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ULTRALIGHTWEIGHT BALLUTE TECHNOLOGY ADVANCES

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ABSTRACT

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 Johnson, and the Jet Propulsion Laboratory has been addressing the technical issues associated with ultralightweight ballutes for aerocapture at Titan. Significant progress has been made in the areas of ballute materials, aerothermal analysis, trajectory control, and aeroelastic modeling. The status and results of efforts in these areas are presented. The results indicate that an ultralightweight ballute system mass of 8 to 10 percent of the total entry mass is possible.

[*keywords*: aerocapture, inflatable, thin-film structures, rarefied flow, Direct Simulation Monte Carlo (DSMC)]

NOMENCLATURE

ΔV	Delta-V, Change in Velocity
Kn	Knudsen number
M	Mach number
p	pressure
q	heating rate

1. INTRODUCTION

Traditional entry 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 entry and aerocapture missions centers on deployment of a large, lightweight, inflatable aerodynamic decelerator (ballute) whose large drag area allows the spacecraft to decelerate at very low densities high in the atmosphere. This "fly higher, fly lighter" concept provides the required aerodynamic deceleration with relatively benign heating rates. The low heating rates experienced during atmospheric entry and deceleration enable the use of lightweight construction techniques for the ballute, resulting in revolutionary mass performance compared to traditional entry technologies. For purposes of evaluating specific performance of ballute technology in a flight like scenario, this paper addresses aerocapture at Titan. The Titan aerocapture mission requirements used for the analyses described in this paper are summarized in Table 1.

Table 1. Titan Aerocapture Mission Requirements

Parameter	**Titan**
Entry Mass (kg)	1000
Ballute Mass (kg)	41
Area with Ballute (m^2)	751
Area without Ballute (m^2)	3.8
Entry C_D	1.7
S/C C_D	2.3
Entry Speed (km/sec)	6.5
Max. Allowable Heating (W/cm^2)	3.0
Entry Flight Path Angle (°)	-39
Entry Altitude (km)	1000
Atmospheric Scale Height (km)	41
Pass duration (s)	~3600
Ballistic Ratio	~150+

The ballute would be stowed in a small volume attached to the spacecraft, then deployed and inflated prior to entry into the atmosphere. After entry, the vehicle decelerates due to drag high in the atmosphere. Once the velocity has been sufficiently reduced, the ballute is separated. For aerocapture missions, the spacecraft exits the atmosphere and continues to apoapsis, where a small propulsive maneuver is used to place the vehicle in the desired final orbit. For entry or landing missions, the vehicle can transition to the use of a traditional parachute or propulsion system for terminal descent and landing.

As mentioned above, compared with chemical propulsion or rigid aeroshell solutions to orbit capture, ballutes offer substantial mass performance benefits. In addition, due to the characteristics of inflatable design, ballutes also offer significant benefits in flight system level packaging and other critical areas. Whereas more traditional systems introduce significant design constraints, such as propellant management, slosh, nutation and control of the center of gravity (c.g.) in the case of chemical orbit capture, or packaging envelopes, thermal control, cruise stage functionality and c.g. in the case of rigid aeroshells, a "fly higher, fly lighter" self contained package of about 0.5 m^3 constitutes a ballute system prior to inflation. This frees the spacecraft configuration from constraints imposed by an aeroshell and enables flexible and reconfigurable entry system designs. Spacecraft components do not have to be packaged within the wake of an aeroshell. The spacecraft center of gravity does not have to be strictly controlled to maintain aerodynamic stability, as the large ballute provides a very stable aerodynamic configuration with large performance margins. Because the ballute is only deployed when needed, there is no aeroshell to impede spacecraft functionality (e.g. heat rejection or obstruction of antenna and instrument views from the spacecraft).

In addition, due to its compact packaging, a ballute solution precludes the tight operational constraints, such as heat rejection, that arise from flying a spacecraft within an aeroshell. Finally, "fly higher, fly lighter" ballutes expand the envelope of orbits that can be reached without incurring a large propellant penalty since capture is achieved at a relatively high periapsis. Thus, ballutes enable aeroassist to be used even where constraints imposed by aeroshells would be prohibitive.

The In Space Propulsion (ISP) program, managed at Marshall Space Flight Center, is conducting development on propulsion technologies. Our team, consisting of Ball Aerospace, ILC Dover, NASA Langley, NASA Johnson, and the Jet Propulsion Laboratory, is working to develop two variants of the "Fly higher, fly lighter" ballute technologies. These concepts are illustrated in Fig. 1a and 1b. As shown, the trailing ballute (Fig. 1a) technology implementation concept uses a large toroid tethered in the wake of the primary spacecraft to decelerate. Critical technology development status on trailing ballutes has been summarized previously [1]. The clamped ballute concept (Fig. 1b) also uses a trailing ballute attached to the aft end of the primary spacecraft, but it uses a conic thin film web to attach the spacecraft to the toroid. There are advantages and disadvantages to each approach, and these will be addressed in this paper. Performance characteristics of the two technology approaches are summarized in Table 2. Our systems analyses on the two technology implementation concepts include trajectory, aerothermal, structural, and thermal analyses, along with materials testing and hypersonic wind tunnel testing. This paper will specifically address recent advances in:

- Aerothermal Analysis and Testing
- Materials Evaluation and Testing
- Trajectory Control
- Aeroelastic Modeling
- System Mass Performance

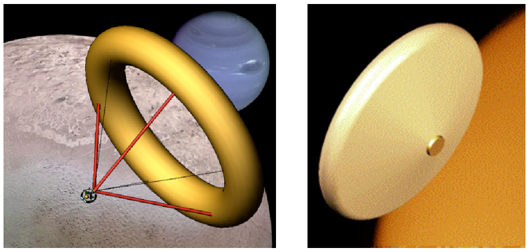

Fig. 1 a and b. Trailing Ballute and Clamped Ballute Technology Implementation Concepts

Table 2. Ultra lightweight ballute performance

	Trailing	Clamped
Peak dynamic pressure	21 Pa	52 Pa
Peak convective heating rate	1.8 W/cm^2	2.1 W/cm^2
Peak temperature on ballute	403 C	435 C
Ballute system mass	97 kg	74 kg
Aerocapture mass fraction	10%	8%

2. AEROTHERMAL ANALYSIS AND TEST

We are performing aerothermal analysis of ballute configurations to define the aerodynamic loads and heating environment for the ballute throughout the aerocapture trajectory. Because the trajectory spans free molecular, transitional, and continuum flow regimes, a suite of tools is required. For Computational Fluid Dynamics (CFD) Navier-Stokes solutions, we are employing the Langley Aerothermodynamic Upwind Relaxation Algorithm (LAURA) code [2]. We are using the Direct-Simulation Monte Carlo (DSMC) technique for high-fidelity free molecular and transitional flow modeling with the DSMC Analysis Code (DAC) [3]. We also make use of the DAC Free-Molecular (DACFREE) tool, which is an engineering level code that implements free-molecular and

Newtonian aerodynamics methods for quick evaluation of ballute configurations.

For the trailing ballute, we have completed quasi-dynamic modeling and analyses for Titan aerocapture. This has included stepwise DSMC and CFD analysis of the entry system over many points in the trajectory, including the peak dynamic pressure and peak heating points. For the clamped ballute, we have completed analysis at the peak heating and peak dynamic pressure points. The results from these analyses (aero loads and heating distribution over the ballute as a function of time) were used as inputs to the structural and thermal analyses. Sizing of the ballute system elements is then based on the structural and thermal analyses. Element sizing includes the number of tethers, cross section of tethers, and tailored film thicknesses for the ballute.

There is a potential for unsteady flow around the spacecraft and the trailing ballute. Therefore, we are also using CFD models of the flow field to examine the trailing ballute two-body flow stability and interactions. Our objective is to identify how changes in geometric design parameters such as ballute trailing distance, ballute aspect ratio, and ballute diameter influence the flow stability.

Hypersonic tests have been conducted on representative ballute configurations at facilities at NASA Langley Research Center and at the University of Virginia. These tests have provided an empirical basis for the DSMC and CFD models. The University of Virginia tests provide data on the three dimensional flow fields and ballute surface response under the rarefied conditions representative of the “Fly Higher, Fly Lighter” trajectory. Results have correlated well with DSMC models. The Langley tests, examining features such as angle of attack, and ratio of trailing distance to ballute diameter over various flow conditions, have provided a basis for understanding of geometries and their effects on shock-shock interaction. Schlieren images from some of the tests, shown in Fig. 2, indicate the shock interfaces as a function of the flight system geometry. In addition, these tests have provided a basis for correlation of models to predict the geometry and conditions for unsteady flow.

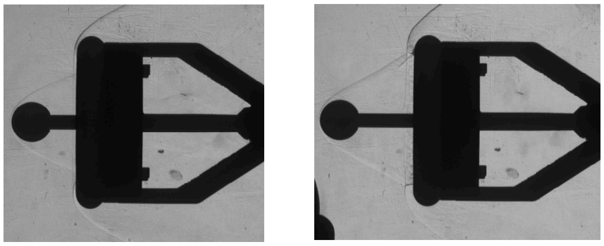

Fig. 2. NASA Langley hypersonic testing of trailing ballute configurations

3. MATERIALS EVALUATION AND TESTING

The objective of our ballute materials efforts is to investigate the availability and applicability of candidate materials, evaluate their mechanical properties, and determine how well they can survive the predicted operating environment within the constraints of our current ballute design concepts. Our current efforts have focused on material performance at elevated temperatures, seaming ability, strength of seams, and impacts on material performance due to folding and packaging.

We have completed a broad survey of potential thin film materials for ballute construction, including several varieties of Kapton, Upilex, and PBO. We have examined PBO and Kevlar tensile materials for tethers. In many instances, material performance data does not exist for the temperature ranges of interest. Therefore, we are conducting tests to determine material properties at operational conditions, plus margin. Our thin film testing has included raw material samples and seamed samples. To examine effects of packaging and storage, we have tested both pristine and creased samples. In all cases, we determined material strength and elongation at room temperature and up to 500°C (see Fig. 3). The results of these tests are incorporated into our nonlinear finite element models for ballute structural design, sizing, and analysis. Based on this work, we have selected Upilex film for the inflatable torus and PBO for the tethers for our reference trailing ballute design concept.

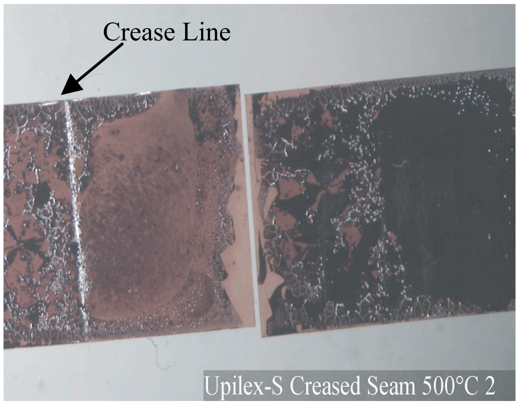

Fig. 3. Thin film material testing has identified candidate materials compatible with "Fly Higher, Fly Lighter" Environments

4. TRAJECTORY CONTROL

The effectiveness of using a drag-only device to capture into orbit relies on critical timing of the ballute separation under navigation, atmospheric, and design uncertainties. We have developed an on-board algorithm that uses measured deceleration due to drag and a numerical trajectory predictor to issue the ballute separation command during flight and achieve the target orbit.

We have tested our ballute separation algorithm using Monte Carlo trajectory simulations of aerocapture at Titan. The simulations include dispersions in entry conditions, uncertainty in navigation knowledge, variability in aerodynamics, and variation in atmospheric density with random perturbations using the Titan GRAM atmosphere model [4]. The results of these simulations, illustrated in Fig. 4, show that the separation algorithm provides excellent performance, with 100 percent of 2000 Monte Carlo cases capturing. A small propulsive maneuver is required after atmospheric exit to achieve the final orbit. Comparing our Monte Carlo results to those for aerocapture using an aeroshell with lift modulation [5] shows that the post-aerocapture propulsive ΔV required for aerocapture with a ballute is the same magnitude as that required for an aeroshell.

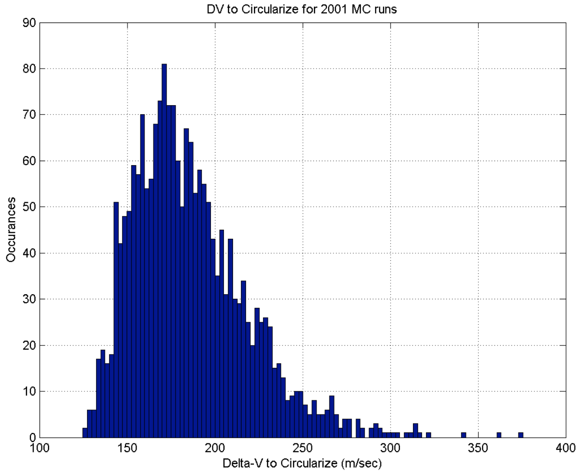

Fig. 4. Monte Carlo trajectory results demonstrate robust aerocapture performance

5. AEROELASTIC MODELING

One of our primary technology development efforts involves the methodology and tools to analyze the aeroelastic problem for ultralightweight ballute concepts. This problem involves the combination of aerodynamics, dynamics, elasticity, and thermal analysis due to the heating encountered in the entry environment (see Fig. 5). There is no known aeroelastic modeling capability for the nonlinear, hypersonic, rarefied flow regime associated with our ultralightweight ballute concepts. Currently, we are using an uncoupled static analyses to evaluate the change in aerodynamic loads and aerothermal performance due to structural deflections, thus necessitating the use of large margins to account for dynamic load factors. A coupled analysis capability will provide better model of the dynamic response of the ballute system, enabling a more robust design with reasonable margins and optimum mass performance.

We are currently working on developing a ballute aeroelastic modeling capability that couples existing nonlinear structures, thermal, and aerodynamic codes (e.g., MSC MARC, LS-DYNA, LAURA, DACFREE, DAC). We have identified an initial tool architecture, are evaluating analysis tools, and developing interface codes. The analytical architecture that we have defined provides a fully coupled solution including aerothermal, structural, and thermal elements. The aeroelastic modeling toolset is specifically designed to provide dynamic performance analysis of non-linear, thin film systems under rarefied, hypersonic conditions. Our plan is to develop a complete working implementation of this tool set, and then test its capabilities through wind tunnel test of flexible ballute models.

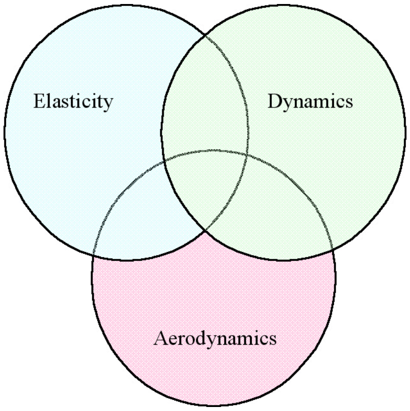

Fig. 5. Aeroelastic modeling approach will provide coupled analyses for non-linear inflatable structures in a rarefied, hypersonic flowfield.

6. SUMMARY

Our ultralightweight ballute technology development efforts have shown that existing thin film materials are compatible with the ultralightweight ballute mission concept for aerocapture at Titan. Aerothermal analysis and testing has been completed to define the design environment and understand the flow field dynamics. Monte Carlo trajectory analysis shows that the aerocapture trajectory can be controlled under dispersions. Based on the analysis completed to date, an ultralightweight ballute system mass of 8 to 10 percent of the total entry mass is possible.

Ultralightweight ballutes offer a revolutionary performance benefit compared to other orbit insertion technologies. Using our current estimate of ballute system mass and the ΔV it provides for aerocapture at Titan, ultralightweight ballutes provide an equivalent specific impulse (I_{sp}) of 5000 sec. This compares very favorably with other orbit insertion technologies as shown in Table 3.

Table 3. Comparison of Equivalent Specific Impulse (I_{sp}) for Various Orbit Insertion Technologies

Technology	**I_{sp}**
Ultralightweight Ballutes	5000 sec
Rigid Aeroshell	1000 sec
Ion Propulsion	3100 sec
Bipropellant Propulsion	330 sec

Based on our systems analysis, testing, and development efforts, ultralightweight ballute system Technology Readiness Level (TRL) is currently at 3 to 4. Our team will continue to advance ultralightweight ballute technology with the goal of achieving system TRL of 6, so that the benefits of this technology can be applied to space science and exploration missions.

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8. REFERENCES

1. Miller, K.; Gulick, D.; Lewis, J.; Trochman, B.; Stein, J.; Lyons, D.; Wilmoth, R.; “Trailing Ballute Aerocapture: Concept Feasibility and Assessment,” AIAA/ASME/SAE/ASEE Join Propulsion Conference, Huntsville, AL, July 2003.
2. Gnoffo, P. A.; “An Upwind-Biased, Point-Implicit Relaxation Algorithm for Viscous, Compressible Perfect-Gas Flows,” NASA TP-2953, Feb. 1990.
3. LeBeau, G. J.; Lumpkin, F. E.; “Application Highlights of the DSMC Analysis Code (DAC) Software for Simulation Rarefield Flows,” Computer Methods in Applied Mechanics and Engineering, Vol. 191, Issue 6-7, 2001, pp. 595-609.
4. Justus, C. G.; Duval, A.; Johnson, D. L.; “Engineering-Level Model Atmospheres for Titan and Neptune,” AIAA-2003-4802, AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, July 2003.
5. Way, D.; Powell R.; Edquist, K.; Masciarelli, J.; Starr, B.; “Aerocapture Simulation and Performance for the Titan Explorer Mission,” AIAA 2003-4951, AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Huntsville, AL, July 2003.