This presentation provides a review of those studies and a starting point for considering Aerocapture/Aerobraking technology as a way to reduce mass and cost, to achieve the ambitious science returns currently desired.

What is Aerocapture: is first of all a very rapid process, requiring a heavy heat shield resulting in high g-forces. Descent into a relatively dense atmosphere is sufficiently rapid that the deceleration causes severe heating requiring.

What is Aerobraking: is a very gradual process that has the advantage that small reductions in spacecraft velocity are achieved by drag of the solar arrays in the outer atmosphere, thus no additional mass for a heat shield is necessary. an aeroshell.
### Aerocapture vs Aerobraking

**Aerocapture**
- Uses very little fuel—significant mass savings for larger vehicles
- Establishes orbit quickly (single pass)
- No turning back, much like a lander
- Has high heritage in prior hypersonic entry vehicles
- Fully dependent on flight software
- Flies in mid-atmosphere where dispersions are lower
- Adaptive guidance adjusts to day-of-entry conditions
- Fully autonomous so not distance-limited

**Aerobraking**
- Needs protective aeroshell
- One-shot maneuver; no turning back, much like a lander
- Fully dependent on flight software
- Flies in mid-atmosphere where dispersions are lower
- Adaptive guidance adjusts to day-of-entry conditions
- Fully autonomous so not distance-limited

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tr>
<td>Little spacecraft design impact</td>
<td>Still need ~1/2 propulsive fuel load</td>
</tr>
<tr>
<td>Gradual adjustments; can pause and resume as needed (with fuel)</td>
<td>Hundreds of passes = more chance of failure</td>
</tr>
<tr>
<td>Operators make decisions</td>
<td>Months to start science</td>
</tr>
<tr>
<td>Operational distance limited by light time (lag)</td>
<td>At mercy of highly variable upper atmosphere</td>
</tr>
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**Pros**
- Energies dissipation
- Autonomous guidance
- Controlled exit

**Cons**
- Target orbit
- Periapsis raise maneuver (propulsive)
- Atmospheric entry
- Hyperbolic approach
- ~300 Passes through upper atmosphere

**Key Terms**
- Periapsis raise maneuver (propulsive)
- Atmospheric entry
- Controlled exit
- Target orbit
- Hyperbolic approach
- Orbit Insertion Burn
- Entry targeting burn
- Atmospheric Drag Reduces Orbit Period

**Diagram Notes**
- Atmospheric Drag Reduces Orbit Period
- Hyperbolic Approach
- ~300 Passes through Upper Atmosphere
- Orbit Insertion Burn
- Entry Targeting Burn
- Atmospheric Entry
- Energy dissipation/Autonomous guidance
- Controlled exit
- Target orbit
- Jettison Aeroshell
- Adaptive guidance adjusts to day-of-entry conditions
- Fully autonomous so not distance-limited
Characteristics of Hypersonic flow around a blunt object (Mach 5-10)
Planets Atmospheric Density Comparison

![Graph showing the comparison of atmospheric density across different planets. The graph plots height in kilometers (km) on the y-axis against density in kilograms per cubic meter (kg/m³) on the x-axis. The graph includes lines for Earth, Neptune, Titan, Mars, and Venus, with labels indicating aerobraking and aerocapture densities.](image-url)
Aeroshell-Aerocapture Configuration

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Aeroshell-Aerobraking Configuration

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**Aeroshell-Aerobraking Configuration**

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## Aeroshell and Aerobrake Options

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Aeroshell and Aerobrake Options

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<td>High heating rates Large aeroshell mass Packing is difficult</td>
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Aeroshell Coordinate System
Aeroshell Concept
Aeroshell Ballute Concept
Aeroshell Design Parameters

- **L/D** – For a human Mars mission, a mid to high L/D is a necessity
  - .5<L/D<1.5 is a reasonable constraint
- **Volume and Volumetric Efficiency**
  - The need to transport a large volume of materials is critical to a human Mars mission. The aeroshell must be both volumetrically efficient and have a large volume payload
- **Structural Mass**
  - In order to launch a crew to Mars along with the necessary living conditions and supplies, the aeroshell must have the lowest structural mass possible.
- **Heating rates**
  - Although a high L/D configuration makes certain conditions better for the vehicle and its contents, it also creates certain problems. The vehicle heating rate is inversely proportional to its coefficient of drag which in turns determines the L/D.
- **Simplicity and Reliability**
  - The simplicity and reliability of the aeroshell for a human mission is especially significant. Consequently, aerobrake or aeroshell designs which rely on elements that must be constructed in space or deployed are disadvantageous. Instead an optimal choice is that system that has the ability to be packed both internally, with cargo and available space for a transfer vehicle, and externally so it can be launched from earth’s surface.
Aerodynamic Coefficient vs. Angle of attack
SYMERIC MATLAB

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MATLAB Graphs

Altitude, y, km

Freestream or vehicle velocity, V, km/s

$T_2 = 6,000 \text{ K}$

$T_2 = 8,000 \text{ K}$

$T_2 = 10,000 \text{ K}$

$T_2 = 12,000 \text{ K}$

$T_2 = 14,000 \text{ K}$

$T_2 = 16,000 \text{ K}$

$T_2 = \text{Shock layer temperature}$
MATLAB Graphs

Angle of attack, $\alpha$, degrees

L/D

Drag Coefficient

Lift Coefficient

$M >> 1$
MATLAB Graphs

Drag coefficient, $C_D$

Cone semivertex angle, $\theta_C$, deg

15
1
0.5
0.2
0.1
0
0

Nose radius/base radius, $r_N/r_B$

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Aeroshell Design Constraints and Selected Design Point

<table>
<thead>
<tr>
<th>Design Parameter</th>
<th>Symbol</th>
<th>Minimum</th>
<th>Maximum Acceptable</th>
<th>Selected Design Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forward Cone Angle</td>
<td>(δ1)</td>
<td>10°</td>
<td>25°</td>
<td>16°</td>
</tr>
<tr>
<td>Rear Cone Angle</td>
<td>(δ2)</td>
<td>&gt;0°</td>
<td>(δ1)</td>
<td>4°</td>
</tr>
<tr>
<td>Nose Radius</td>
<td>(Rn)</td>
<td>.25m</td>
<td>1.5m</td>
<td>1.0m</td>
</tr>
<tr>
<td>Base Radius</td>
<td>(Rb)</td>
<td>N/A</td>
<td>2.5m</td>
<td>2.3m</td>
</tr>
<tr>
<td>Intermediate base Radius</td>
<td>(Rb1)</td>
<td>Rn</td>
<td>Rb</td>
<td>2.0m</td>
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### Aeroshell Performance at Selected Design Point

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<th>Performance Parameter</th>
<th>Symbol</th>
<th>Relation to design parameters</th>
<th>Performance at Design Point</th>
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<tr>
<td>Lift to Drag Ratio</td>
<td>L/D</td>
<td>$F(\delta_1, \delta_2, R_n)$</td>
<td>0.6 (A/C), 0.5 (Lander)</td>
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<tr>
<td>Drag Coefficient</td>
<td>$C_D$</td>
<td>$F(\delta_1, \delta_2, R_n)$</td>
<td>0.28(A/C); 0.38 (Lander)</td>
</tr>
<tr>
<td>Ballistic Coefficient</td>
<td>$C_\beta$</td>
<td>$F(W, \delta_1, \delta_2, R_n)$</td>
<td>522Kg/m² (A/C);</td>
</tr>
<tr>
<td>Max Heating rate</td>
<td>$q_{omax}$</td>
<td>$F(v, R_n, C_\beta)$</td>
<td>20 W/cm² (A/C); 60 W/cm² (Lander)</td>
</tr>
<tr>
<td>Total integrated heating</td>
<td>$Q_0$</td>
<td>$F(L/D, \delta_1, \delta_2, R_n)$</td>
<td>6kJ/cm² (A/C); 33 kJ/cm² (Lander)</td>
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Aeroshell Design Shape Selection

- As the nose radius increases, drag increases, which lowers L/D, shortens the trajectory (aerocapture or descent) and thus lowers the total integrated heating.
- As the forward cone angle increases, L/D decreases but volumetric efficiency improves.
- The nose radius must be large enough to avoid adverse heating and high enough $C_D$ and small enough to keep L/D within acceptable range.
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Inflatable Aerodecelerators

- Inflatable Aeroshell
- Ballutes
- Hypercones
Aerodecelators

- Hypersonic entry vehicles might also be reduced by constructing very large inflatable aerodecelators
  - Inflatable aeroshell provide a low-volume, low mass modular alternative to the rigid aeroshell
  - Permits larger sizes to be deployed
  - Will result in higher thermal & safety constraints
Inflatable Aeroshell

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Inflatable Aeroshell
Navigation Landing Capsule

- Inflatable Aeroshell Concept
  - Testbed to larger Lander/Crew Modules
  1. Parachute
  2. Engines For Soft Landing
  3. Solid Deboost-Engine
  4. Scientific and Service Systems
  5. Thermal Insulation
  6. Engines For Orientation
  7. Inflatable Structure (Silicone coated Kevlar Fabric and Kapton to act as a gas barrier)
  8. Propellant Tank
Toroid Aeroshell Cross-Section

- Aeroshell Loads
  1. Toroid Fabric Loads
  2. Spar Fabric Loads
  3. Restraint Wrap Loads

\[
N_{\text{MAX}} = \frac{PD_T}{4} \left[ 2 + \frac{D_T}{D_c} \right]
\]

\[
N_{\text{MAX}} = \frac{PW_s}{2} \left[ 1 + \frac{1}{1 - \frac{H_s \cos(\alpha)}{D_c + D_T + W_s \sin(\alpha)}} \right] \approx PW_s
\]

\[
N_{\text{MAX}} = \frac{m_c \alpha}{2\pi D_c \cos(\alpha)}
\]
Attachable Inflatable Aeroshell

Inflatable Aeroshell Cross-Section

1. Inflation Subsystems/Propulsion Tanks
2. Inflatable Toroids are laced together and contained within a restraint wrap
3. Restraint Wrap (dry Kevlar fabric for structural loads, layers of Nextel cloth for thermal protection and Kapton layers to act as gas barrier)
4. Parachute
5. Engines for Soft Landing
6. Solid Deboosy Engines
7. Thermal insulation
8. Structure
Hypercone
Inflatable Hypercone
Inflatable Hypercone
Hypercone

- Donut-shape Hypercone would be 30-40 meters in diameter
  - Inflatable supersonic decelerator-only CGI –would decelerate the vehicle to Mach 1
  - Acts as an aerodynamic anchor –Inflation would occur at an altitude of ten kilometers while the vehicle is traveling at Mach 4 or 5
  - Intended to supplement other deceleration mechanisms
Inflatable Ballute
Inflatable Ballute
Inflatable Ballute
Ballutes-Ultra Lightweight Ballute (ULWB)

- A Deceleration solution similar to the Hypercone
  - The large drag area of the ballute enables the vehicle to decelerate even in a Martian atmosphere and it allows more payload to be carried by the vehicle because of its lightweight construction.
Inflatable Aeroshell & Ballutes-Ultra Lightweight Ballute (ULWB) Combo
Ballute = Balloon + Parachute Concept
Pros & Cons

- Spar with Rim Inflatable Baseline Configuration
  - Pros: Efficient Structure; Efficient gas usage; Good Heat Transfer; Potential for Shape-morphing; Inflatable Components Thermally Protected
  - Cons: Surface Deflection-Assessed in Guidance Analysis-Minimal; Cross-flow Wavy-Minimal impact

- Ribbed Double Surface Inflatable
  - Pros: Good Surface Control; Streamwise Smooth; Efficient material use
  - Cons: Manufacturing issues (joining/seaming; structural reinforcement); Inefficient use of inflation gas; cross-flow Wavy

- Single Surface Hypercone
  - Pros: Lightest weight structure; Efficient use of inflation gas; Good heat transfer
  - Cons: Concave shape causes adverse shock interaction and high local heating

- Inflatable Aeroshell
  - Pros: Good Structural Stability
  - Cons: Poor use of inflation gas; Difficult interfaces (Tube-Tube; inflation); poor heat transfer; poor shear stiffness
Challenges

- Maneuverability  Challenges with Ballute/Hypercone
  - One option is to use Drag Modulation as a method for controlling with a combination of Pneumatic Muscle Actuators (PMA) similar to Military applications
  - Built-in within each suspension lines, a PMA, a braided fiber tube that contracts in length and expands in diameter when pressurized, including a GPS receiver and a compass as navigation sensors, a guidance computer to determine and activate the desire control input for each PMA.
Biconical Crew/Cargo Lander

1. Landing Engines Bay 1
2. Ascent Module
3. Second Stage Ascent Vehicle
4. Landing Engines Bay 2
5. Horizontal Rudder
6. Living Module
7. Landing Gear
8. First Stage Ascent Vehicle
9. Ascent Module Bay
10. Vertical Rudder

1. Landing Engines Bay 1
2. Cargo Module
3. Landing Engines Bay 2
4. Horizontal Rudder
5. Cargo and Living Module
6. Landing Gear
7. Rover
8. Elevator
9. Bay to Race Rover
10. Vertical Rudder
DRM1 Biconic Aeroshell Dimensions for Mars Lander and Surface Habitat Modules
DRM3 Biconic Aeroshell Dimensions for Mars Habitat Module

10 m

7.5 m
Nomenclature

\[ A \] = reference area of entry vehicle
\[ a \] = acceleration
\[ C_D \] = drag coefficient
\[ C_L \] = lift coefficient
\[ D \] = drag
\[ g \] = acceleration of gravity
\[ h_\infty \] = freestream enthalpy
\[ L \] = lift
\[ m \] = vehicle mass
\[ R_o \] = planetary radius
\[ r_n \] = nose radius
\[ V \] = flight velocity (m/s)
\[ W \] = vehicle weight
\[ \alpha \] = angle of attack
\[ \gamma \] = flight path angle
\[ \Lambda \] = sweepback angle
\[ \rho \] = free stream density (kg/m\(^3\))
\[ \Delta \gamma_E \] = flight path entry angle
Major References

- http://ntrs.nasa.gov
- http://www.isunet.edu/