A REVIEW OF BALLUTE TECHNOLOGY FOR PLANETARY AEROCAPTURE

Jeffery L. Hall

Jet Propulsion Laboratory, California Institute of Technology
4800 Oak Grove Dr., Pasadena, CA. 91109

ABSTRACT

The aerocapture concept has long offered the potential for substantial mass savings over propulsive orbit insertion at other planets. Although incompletely developed and never flown, aerocapture is currently viewed as an enabling technology for a number of ambitious future robotic missions like Venus Surface Sample Return, Neptune Orbiter, Titan Organics Explorer and Saturn Ring Observer. This has spawned renewed interest in possible technological implementations, with particular emphasis on moderate lift aeroshells and inflatable ballutes. Although much less mature than aeroshells derived from atmospheric entry capsules, ballutes have a number of potential advantages including reduced mass and simplified navigation and control. Recent ballute studies have proposed design concepts that either mitigate or remove some of the key technical obstacles that have prevented ballutes from being implemented in the past. This paper reviews the recent work and discusses the remaining technical issues and uncertainties that must be addressed to produce working ballutes for planetary aerocapture.

INTRODUCTION

A ballute is an inflatable device used to increase the drag of the vehicle to which it is attached. As such, the ballute combines features from the two devices that give it its name: the inflatable <u>ball</u>oon and the parach<u>ute</u>. There are three basic configurations of ballutes: cocoon ballutes that enclose the parent vehicle, attached ballutes (also called attached inflatable decelerators) that connect directly to the base of the vehicle, and towed ballutes that trail the parent vehicle at some distance with a connecting tether (Fig. 1). Multiple geometries are possible within each category depending on the flight regime and application. All, however, share the common premise of increasing the drag of the vehicle by increasing the cross sectional area presented to the flow. A key advantage of ballutes is that a very large increase in drag can be achieved with a modest mass penalty because of the inherently lightweight nature of thin film ballute (balloon) materials. In addition, the deployable nature of ballutes is particularly attractive for those payloads that are initially volume constrained.

Instability problems with early supersonic parachutes led to the invention of the ballute by the Goodyear Aerospace Corporation circa 1960.[1] The first concept was a towed, ram-air inflated device that demonstrated superior stability characteristics to parachutes in this flow regime.[2] Many different ballutes designs have been proposed since that time for a wide variety of missions. These include:

1. Stabilization and deceleration of bombs and other munitions with attached inflatable decelerators.[2,3]
2. Venus atmospheric probes in which the ballute is used for both atmospheric entry and the buoyant support for the payload at the float altitude.[4,5] Ref. 4 proposed both a towed ballute and an attached inflatable decelerator, while Ref. 5 proposed a cocoon ballute.
3. Attached inflatable decelerators for Mars landers and atmospheric entry probes.[6] These ram-air filled devices were seen as a parachute alternative with deployment occurring after delivery into the Martian atmosphere.
4. Attached ballutes for direct atmospheric entry at Mars.[7]
5. Cocoon ballutes for aeroassisted orbital transfer vehicles at Earth.[8,9,10] Ref. 10 concluded

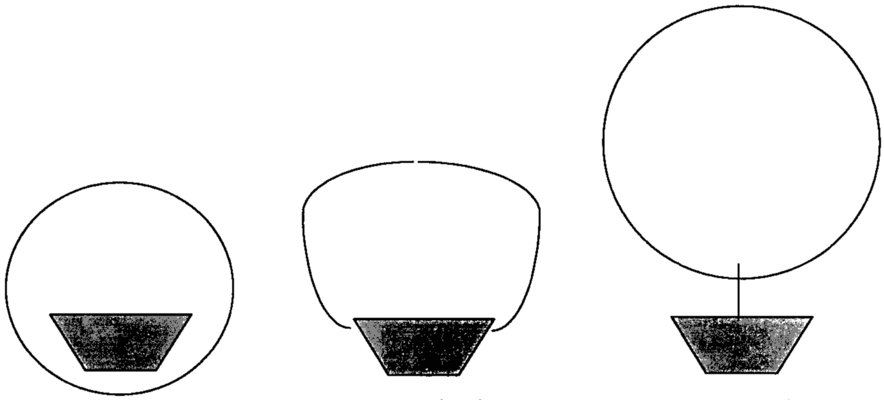

Fig. 1: The Three Basic Ballute Configurations

that cocoon ballutes were the worst of the five technologies considered because of concerns with ballute material survivability and trajectory modulation concerns. Other ballute configurations were not discussed.

6. Large, towed ballutes for planetary aerocapture and entry at Mars, Venus, Neptune and Pluto.[11,12,13] As will be discussed shortly, it is largely on the basis of these recent efforts that aerocapture ballute interest has been rekindled.

Although ballute prototypes have been flight tested at Earth for various applications, no planetary aerocapture ballutes have yet flown. In fact, with the exception of attached inflatable decelerators for Mars entry probes, insufficient engineering development work has been done on any of the planetary ballute concepts to verify essential mission feasibility, let alone provide a mature technology for flight operations. Some of the key technical issues yet to be resolved include survivability of the ballute in the severe convective and radiative heating environment, flow stability concerns, control authority in the face of atmospheric uncertainties and targeting errors, and mass constraints on ballute size and envelope material selection. Another barrier to the use of ballutes has been the availability of the proven alternative technology of ablative aeroshells for direct entry missions to Mars (Viking, Pathfinder), Venus (Pioneer, Venera) and Jupiter (Galileo). Considerable effort has been and continues to be expended to adapt this ablative aeroshell technology to the more difficult problem of planetary aerocapture.[14,15] Although no aeroshell aerocapture flight tests have yet been done, use of the technology is planned for the CNES/NASA Mars '05 sample return mission.

Recent interest in and enthusiasm for planetary ballutes comes from three main sources. First, the work of A. McRonald[11-13] has revealed that sufficiently large ballutes will reduce aerocapture and direct entry heat fluxes by two or more orders of magnitude compared to small ablative aeroshells. Second, recent work on high temperature materials for Venus deep atmosphere balloons[16,17] have indicated that both Kapton and polybenzoxazole (PBO) can provide adequate strength in the 400+ °C range, which is sufficient for radiative cooling of thin ballute materials at the heat fluxes computed by A. McRonald. Third, there is concern that aeroshell aerocapture technology will either not be ready or not feature adequate performance to meet the needs of some high priority future robotic missions. Of particular importance are the Neptune Orbiter, Saturn Ring Observer, Titan Organics Explorer and Venus Surface Sample Return missions. All of those missions require the mass savings afforded by aerocapture versus propulsive orbit insertion.[18]

The towed ballute is currently viewed as the preferred configuration for planetary aerocapture because of three key advantages. First, it avoids the cocoon problem of having to deploy and then remove a membrane around fragile spacecraft components like solar panels, antennae, and scientific instruments. Second, it physically separates the ballute and spacecraft, thereby preventing lateral ballute forces from affecting the orientation of the spacecraft. This can be particularly important given the likelihood for unsteady shock waves and vortex shedding associated with the flow around ballutes. Third, a towed ballute is easily detached from the parent spacecraft by cutting the connecting tether. Given the large drag disparity between the ballute and spacecraft, this enables the drag to be essentially "turned off" once the desired decrease in vehicle kinetic energy has been achieved.

This ability to turn the drag off in mid-flight is a towed ballute advantage over aeroshell technology as well. Forward facing heat shields cannot possibly be jettisoned in atmospheric mid-flight, resulting in the need for appreciable vehicle lift and control authority to adequately modulate the trajectory in the face of atmospheric uncertainties and targeting errors. This very difficult guidance and navigation problem has been considered "the most critical of all technological issues" for aeroshell aerocapture.[10]

The other key advantage that towed ballutes are considered to have over aeroshells is lower system mass. Ballutes constructed from thin film materials are expected to be lighter than thick ablative heat shields for comparable missions. This conclusion is predicated, however, on a number of key assumptions and extrapolations that have yet to be verified. An alternative way to view the mass issue is to use ablative aeroshells as a benchmark against which ballutes have to be superior in order to be selected for future missions. A preliminary attempt at this kind of mass benchmarking has been compiled by the author and presented as Table 1. The four planetary missions described previously plus a Mars comm.nav microsat orbiter form the basis of comparison, with the towed ballute compared to both propulsive orbit insertion and aeroshell aerocapture. It is seen that aerocapture saves considerable mass as compared to propulsion in all cases. Also, the current best estimate (CBE) mass for ballutes is predicted to be less than aeroshells in all cases. However, these ballute mass estimates could easily grow to surpass the aeroshell values if the current preliminary analyses are not supported by higher fidelity simulations and wind tunnel testing.

BALLUTE TECHNICAL ISSUES AND UNCERTAINTIES

Although the aerocapture ballute is a conceptually simple device, its detailed analysis and design is fairly complex. The extremely high flow velocities of 6 to 30 km/s around the ballute produce a rich variety of aerothermodynamic phenomena including shock waves, mixed regions of subsonic, supersonic and hypersonic flow, non-equilibrium atmospheric gas chemistry, and convective and radiative heat transfer. Also, there is an inherent conflict between the need to minimize the ballute mass and to maximize the ballute size for tolerable heat fluxes. Resolution of this conflict requires a very thin material for the ballute envelope, one that can provide significant tensile strength at high temperature, a high emissivity surface for radiative cooling and sufficient flexibility to allow compact storage and easy inflation and deployment. This is clearly a formidable materials challenge. In summary, aerocapture ballute design and analysis is an inherently multidisciplinary process, one for which only a few tentative steps have been taken.

Table 2 lists the key technical issues to be resolved for planetary aerocapture ballutes. Each item will now be discussed in detail.

1. Determination of the optimal ballute shape.

A spherical ballute is the simplest towed geometry, one that possesses two key advantages: the drag and heating is insensitive to ballute orientation and the ballute requires only a single tether whose own heat load will be minimized due to its alignment with the velocity vector. The main disadvantages of the sphere are that both the envelope mass (M_e) and the inflation gas (M_g) mass grow quickly with diameter, d ($M_e \sim \pi d^2$, $M_g \sim d^3$). Calculations suggest that these masses may become prohibitive for the 100+ meter diameter ballutes required for the Venus and Saturn missions in Table 1. Alternatives to spheres include a disk that requires half

Table 1: Comparison of propulsion and aerocapture options for future robotic missions

Mission					Propulsive Option			Aerocapture Options			
								Aeroshell		Ballute	
	Entry speed	Target orbit	Orbit insert. ΔV	Non-braking mass delivered to orbit	Propellant mass for orbit insertion[1]	Propellant mass fraction	Periapse raise propel-lant	CBE aeroshell mass	CBE aeroshell mass fraction	CBE ballute system mass[4]	CBE ballute system mass fraction
	(km/s)	(km)	(km/s)	(kg)	(kg)		(kg)	(kg)		(kg)	
Mars Comm/Nav Sat	6.4	600 circ	2.9	100	170	63%	4	20	18%[2]	10	10%
Venus Sample Return	11.6	300 circ	4.5	2950	10500	78%	60	1300	30%[3]	750	20%
Titan Organics	9.6	1000 circ	8.0	310	4100	93%	13	230	35%	140	25%
Saturn Ring Observer	26.1	56000 circ	8.0	250	3300	93%	1240	1000	40%	640	30%
Neptune Orbiter	28.9	$500x10^6$ ell	5.9	230	1400	86%	20	170	40%[5]	110	30%

Notes:
1. Assumes Isp = 300 s
2. Uses Mars Pathfinder aeroshell mass fraction.
3. Uses the Pioneer-Venus aeroshell mass fraction.
4. Non-braking mass includes periapse raise propellant.
5. Uses an estimate generated by P. Wercinski et al, ARC, 1997.

envelope area and potentially much less gas ($M_e \sim \pi d^2/2$, $M_g \sim d^2 t$ where t is the disk thickness, and t << d) and the toroidal ballute that can be more or less massive than the sphere depending on the ratio of ring to cross section diameters (D/d). However, both the disk and toroidal ballutes are orientation sensitive and hence they require multiple tethers that may see appreciable heating due to only partial alignment with the flow. Selection of the optimal ballute shape will require a synthesis of detailed numerical simulations of flow and heating around the candidate geometries, verification with wind and shock tunnel testing, and calculations of ballute system masses for each case.

2. Survivability of the ballute material

Heat fluxes on aeroshell heat shields are so large (e.g., $\sim 10^8$ W/m^2 for Pioneer-Venus[19]) that the prospect of thin membranes surviving such environments has not seemed too likely.[10] However, recent calculations by A. McRonald have yielded stagnation point heating rates of only $\sim 10^4$ W/m^2 for 100 m diameter spherical ballutes at Venus.[12] This four order of magnitude reduction results from three factors. First, blunt body convective heat transfer scales like the inverse square root of the radius of curvature,[20] so the use of a 100 m diameter ballute instead of a 1 m diameter aeroshell yields a one order of magnitude reduction. Second, ballute aerocapture can work with a very shallow entry angle of only 2° to 4° to achieve another order of magnitude heat flux reduction. Third, the combination of large ballute diameter and shallow entry angle yields a ballute trajectory that experiences peak heating and deceleration at a much higher higher altitude than small aeroshells. This altitude corresponds to a low atmospheric gas density of $\sim 4x10^{-8}$ kg/m^3 at Venus. Given that stagnation point heating scales with the square root of gas density,[20] and that a small aeroshell experiences peak heating at $\sim 10^{-4}$ kg/m^3 gas density at Venus, this provides two more orders of magnitude reduction in stagnation point heating.

A central feature of the towed ballute concept is that the membrane material will self-cool by radiated energy emission at a tolerably low temperature. This temperature can be calculated

Table 2: Summary of Unresolved Ballute Technical Issues

#	Issue	Description
1	Optimal ballute shape	Which shape (sphere, disk, toroid, ?) for which missions?
2	Survivability of the ballute	Can the membrane material survive the heating and drag?
3	Flow stability	If the flow is not stable, can its effects be tolerated?
4	System mass	Will ballutes be low mass enough to be competitive?
5	Trajectory robustness	How to compensate for atmospheric uncertainties?
6	Structural integrity	How to ensure structural integrity?
7	Tether design	Can the tether(s) be designed to take the heating and stress?
8	Parent spacecraft protection	What auxiliary thermal and aerodynamic protection does the spacecraft require? Can its mass be tolerated?
9	Deployment and inflation	Can this tech. be borrowed from other inflatable efforts?
10	Experimental verification	What is a good ground vs space testing mix?

using the well known relationship $Q = \varepsilon\sigma T^4$ where Q is the emitted power flux, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant and T is the surface temperature in Kelvin. A radiatively cooled ballute in thermal equilibrium with a 10^4 W/m^2 external heat input therefore requires a 665 K surface temperature if ε=0.9 and 770 K if ε=0.5. Note these temperatures will be lower if one accounts for the fact that a thin ballute material will emit thermal radiation from both the outside and the inside surface, although this improvement will be mitigated by some extra energy input on the inside surface from the rest of the ballute interior. Nevertheless, the range of 665 K to 770 K serves well as a prediction of peak ballute material temperature for this mission.

Recent data indicates that temperatures of up to 770 K are survivable with Kapton (polyimide) thin films.[17] The tensile strength of this material at 770 K is 38 MPa, which is significant though not outstanding. However, this material will almost certainly be stronger if used in a ballute application because of the fact that polymer materials gradually lose strength with continued exposure to high temperatures. Therefore, aerocapture ballutes that experience peak heating for only a minute or two should have greater than the 38 MPa strength measured in the lab after multi-hour exposure. Another material that may be useful for ballutes is polybenzoxazole (PBO), either in thin film or fiber (fabric) form.[16,17] Laminates of Kapton film and PBO fiber are seen as particularly attractive at the present time because the film can retain the inflation gas and the fiber can provide the necessary strength and durability.

The current state of knowledge is highly suggestive that survivable ballute materials can be fabricated from Kapton and PBO materials. However, additional sample fabrication and testing is required to confirm this, especially in the required 20 g/m^2 or less range of areal densities. In addition, a high emissivity coating may be required if the underlying membrane material is not itself sufficiently emissive. Finally, the need for structural reinforcing elements like ribbons or nets must be evaluated under the loading conditions of each mission.

3. Flow stability

There are a number of different facets to the issue of flow stability of the towed ballute. First, there is the problem of large lateral forces on the ballute due to vortex shedding that can alter the orientation of the ballute and the parent spacecraft. Second, there can be aeroelastic phenomenon associated with the non-rigid nature of the ballute leading to possible shape changes under aerodynamic loads. Third, there is the possibility of flow instability due to wake and shock wave interactions between the ballute and spacecraft.

Recent numerical simulations of the flow around the spacecraft plus ballute configuration have indicated that flow instability can occur due to shock wave interactions without either relative motion of the spacecraft and ballute or aeroelastic deformation of the ballute itself.[21] The impact of this flow instability on ballute performance has not yet been studied; however, it seems likely that the overall drag coefficient, tether force and ballute heating will all be affected, perhaps in catastrophic ways. Avoidance techniques for flow instability exist and are being studied; for example, it appears that toroidal ballutes of sufficient size can swallow the wake of the spacecraft and avoid this kind of instability.[21] However, the drag and heating performance of toroidal shapes has not been explored.

No work has yet been done on the aeroelastic phenomenon of towed aerocapture ballutes. It is generally thought that one needs only to pressurize the ballute to a certain level to maintain sufficient rigidity; however, the magnitude, and hence feasibility, of this pressure has not been determined. Finally, the problem of lateral forces on the ballute would appear to be a non-issue for spherical ballutes attached with long tethers. Other geometries require more analysis and testing to determine if this kind of flow stability will be a problem.

4. Ballute system mass

The preliminary results presented in Table 1 above are highly suggestive that ballute system masses can be lower than any known alternative technology for planetary aerocapture. However, it is clear that much work remains to be done to reduce the very large uncertainties associated with ballute system masses. The key factors to address are: ballute shape and size, material selection and level of gas pressurization for each of the candidate missions. Systems engineering is required to trade off the many technical issues that shape these factors to achieve a good balance between a low mass yet robust final design.

Although the ballute membrane itself is generally the largest mass item, it is important to note that the inflation and deployment hardware and tether masses could be significant for some designs depending on the size of the ballute and the amount of inflation gas required.

5. Trajectory robustness

As mentioned previously, the issue of targeting errors and atmospheric uncertainties has been a major concern for aeroshell aerocapture applications. In the crudest sense, the spacecraft must not decelerate too much or it will crash, and it must not decelerate too little or else it will simply continue past the planet never to return. Most missions require a specific orbit which further restricts the range of acceptable aerocapture trajectories. Towed ballutes feature both a major deficiency and major advantage in their ability to fly in this narrow range. The deficiency is the lack of aerodynamic lift to modulate the trajectory inside the atmosphere, a property that is in marked contrast to lifting aeroshells. The advantage is that the towed ballute can be jettisoned at any point in the trajectory.

To the extent that the drag of the small spacecraft is insignificant compared to that of the large ballute, this jettisoning ability can be accommodating of atmospheric uncertainties. The strategy is to bias the ballute towards the more dense region of the atmosphere, fly until enough deceleration has occurred, detach the ballute and continue (essentially) drag free through the atmosphere and back into space. There are three caveats to this plausibility argument: first, the actual non-zero drag of the parent spacecraft must be tolerable; second, the parent spacecraft must have aerodynamic stability in the absence of a ballute; and third, the ballute will be much less able to recover from a targeting error biased to the less dense part of the atmosphere. At the present time, no detailed parametric studies have been performed to investigate these caveats and to quantify trajectory robustness issue.

6. Structural integrity

It is important to recognize that the proposed use of thin film material (i.e. ~20 g/m^2) for the large, towed ballute concept is in marked contrast to the coated cloth materials considered for most previous ballute projects. For example, the ballutes built and tested by Langley Research Center for the Mars decelerator program (Ref. 6) used coated Nomex cloth with an areal density of 80 g/m^2 plus additional meridional tapes to support the pressure load. Other materials suggested or tested include silicon fiber canvas,[7] Kevlar,[5] and elastomer coated Rene fabrics or fiberglass.[4] Selection of these heavier and stronger materials was dictated by the relatively high dynamic pressures encountered in the previous applications. Indeed, concerns with structural loads on the ballute dominated the earlier designs and led to not only heavy materials of construction but also the use of isotensoid shapes to minimize membrane stresses. However, using Mars ballutes as an example, the aerocapture application is expected to have two orders of magnitude reduced dynamic pressure loads as compared to the previous supersonic decelerator designs. The trajectory simulations indicate[11] that large towed ballutes for Mars aerocapture will experience a peak dynamic pressure of only 20 Pa at an atmospheric density of roughly 5×10^{-6} kg/m^3. This density is four orders of magnitude lower than that encountered by the previous supersonic Mars decelerator ballutes, so that even though the aerocapture velocities are one order of magnitude higher (i.e. 6000 m/s vs ~600 m/s), the net result is a dynamic pressure two orders of magnitude reduced. This means that lighter materials can be used for towed aerocapture ballutes and the need for isotensoid shapes is much reduced. The overall drag force remains large, however, indicating the need for careful design of the tether–ballute interface and for understanding the local deformed geometry and its effect on the flowfield and heat fluxes.

7. Tether design

Ballutes achieve some of their heat flux reduction by virtue of their large size. The converse argument suggests that small diameter tethers will experience large heat fluxes and correspondingly high temperatures. One way to mitigate this problem is to make the tether out of a material that can tolerate extremely high temperatures. Metal or graphite tethers are possibilities here depending on the actual temperatures. Alternatively, the tether can be designed to have a reduced heat flux over the worst case value. For example, tethers normal to the flow will have very much greater heating than tethers aligned with the flow. This is one advantage of a spherical ballute mentioned previously. Also, it may be possible to surround the tether with a small inflated tube to greatly increase its diameter.

Little quantitative work has been done to explore ballute tether design, either to predict the magnitude of tether temperatures or to test candidate materials. There is also a concern that the presence of tethers may also perturb the flow field and exacerbate flow stability problems. Numerical simulations and experiments are required to resolve these issues.

8. Parent spacecraft protection

An important problem of the towed ballute is the fact that it affords no direct shielding of the parent spacecraft itself. This will almost certainly require additional thermal protection hardware to prevent overheating of spacecraft components that would otherwise be exposed to the free stream flow. This is conceptually not too difficult for the spacecraft bus itself since a flat or slightly convex shield will experience heat fluxes comparable to the ballute itself, and those temperatures are easily tolerable for metal or ceramic materials. More difficult to protect are extended booms, solar panels and antennae. One possibility is to keep these elements behind the main bus shield until after aerocapture. The drawback of that approach is the same one that plagues rigid aeroshell and cocoon ballute designs, namely that alternate methods of providing spacecraft power and communications are required during interplanetary cruise. Retractable devices can alleviate these drawbacks at the expense of the additional mechanism complexity.

Alternatively, the deployed components can be either constructed from high temperature tolerant materials or hidden behind their own forward facing shields.

The great limiting factor of any secondary protection hardware is available mass. The main reason for using ballutes is to save braking mass, and if this advantage is consumed by the need for secondary shields on exposed spacecraft surfaces there is no point to the ballute. Detailed mass estimates for this trade-off have yet to be done. One possible but unexplored strategy for minimizing the heat flux on the parent spacecraft is to position the ballute only a short distance behind so that the ballute bow shock lies in front of the spacecraft. While this strategy may have problems with flow stability, it provides a form of shielding that could significantly reduce the incident heat flux on the parent spacecraft.

9. Deployment and Inflation

The towed ballute has to be deployed and inflated before encountering the atmosphere of the target planet. To a large extent, the technology for doing this can be readily borrowed from flight experiments like the IN-STEP Inflatable Antenna Experiment.[22] The basic concept is to eject the ballute from a storage container at the rear of the spacecraft and then fill the ballute with nitrogen or helium gas from a high pressure tank through appropriate plumbing. Although alternative pressurants and lightweighted plumbing can be explored, this aspect of ballute technology seems well in hand.

Ballutes do, however, have an inflation issue that is not shared by the devices flown to date. Specifically, during passage through the atmosphere, the pressurant gas will heat up along with the ballute membrane. It is likely that this heating will raise the gas pressure beyond the point that it can be contained by the membrane. If so, this will require a pressure relief mechanism to prevent rupture. Given the large size of the ballutes contemplated, the size of the relief mechanism may also be large and pose a significant mass penalty.

10. Experimental verification

A problem shared by all forms of atmospheric entry and aerocapture test hardware is that the complete aerothermodynamic environment cannot be duplicated on Earth. In particular, the combination of high velocity (6+ km/s), high enthalpy (10+ MJ/kg), gas composition (CO_2, N_2, H_2, etc.) and long duration (30+ s) cannot be duplicated on the ground. For example, the Caltech T5 shock tunnel can provide 5-6 km/s velocity and 20 MJ/kg enthalpy, but only for millisecond durations.[23] Conversely, the NASA Langley 22 inch Mach 20 tunnel can provide up to 30 seconds of flow, but only with helium gas of up to roughly 3 MJ/kg enthalpy.[24] Even if a new facility were contemplated for ballute development, there remains the critical obstacle that sufficiently high enthalpy flows require extremely high stagnation temperatures (>20,000 K) that cannot be tolerated by known materials of construction. Aerocapture ballutes have an additional problem in that they are very large devices of 100 meters or more in diameter. This is well beyond any wind tunnel currently available for any Mach number regime.

Lacking the ability to completely simulate aerocapture ballutes on the ground, the only recourse is to do wind tunnel testing on subsets of the ballute problem and then do flight testing for a complete systems validation. For example, heat flux and flow field measurements with proper gas chemistry can be made on rigid models using shock tunnels, while aeroelastic effects at high Mach number can be explored in moderate duration helium wind tunnels. Tether and membrane materials can be tested in ovens or, for short duration heating measurements, in arc jet or radiant heater facilities. Inflation systems can be tested in vacuum chambers. Other such tests can be devised to yield important data on ballute subsystems.

It seems credible that much of the data generated from Earth orbit flight testing will be relevant to other planet aerocapture missions. The keys to such flights are attaining sufficiently high velocity and acquiring pressure, temperature and video data of the ballute throughout its trajectory. Small scale ballutes can be lifted to sufficient altitude by sounding rockets or deployed as piggyback payloads from launch vehicles to low earth orbit or geosynchronous transfer orbit. The application of Earth orbit ballute data to Venus, Mars or Titan missions is less speculative because of the similarity of velocity and gas composition. However, the outer planet aerocapture missions are so much faster (25+ km/s vs 5-10 km/s) and involve such different gas chemistry (H_2/He vs N_2 or CO_2) that extrapolations will be more difficult.

BALLUTE TECHNOLOGY DEVELOPMENT PLAN

The ten aerocapture ballute issues discussed above provide the skeleton of a technology development plan for advancing ballutes to flight ready status. Each issue must be addressed and resolved to an acceptable level for ballutes to become ready for future aerocapture missions. The overall problem is clearly multidisciplinary in nature and will require engineering expertise in the many areas including aerodynamics, gasdynamics, heat transfer, materials, structures, space inflatables, trajectory analysis, guidance and control, and systems engineering. Prioritization among the ten issues is somewhat arbitrary, although a strong case can be made that the shape, heating and flow stability issues (#1-3) should take precedence. These three highly coupled issues will dictate the size of the ballute and its flight regime, from which all other design requirements must follow. Experimental verification (#10) is an equally high priority item, but it must necessarily lag behind the analysis tasks so that the test models are representative of the preferred designs. The system mass issue (#4) is one that needs to be essentially ongoing throughout the development process, incorporating new information as it is generated to provide guidance on how to optimize components on the basis of mass reduction. The remaining items (#5-9) become lower priority by default, although given the potential for show stoppers with the trajectory, tether and spacecraft protection issues, they clearly cannot be neglected for very long.

A key analysis tool that has seen very limited application to the aerocapture ballute problem is computational fluid mechanics. This tool lies at the heart of understanding the flow and heating environment around the spacecraft and ballute, particularly given the limitations of full scale ground based testing. The ideal situation would be to numerically simulated the entire ballute trajectory, computing the flow, heating and aeroelastic phenomenon at each point along the way. Such a tool does not currently exist, however, and its creation is a formidable challenge. However, computer programs do exist that can tackle certain aspects of the ballute problem and it seems plausible that enough can be learned without a completely integrated package. For example, the Venus aerocapture heating rates reported in Ref. 12 included data from an aerothermodynamic calculation based on the NASA/Langley LAURA code.

CONCLUSIONS

Several high priority future missions to other planets will not be done without the mass savings afforded by aerocapture technology. The idea of using ballutes for planetary aerocapture is not new, but recent work has suggested that 10 to 100 meter diameter ballutes towed behind the spacecraft can form the basis of a feasible design that mitigates previously identified obstacles. However, considerable work remains to be done to verify this feasibility and to produce mature designs for flight hardware. The many technical issues and uncertainties have been listed and discussed herein.

ACKNOWLEDGMENTS

The author would like to acknowledge helpful discussions and support from Angus McRonald, Andre Yavrouian, Jim Cutts, Bob Gershman and Dan Lyons of JPL, Hans Hornung of Caltech and Peter Gnoffo of NASA/Langley. This work has been funded by NASA through both the Mars Surveyor Program Office and the Solar System Exploration Strategic Studies program at JPL.

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