**ULTRALIGHTWEIGHT BALLUTES TECHNOLOGY ADVANCES.** J. P. Masciarelli[1] and K. L. Miller[1], [1]Ball Aerospace & Technologies Corp., 1600 Commerce St, Boulder, CO 80301.

**Introduction:** Ultralightweight ballutes offer the potential to provide the deceleration for entry and aerocapture missions at a fraction of the mass of traditional methods. A team consisting of Ball Aerospace, ILC Dover, NASA Langley, NASA JSC, and the Jet Propulsion Laboratory made significant technology advances under funding provided by NASA. The results show that ultralightweight ballutes provide excellent performance and packaging benefits not only for aerocapture, but also for de-orbit, entry, descent, and landing missions to planetary bodies with a sensible atmosphere.

A ballute (a compound word combining balloon and parachute) is a deployable, inflatable drag device designed to provide deceleration at high altitudes and high velocities. Ballutes have been used in several terrestrial applications, and can also provide aerodynamic deceleration for aerocapture, entry, descent, and landing missions in space.

Traditional aerocapture technology relies on an aeroshell or heat shield to provide aerodynamic deceleration and protect the spacecraft from high entry-heating rates. The innovative concept behind using ballutes for aerocapture centers on deployment of a lightweight ballute with sufficient drag area to decelerate the spacecraft at very low densities high in the atmosphere. By flying higher in the atmosphere, deceleration required for aerocapture is achieved with relatively benign heating rates. The low heating rates experienced during atmospheric entry and deceleration enable the use of ultralightweight construction techniques for the ballute. This 'fly higher, fly lighter, fly cooler' approach to aerocapture results in revolutionary mass performance compared to traditional technologies.

Two different configurations with the ballute trailing the spacecraft were investigated: a tethered trailing ballute, and an aft attached, or clamped ballute. Both are illustrated in Fig. 1. Over the course of the technology development effort, advantages and disadvantages have been identified with each configuration, but both configurations offer the benefits ascribed to the 'fly higher, fly lighter, fly cooler' methodology for aerocapture.

The ballute technology development effort focused on and made significant progress in the following areas:

- Ballute materials and construction techniques
- Aerothermal analysis and hypersonic testing
- Aeroelastic modeling
- Trajectory control

This presentation provides a brief summary of the work accomplished. The details of the technology development effort have been published in a series of papers and conference presentations as well as a NASA Contractor Final Report.

**Ballute Materials and Construction:** A broad variety of lightweight films were tested to determine and evaluate properties at relevant temperatures. Testing of pristine and creased material samples at room and elevated temperatures (up to 600 C) was completed. Key parameters evaluated include material strength, flexibility, manufacturability, and mass. The results are available for use in aeroelastic and finite element modeling for full scale design.

**Hypersonic Aerothermal Analysis:** Computational Fluid Dynamics (CFD) models were used to compute drag efficiency, aerodynamic loads, aeroheating, and investigate flow stability for candidate ballute

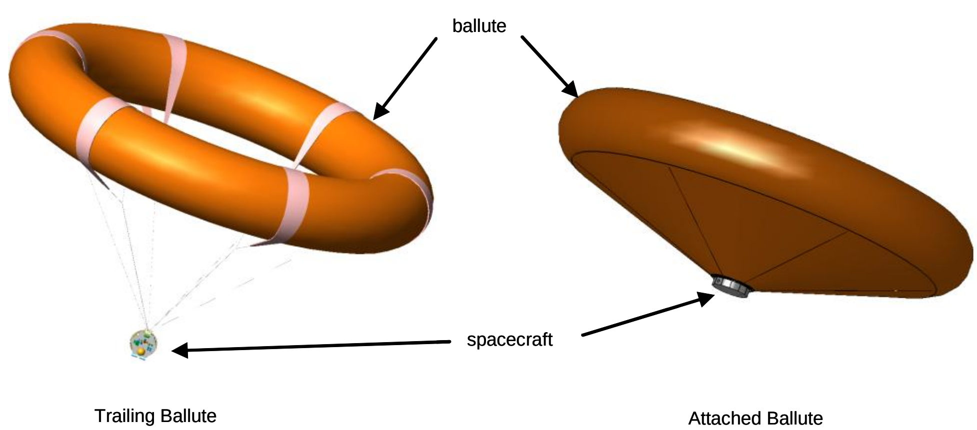


Fig. 1. 'Fly higher, fly lighter, fly cooler' approach to aerocapture can be accomplished with trailing and clamped ballute configurations.

configurations. Aerothermal CFD models were validated with hypersonic testing of scale models in ground facilities. Significant progress in the aerothermal analysis area includes confirmation that CFD tools can be used to predict steady or unsteady flow for the trailing ballute configuration. Another significant first is the use of unstructured grid methods to accurately model widely variant feature sizes associated with ballute systems.

**Hypersonic Testing:** Experiments were conducted in continuum and rarefied hypersonic flows to evaluate critical ballute geometry parameters and capture flow/ballute interactions for aerothermal analysis model validation. Continuum flow testing occurred in NASA Langley's air and CF4 wind tunnels up to Mach 10. Models tested included those made from flexible thin film materials, with rotational and translational degrees of freedom to simulate flight like conditions (see Fig. 2 and 3). Tests were also conducted in a hypersonic, low density facility at the University of Virginia to provide a good match for design Knudsen numbers. Test cases in the low density facility provided data for two body interactions, and for tether/ballute interfaces.

**Aeroelastic Modeling:** Significant progress was made in aeroelastic modeling and analysis of ultra-lightweight ballutes. The aeroelastic problem involves non-linear structures and hypersonic flow through continuum to rarefied flow conditions, which required development of a new analysis capability. The approach taken was to couple together existing validated tools for the individual disciplines. LS-DYNA was used for the structural analysis, and aerothermal codes included DAC and NASCART-GT. The coupled tool set was used to obtain solutions for the ballute problem, and comparison of the solutions with wind tunnel test data of flexible ballute models shows good agreement.

**Trajectory Control:** Successful ballute aerocapture relies on critical timing of the ballute separation under dispersions in navigation, atmospheric density, aerodynamics, and other ballute design parameters. A predictor-corrector algorithm, that uses on-board accelerometer measurements, was developed. Monte-Carlo trajectory simulations showed that the algorithm provides excellent performance, with 100 percent successful capture under realistic dispersions. The algorithm was independently coded and tested at NASA JSC, where the performance results were verified.

**Conclusion:** Significant progress was made across several key areas during the ballute technology program, and systems analysis shows that excellent performance and packaging benefits are possible compared to traditional aerocapture technology. Ultra-lightweight ballute technology benefits a broad set of mission types, including aerocapture, de-orbit missions and entry, descent and landing systems to planetary bodies with a sensible atmosphere. This technology could be used for Mars missions to deliver small, low-cost probes to the surface as well as orbit insertion, entry, descent, and landing for the primary spacecraft.

Fig. 2. Several thin film and free flying ballute wind tunnel models of various configurations were constructed and tested at NASA Langley.

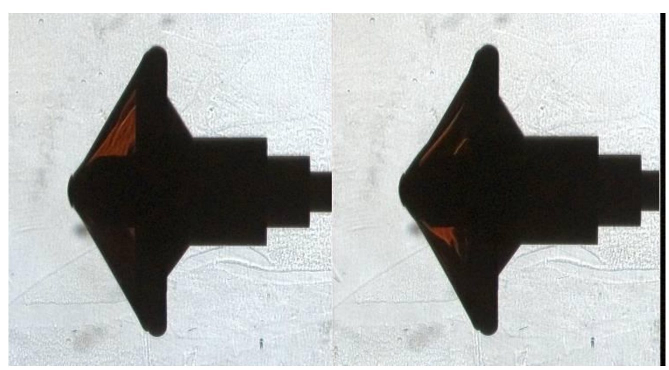

Fig. 3. Hypersonic wind tunnel testing of thin film ballute articles provides flow field and deformation data for CFD and aeroelastic model validation.