Ballute Aerocapture Trajectories at Neptune

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Using an inflatable ballute system for aerocapture at planets and moons with atmospheres has the potential to provide significant performance benefits compared not only to traditional all propulsive capture, but also to aeroshell based aerocapture technologies. This paper discusses the characteristics of entry trajectories for ballute aerocapture at Neptune. These trajectories are the first steps in a larger systems analysis effort that is underway to characterize and optimize the performance of a ballute aerocapture system for future missions not only at Neptune, but also the other bodies with atmospheres.

I. Introduction

The name "Ballute" is a cross between a "balloon" and a "parachute". The inflated components provide the stiffness needed to deploy the structure in a vacuum and then maintain the proper shape of a very light weight structure while generating sufficient atmospheric drag to capture the vehicle into orbit. The large drag area acts like a parachute to slow the spacecraft rapidly once it enters the upper atmosphere of the target body. Preliminary studies of ballutes for aerocapture at several planetary bodies were pioneered by Angus McRonald.[1,2,3] Jeff Hall has also made recent contributions to the advancement of ballute technology.[4] Currently, the In Space Propulsion program is funding an interdisciplinary team of engineers lead by Kevin Miller and Jim Masciarelli (Ball Aerospace). This team is taking a closer look at characterizing and refining the use of ballutes for future aerocapture missions.[5,6] The team includes experts from Ball Aerospace (system engineering, thermal, structures, control, and management), ILC Dover (inflatable structures), NASA Langley Research Center (aerothermodynamics and hypersonic performance verification and wind tunnel testing), and the Jet Propulsion Laboratory (trajectories, mission design, and instrumentation). Preliminary calculations have shown that Titan aerocapture ballutes could be constructed using existing materials such as Kapton or Upilex. These large, lightweight inflatable structures would provide a significant mass savings over traditional all-propulsive vehicles. A ballute even provides a significant mass saving when compared to aerocapture using an aeroshell. The mass savings are even larger if the aeroshell design includes a special transfer stage to provide power and attitude control during cruise. In addition to the low additional mass of the ballute for aerocapture, one of the fundamental benefits of carrying a ballute is that the primary spacecraft bus does not have to remain tightly packed inside the aeroshell during cruise, but can be deployed and flown like an orbiter during the long cruise phase from Earth to Neptune.

All propulsive capture requires that the spacecraft must carry all of the propellant needed for the mission. For low altitude orbiters, the mass of the propellant for a traditional all propulsive spacecraft becomes so large that the useful science payload becomes too small to be cost effective. In some cases, such as missions to Titan and Neptune, it may not be possible to conduct an orbital mission without aerocapture and/or other advanced propulsion technologies. One alternative for reducing the amount of propellant that must be carried is to use atmospheric drag to provide the velocity change required to capture into orbit..

A. Ballute Aerocapture Basics: High Drag, Low Heating

The traditional aerocapture approach is to pack the spacecraft tightly inside a protective aeroshell and dive deep into the atmosphere, where the heat shield must provide protection against the extremely large heating rates that will

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be encountered. It is easy to make the mistake of assuming that high heating is an unavoidable fact of life for all forms of aerocapture. High heating is not inevitable for aerocapture when a large ballute is used to supply the drag.

Imagine the approach used for aerobraking, where the spacecraft is so high in the atmosphere that the heating rate is tolerable even for an unprotected spacecraft. For a given initial entry orbit, if the area of such a high altitude spacecraft is increased, the amount of drag force on the spacecraft increases, but the heating per unit area remains relatively constant. The ballute concept takes this idea to the limit by dramatically increasing the area of the spacecraft. Enough drag is produced by the very large area of the ballute to remove the energy required to capture into orbit in a single pass through the atmosphere, while the vehicle remains high in the atmosphere where the heating rates are relatively low. Assuming that the entry velocity is determined by the interplanetary trajectory, the heating rate is primarily a function of the atmospheric density, but the drag force is a function of both the density and the projected frontal area. The ballute system can be designed so that an unprotected spacecraft could survive the aerocapture heating rates if the drag-producing area is made large enough. If the thermal limits are set at about 500°C by the thin film Ballute material, such as Kapton, then the spacecraft bus would require a thin thermal blanket to protect the exposed surface during the peak heating pulse. If the thermal limits are set low enough for an unblanketed spacecraft, then a much larger ballute is needed. The system design of the specific project would have to balance the size and mass of the ballute against the mass of the thermal protection and mission objectives of the primary spacecraft to optimize the design.

B. Ballute Team History

The work described in this paper is a very small part of a much larger on-going effort to increase the Technical Readiness Level of ballute technology. The team was formed in the last quarter of 2000 by Kevin Miller (Ball Aerospace) for a proposal to the Gossamer program. The team was a consortium of individual specialists from Industry, Academia, and NASA. Ball Aerospace has been studying the spacecraft system, including thermal analysis, structures, control, and mass budgets. Dick Wilmoth at NASA Langley was the coinvestigator in charge of computing the flow field around the ballute/spacecraft system. Peter Gnoffo took the lead on the computational flow analysis when Dick retired. Professor Jim McDaniel was subcontracted through Langley to perform wind tunnel tests in a special facility he runs at the University of Virginia. Ballute models are also being tested in the NASA Langley ?? and CF4 wind tunnels. Jim Stein is leading a materials test and fabrication study at ILC Dover to evaluate various candidate ballute materials and construction techniques. The focus of the study for the Gossamer program was for aerocapture at Mars using a towed ballute. Although the Gossamer program was phased out, the team was able to win an award for the In Space Propulsion program to study aerocapture at Titan and Neptune. Titan aerocapture using a trailing ballute concept was studied extensively in 2003[7]. The In Space Propulsion program funded a second study of an attached ballute concept in 2003, however, budget uncertainties delayed the start of that study until this year. The co-principal Investigator for the attached ballute study is Jim Masciarelli. The current emphasis is to bring the attached ballute concept to the same level as the trailing ballute study by the end of the 2004 fiscal year. Although ballute technology is in constant danger of "infant mortality" when competing for funding against technology that has a more immediate payoff, the impressive progress that has been made by our team has been enough to keep ballute technology development alive.

II. Neptune Results

The trajectories described in this paper are a very preliminary analysis that will be used to size the ballute that will be used for more detailed analysis. A simple ballistic transfer from Earth to Neptune was used to characterize the arrival $V_{infinity}$ that might be reasonably expected at Neptune. Then a series of ballute aerocapture trajectories were generated for several different values of ballute area for a range of arrival $V_{infinities}$ (entry speeds) that spanned range of probable values. An aeroshell aerocapture study for Neptune[?] that was conducted by the In Space Propulsion Program provided a starting mission scenario, including the final target orbit parameters.

C. Arrival $V_{infinity}$ Characterization

Figure 1 shows the arrival $V_{infinity}$ (the lower, red curve) and the launch $V_{infinity}$ (upper blue "stalactites") versus the flight time in years for an arbitrary fixed arrival date of Dec. 29, 2049. Although the aeroshell reference mission was based on a low thrust trajectory with gravity assists from the inner planets, the arrival $V_{infinity}$ will be in the same range as the ballistic trajectory – especially if the last flyby is at Earth, rather than Venus – but the flight time will be several years longer than for the purely ballistic trajectory shown here. The figure shows that really short flight times have very high arrival speeds. Similarly, extremely long flight times can reduce the arrival $V_{infinity}$ to about 4 km/sec. Unfortunately, extremely long flight times drive up the operations cost for the mission, while extremely short flight times result in extremely high heating, so the design goal is to find the appropriate design point that will minimize the total cost of the mission.

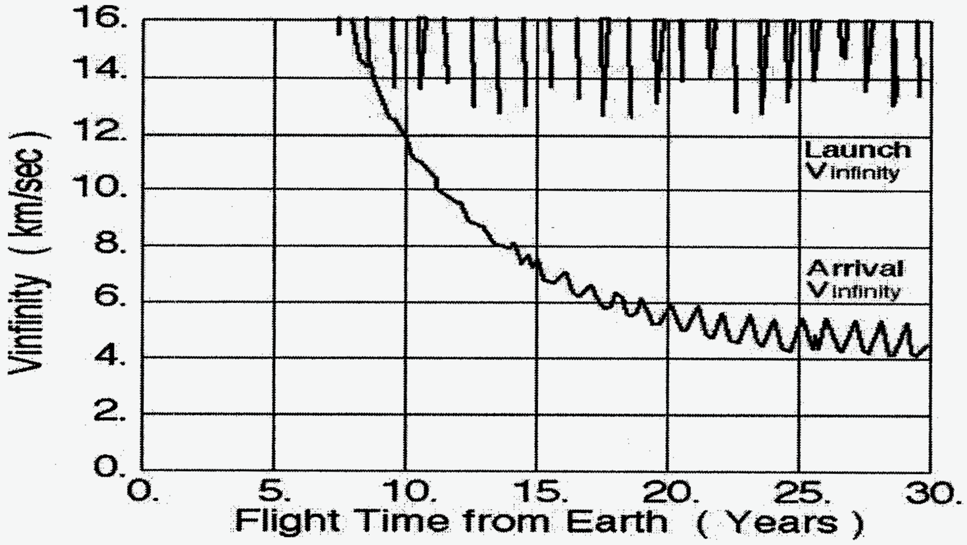


Figure 1. Launch and Arrival $V_{infinity}$ versus Flight Time for a fixed Arrival Date.

Figure 2 shows the "Entry" Speed versus the Arrival $V_{infinity}$. Two curves are shown for two different reference altitudes. The 1000 km reference altitude is believed to represent the entry altitude used in the aeroshell analysis. The 4000 km altitude is the highest altitude for which the density is defined in the NeptuneGRAM atmospheric model that was developed by Jere Justus for the Neptune aeroshell study that was sponsored by the In Space Propulsion Program. The ballute team will pick an altitude between these two values to use as the "Entry Altitude" for the ballute mission. Later discussion will show that 4000 km is well above the altitude at which drag becomes a factor for ballute entry, but that 1000 km is a little below the point where noticeable drag begins. Some of the later figures reference entry to 4000 km because we didn't know what value would be best for ballute aerocapture at the time the figures were generated. Using the arrival $V_{infinity}$ as the reference quantity eliminates the confusion associated with picking a particular entry altitude.

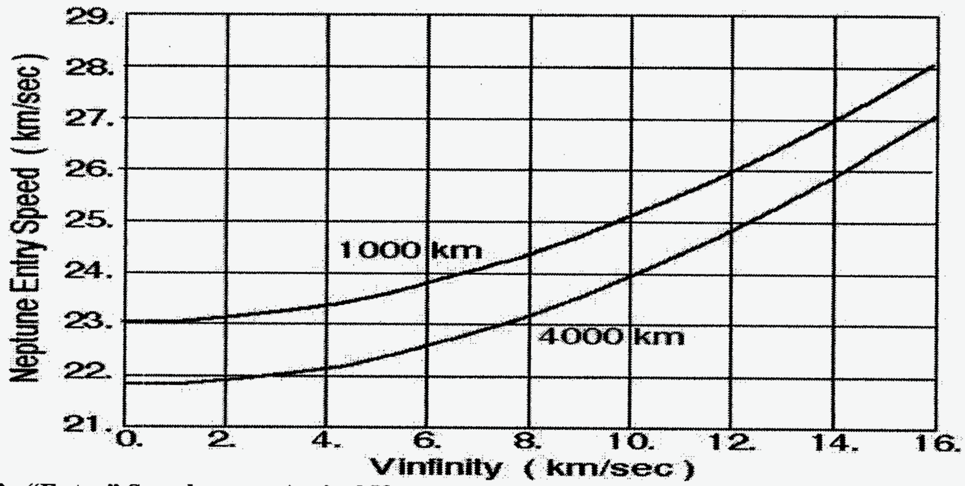


Figure 2. "Entry" Speed versus Arrival $V_{infinity}$

The aeroshell reference mission targeted a highly eccentric final orbit with an apoapsis altitude of 430,000 km. The eccentric orbit was selected to provide close, periodic flybys of the moon Triton. Since the energy of the target orbit at atmospheric exit is nearly constant, the spacecraft must leave the atmosphere with a particular speed for all cases. The entry speed at that reference altitude is determined by the arrival $V_{infinity}$. The difference between the entry and exit speeds at a given reference altitude represents the change in speed that was caused by atmospheric drag. Figure 3 shows that for the lowest arrival $V_{infinity}$ under consideration (4 km/s), a change of only 1 km/sec is needed to capture into the desired orbit, while a 6 km/s change is required for an arrival $V_{infinity}$ of 16 km/s.

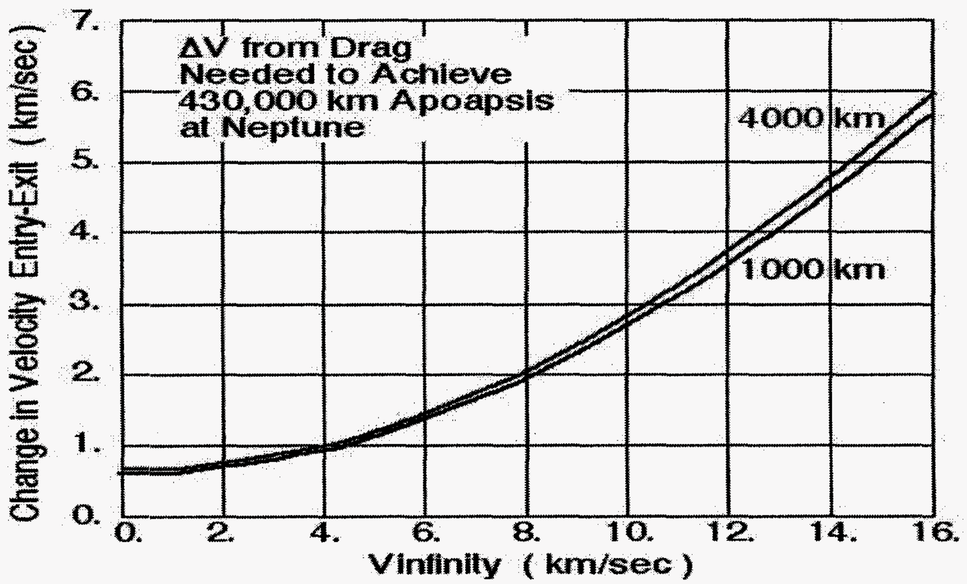


Figure 3. Change in Velocity to Achieve 430,000 km Apoapsis vs Arrival $V_{infinity}$

Based on the ballistic transfer from Earth to Neptune, arrival $V_{infinities}$ between 4 and 16 km/s were selected for evaluation as part of the ballute study. $V_{infinity}$ = 4 km/sec requires an extremely long transfer time from Earth to Neptune! $V_{infinity}$ = 16 km/sec represents such a short transfer time, that the departure $V_{infinity}$ becomes extremely high for the ballistic transfer. The low-thrust baseline developed for the aeroshell study has an arrival $V_{infinity}$ similar to that at the high end of the range studied, although the aeroshell used a low-thrust vehicle and several gravity assists from the inner planets to minimize the launch costs. A ballistic transfer from Earth to Neptune with the same 10 year cruise duration as the low-thrust aeroshell trajectory would have a lower arrival speed ($V_{infinity} \approx 12$ km/sec rather than 16 km/sec), but would require a larger launch vehicle for the same payload.

III. Ballute Entry Trajectory Simulations.

The preliminary ballute entry trajectory simulations used the following parameters. The entry mass was 500 kg for all cases to make it easier to compare to the preliminary analysis that was run at Titan. Most cases use an area of 1477 m^2, because the first guess at a possible entry speed needed this area to achieve a reasonable heating rate. Two other areas (750 m^2 & 3000 m^2) are evaluated to show the sensitivity of the trajectory to other areas for the same entry mass. A constant drag coefficient = 1.37 was used for the ballute, because this was a reasonable value to use at Titan. Note that the detailed flowfield analysis by the NASA Langley flow computations shows that both the size and configuration of the ballute system, as well as the instantaneous Reynolds and Knuden numbers play an important role in the actual drag coefficient. The ballute never separates in these preliminary trajectories, so the S/C C_D is not an issue, although it will be for the coming more detailed analyses. The Target Apoapsis = 430,000 km (from the aeroshell study) is achieved by searching for the periapsis altitude of approach hyperbola that results in a trajectory with an osculating apoapsis altitude at atmospheric exit equal to the target value.

Figure 4 shows the maximum Qdot (0.5 Rho•V^3, W/cm^2) versus arrival $V_{infinity}$ (lower curve). Qdot increases rapidly as the arrival $V_{infinity}$ is increased. Plotted on the same graph is the "Entry" speed in (km/sec – using the numerical Y-axis) at a reference altitude of 4000 km (upper curve). Later plots will show that the reference altitude should be less than 4000 km, but that was unknown at the time this figure was generated.

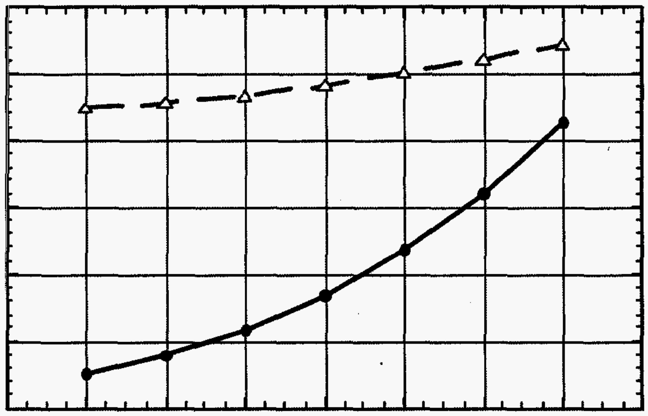


Figure 4. Maximum Qdot versus Arrival $V_{infinity}$

At least 3 different heating rates are needed to characterize ballute aerocapture with a towed ballute configuration because there are three different characteristic sizes. The Qdot shown in Figure 4 is appropriate for nearly free molecular flow, which is the case for the thin tethers that would be used to connect the large inflated towed ballute with the main spacecraft. Although the inflated ballute is flying through the same atmosphere as the rest of the spacecraft, the ballute is orders of magnitude larger than the tether, and can reach conditions that are best characterized by continuum flow approximations where the heating is proportional to the square root of the density rather than than the density itself. The characteristic size of the spacecraft is in between these extremes, and so is the heating.

Figure 5 shows the Maximum Qdot (W/cm^2) versus arrival $V_{infinity}$ for several ballute sizes. Figure 6 shows the same data plotted versus "Entry" speed for a 4000 km reference altitude. Doubling the area essentially cuts Qdot in half. Halving the area doubles Qdot.

Figure 7 shows Qdot as a function of time since the start of the simulation. Since the initial state is outside of the atmosphere, nothing "interesting" happens before about 700 sec, so the x-axis has been scaled to show the region of interest. All of these trajectories are for initial conditions which have been independently targeted for each case such that each case exits the atmosphere with a 430,000 km apoapsis altitude without releasing the ballute. Thus the maximum Qdot occurs near periapsis for each case. Once a ballute size is selected, the nominal entry trajectory will be targeted lower in the atmosphere to accommodate Navigation and atmospheric uncertainties, and the peak Qdot will increase and move earlier. The maximum values from this data were plotted in Figures 4-6.

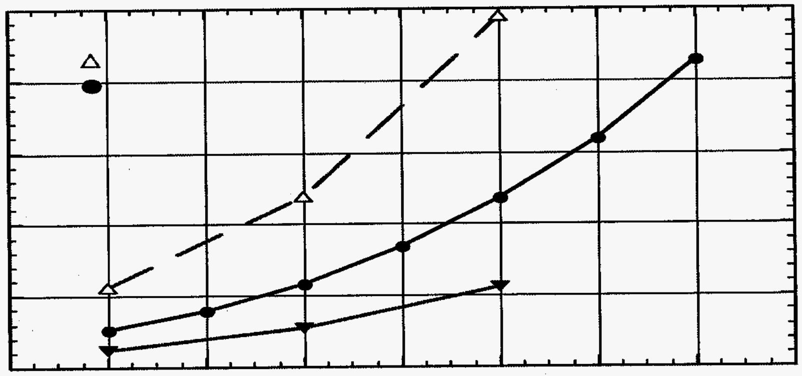


Figure 5. Maximum Qdot versus $V_{infinity}$ for Three Ballute Sizes.

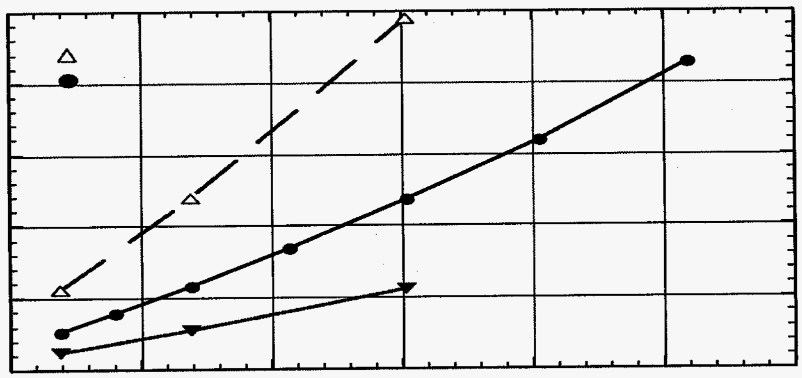
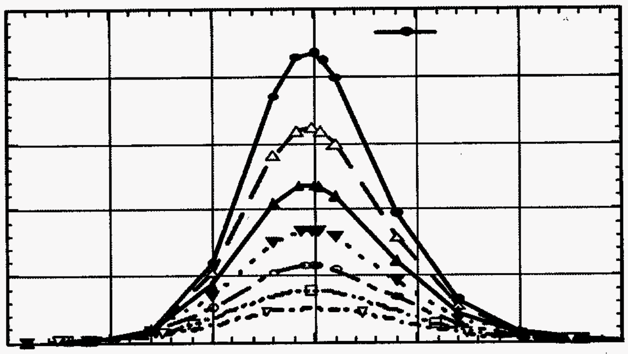


Figure 6. Maximum Qdot versus "Entry" Speed at 4000 km

In the legend,
Smaller speed is Vinfinity
Larger speed is at 4000 km.



Time History of Qdot for various Arrival Vinfinities . Maximum Qdot is near periapsis , because targeted to achieve 430,000 km without releasing the ballute .

Figure 7. Qdot versus Time for Range of Arrival $V_{infinities}$

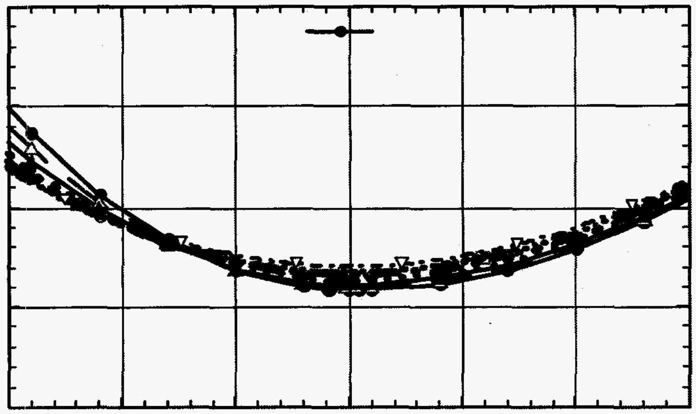
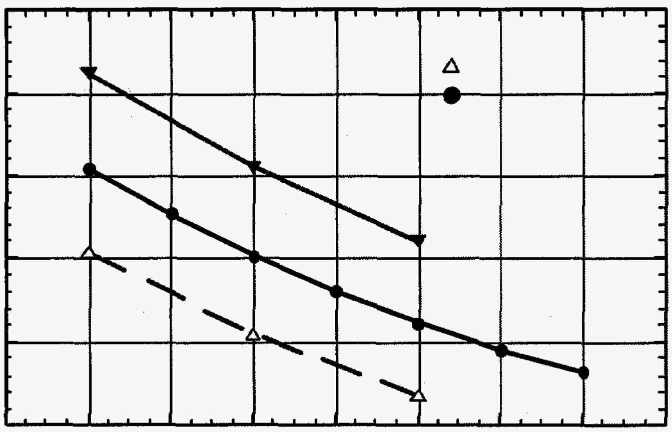


Figure 8. Altitude versus Time for a Range of Arrival $V_{infinities}$

Figure 8 shows the altitude versus time since the start of the simulation. Comparing Figure 7 & 8 shows that observable heating, where the Qdot values are distinguishable from zero in Figure 7 begins at an altitude of about 1200 km. Thus a good definition of "Entry" for the ballute cases would be about 1500 km.

Figure 9 shows the periapsis altitude versus Arrival $V_{infinity}$. Faster arrival speeds and/or smaller ballute areas require the trajectory to be targeted lower in the atmosphere (equivalent to a steeper entry angle of attack). Each of the trajectories described in this section required an iterative search to find the periapsis altitude that resulted in achieving the target apoapsis altitude at atmospheric exit (without releasing the ballute) for the specified approach $V_{infinity}$.

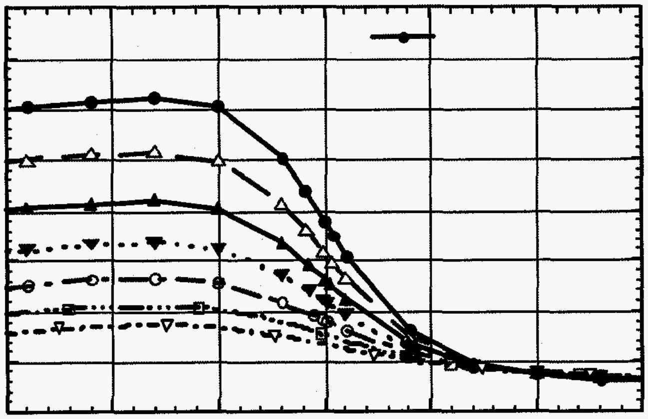


Smaller Area means target deeper in the atmosphere to get enough drag.

Figure 9. Periapsis Altitude versus Arrival $V_{infinity}$ for several Ballute Areas

Figures 10 and 11 show the time history of the velocity and deceleration of the cases for the 1477 m^2 ballute area. Higher arrival $V_{infinity}$ means higher speed at entry. Achieving a specific target apoapsis altitude at exit means that all trajectories exit the atmosphere at the same speed. Larger entry speeds require a larger change in velocity while in the atmosphere which results in higher heating for a given ballute size. Although the deceleration levels are higher for the faster entry speeds, the highest entry speed under consideration has a g-load of only 3.5 g's which is actually less than the 4.5 g's that were considered acceptable as part of the Titan aerocapture study. The equivalent case for Titan, where the spacecraft achieves the target orbit without releasing the ballute, only has a g-load of about 3.0 g's, so the g-load will be higher than for these preliminary cases – once the arrival is targeted lower in the atmosphere to accommodate Navigation and atmospheric uncertainties. In order for the maximum Qdot to be below 10 W/cm^2 for this 1477 m^2 ballute, the arrival $V_{infinity}$ must be below about 10 km/sec, which corresponds to a peak deceleration of only 1.5 g's in Figure 4.11. Thus deceleration g-loads are not the issue at Neptune.

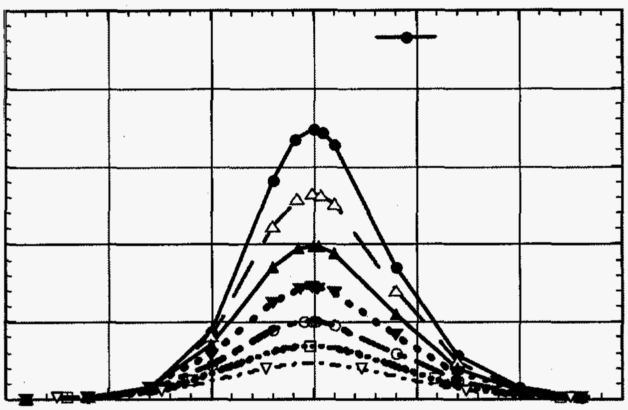
In the legend,
Smaller speed is Vinfinity
Larger speed is at 4000 km.



Larger Entry speed requires more velocity change, & higher heating.
All vehicles leave the atmosphere with the same speed.

Figure 10. Velocity versus Time for Range of Arrival $V_{infinity}$

In the legend,
Smaller speed is Vinfinity
Larger speed is at 4000 km.



Larger Entry speed requires a Higher G-load, BUT these G-loads are NOT excessive. HEATING is the big issue at Neptune.

Figure 11. Deceleration versus Time for Range of Arrival $V_{infinity}$

In the legend,
Smaller speed is Vinfinity
Larger speed is at 4000 km.

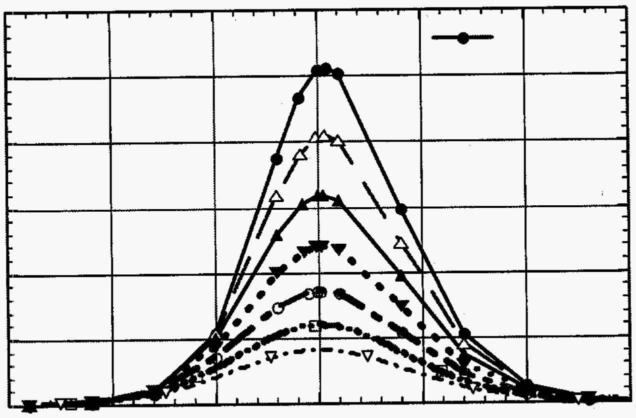
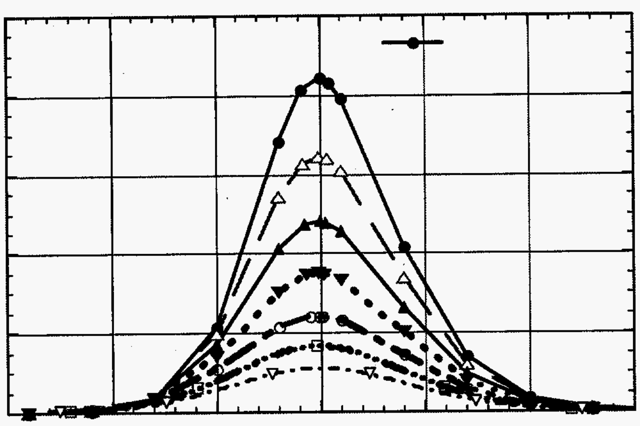


Figure 12. Atmospheric Density versus Time for a Range of Arrival $V_{infinities}$

Figure 12 shows the atmospheric density as a function of time for the 1477 m^2 cases. Higher entry speeds require trajectories that dive deeper into the atmosphere, so the maximum atmospheric densities are higher. Note that the density is a smooth function of time. Later studies will introduce "noisy" atmosphere models to evaluate performance in Monte Carlo studies.

In the legend,
Smaller speed is Vinfinity
Larger speed is at 4000 km.



Dynamic Pressures
Are less than for
Titan (at the same
Qdot), so Dynamic
Pressure is not a
Driver for Neptune.

Figure 13. Dynamic Pressure versus Time for a Range of Arrival $V_{infinities}$

Figure 13 shows the time history of the dynamic pressure. The dynamic pressure is typically less than for Titan entry, so a ballute system that was designed to withstand the dynamic pressures at Titan would also survive the pressure loads at Neptune.

IV. Conclusions

For ballute aerocapture at Neptune, heating is to be the limiting factor. Reasonable heating is possible for ballistic trajectories with long interplanetary flight times. The aeroshell reference study used low thrust interplanetary cruise with multiple planetary flybys to try to minimize flight time without regard to the entry speed. Since ballutes benefit from low entry speeds, searching for interplanetary trajectories that try to minimize both the flight time and the arrival speed will be required.

This paper has illustrated the very preliminary ballute aerocapture trajectories needed to size the ballute for Neptune. Previously reported Titan results[7] are more detailed because more resources were available. Similar results for Neptune will be available once the funding becomes available.

These preliminary trajectory results are part of a system wide trade study which indicate that ballutes appear to be a feasible option for aerocapture at Titan and Neptune. The mass of the ballute required to achieve temperatures that are survivable with only minimal thermal shielding of the spacecraft is significantly less than the mass of an aeroshell for the same system mass at atmospheric entry. A detailed mass comparison by the Ball team members showed that a ballute system mass is about 10% of the entry mass, while the equivalent aeroshell system mass is more than 40% of the entry mass for aerocapture at Titan. Ballute aerocapture systems have the potential to significantly increase the mass available for a scientific payload for a given mission to Titan or Neptune. The tremendous mass saving, coupled with very positive developments from the current ballute studies, make further investment in ballute technology highly desirable.

Acknowledgements

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