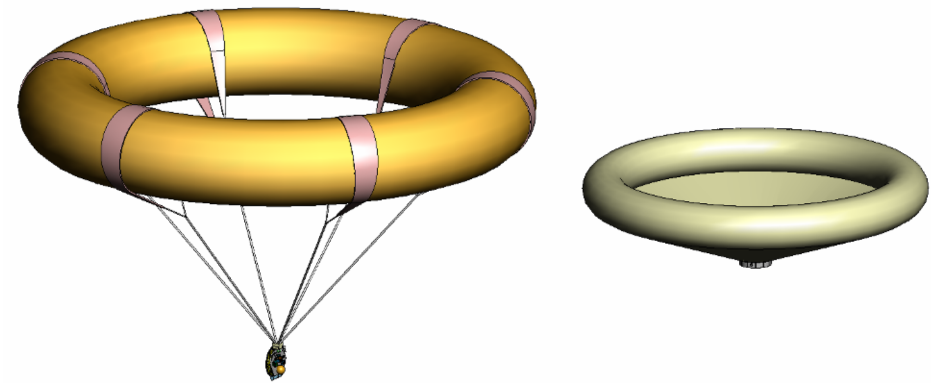
Ballute System Design Relies on Several Disciplines

- Highly coupled design/analysis problem with:
  - Nonlinear temperature dependent material properties
  - Nonlinear structures
  - Hypersonic aerodynamics in continuum, transitional, free molecular flow
  - Wide range of geometric scale for design details
- Requires development and validation of new analysis models, methods, and tools

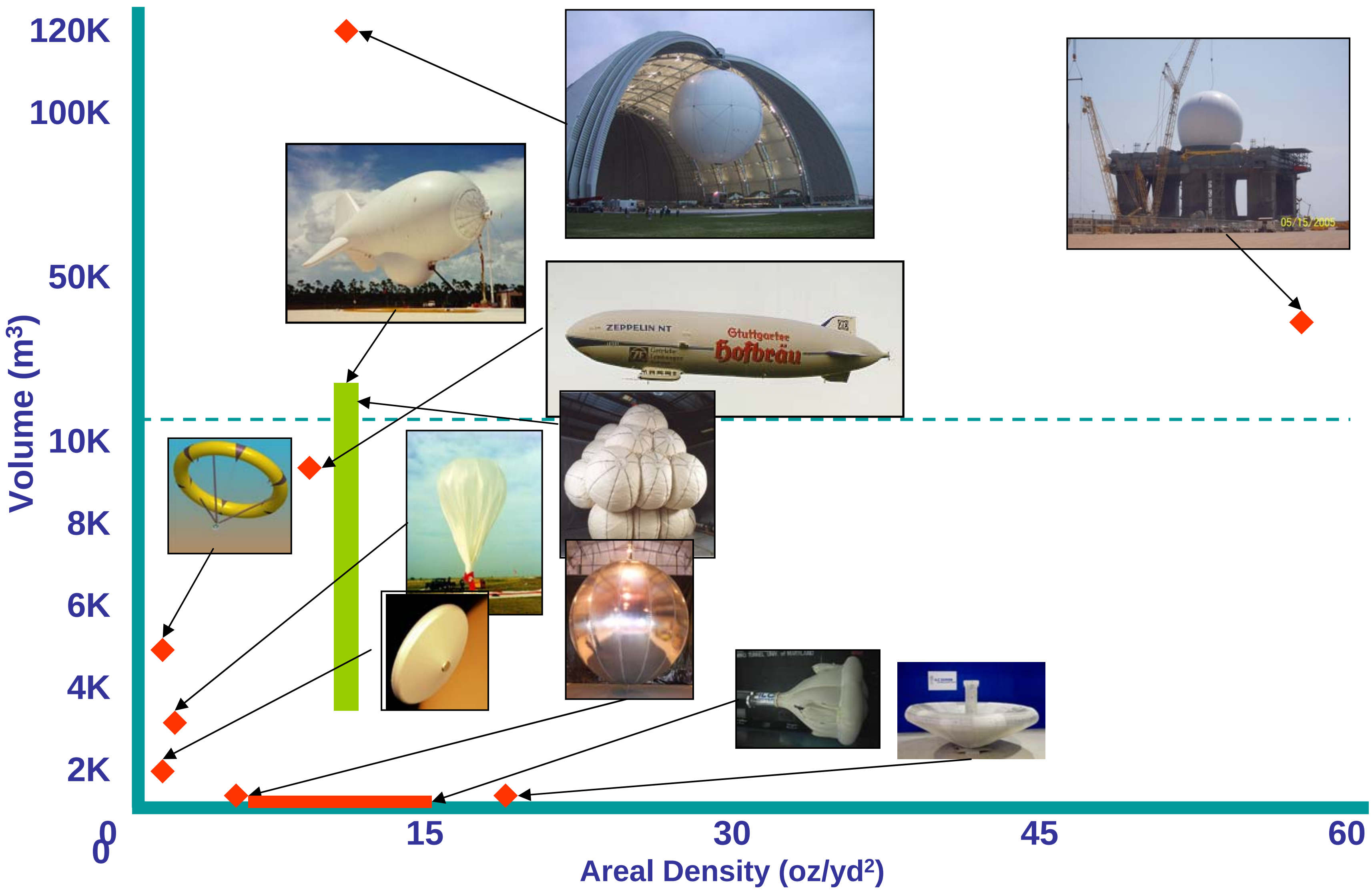


Ultralightweight Ballute Concepts

- Trajectory, aerothermal, structural, thermal analyses used to develop ballute system concepts for robotic and human missions
- Analysis tools and models incorporate results from test data as available to increase fidelity of analyses and design concepts
- Concepts developed through integrated systems analysis verifies excellent ULWB performance
  - Aerocapture of 1000 kg at Titan
  - Thin-film construction, local fabric reinforcement, major diameter 27 m (clamped ballute) to 41 m (trailing ballute)
  - Ballute system mass fraction of 10%



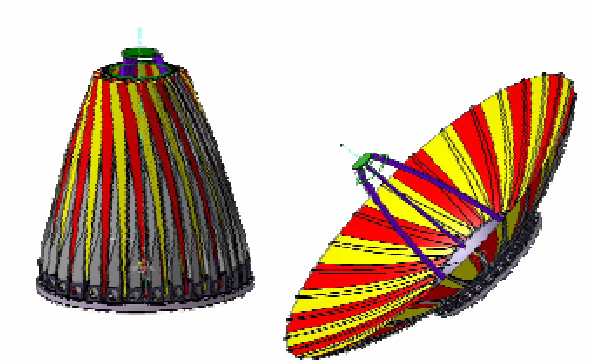
Ultralightweight Ballutes are Within Inflatable Manufacturing Experience Base

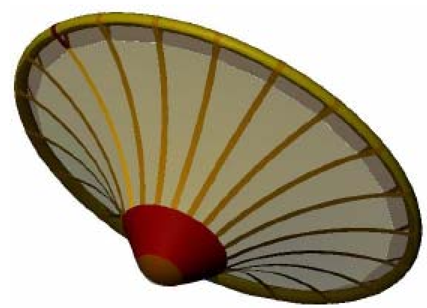


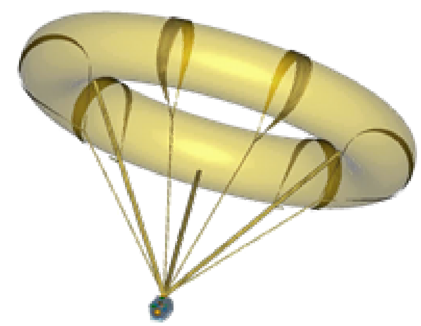
Continuation of Ballute Studies

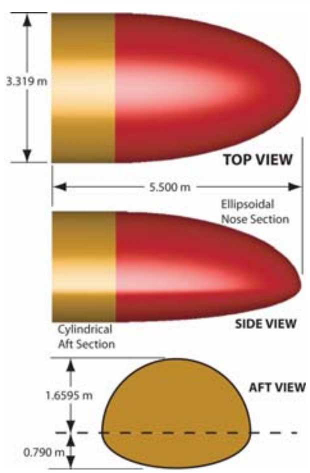
- Current work funded through NASA ARMD NRA from LaRC
  - High mass Mars entry system study

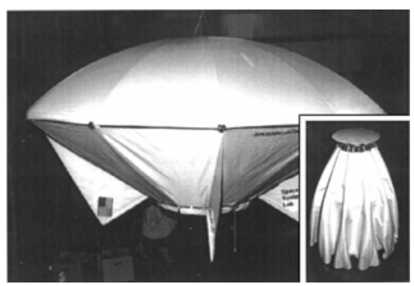
- Explore deployable options for landing large masses (2-100 MT) on Mars

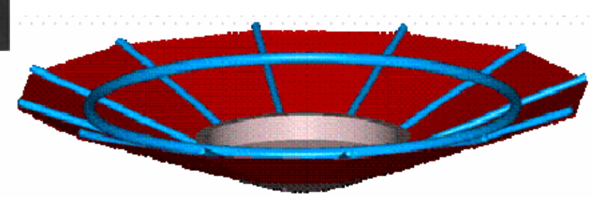












Summary

- Ultralightweight ballutes offer revolutionary performance benefit compared to other entry or orbit insertion technologies
  - Ballute mass fraction 8 - 10% vs. traditional aeroshell of 20% - 40%
  - General purpose, lightweight decelerator applicable to human and robotic missions at many destinations
  - Packaging benefit enables aeroassist to be used where constraints imposed by structural aeroshells are prohibitive
- Future work planned to refine and validate aero/aeroelastic tools, and to further develop materials and manufacturing processes
- System design fidelity will continue to increase as results from higher fidelity analyses and test are incorporated
- Flight validation testing is the most critical step to applying this technology

For Further Information

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