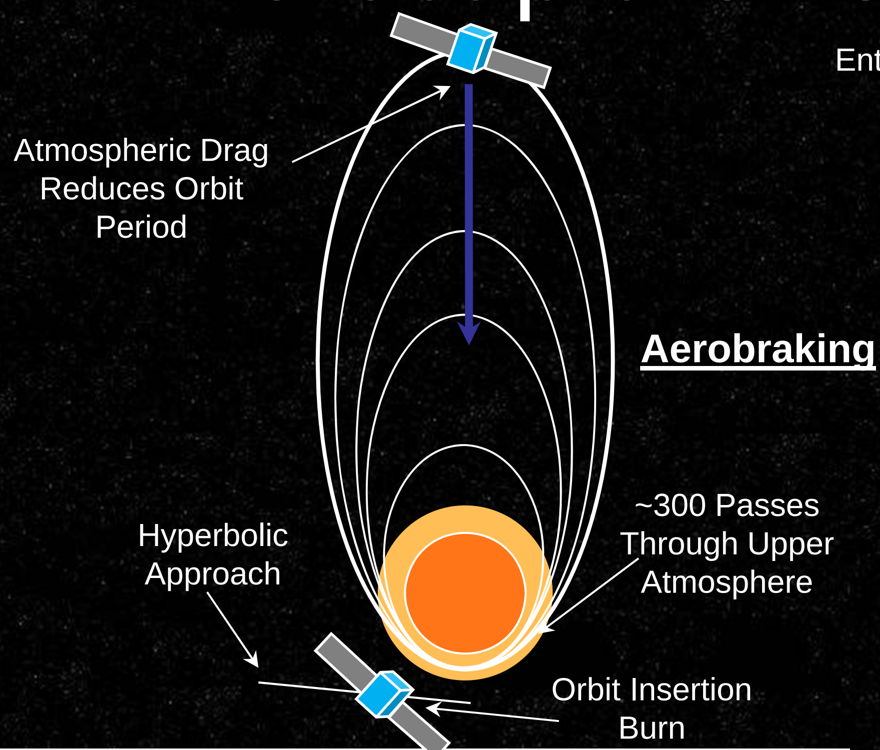
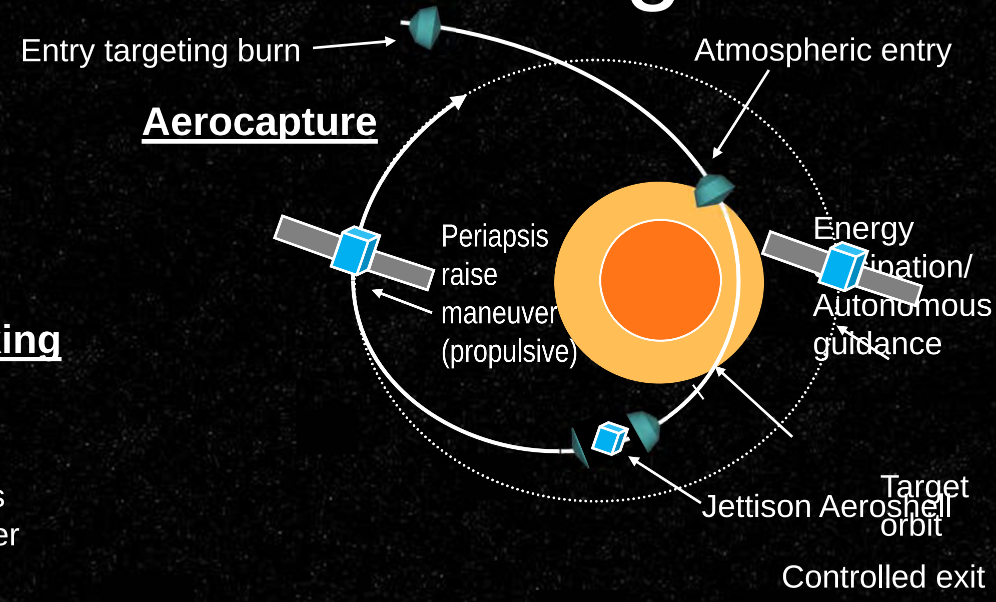
Mars Aerocapture/Aerobraking Aeroshell Configurations

by Abraham Chavez

- 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 suffciently 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

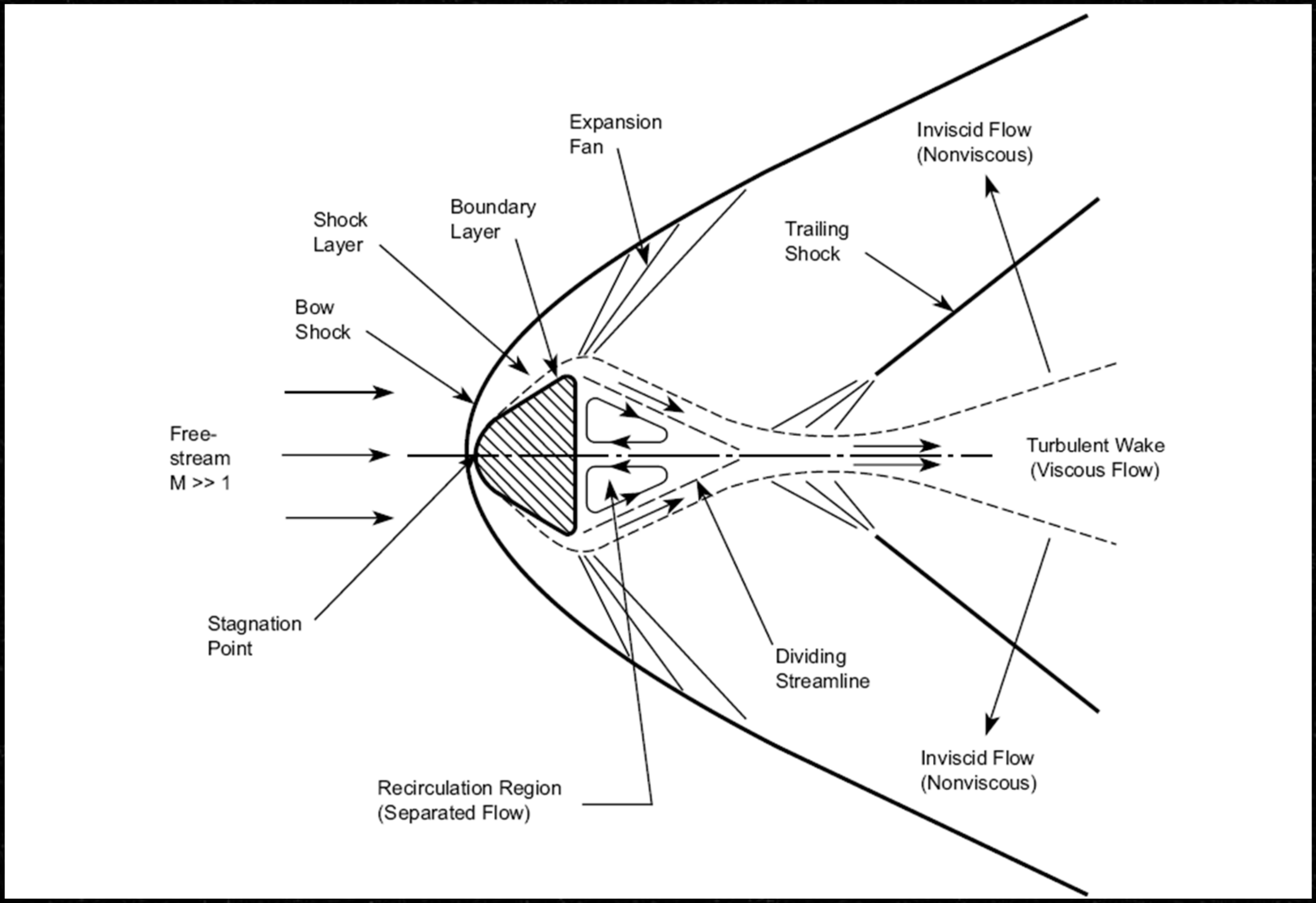




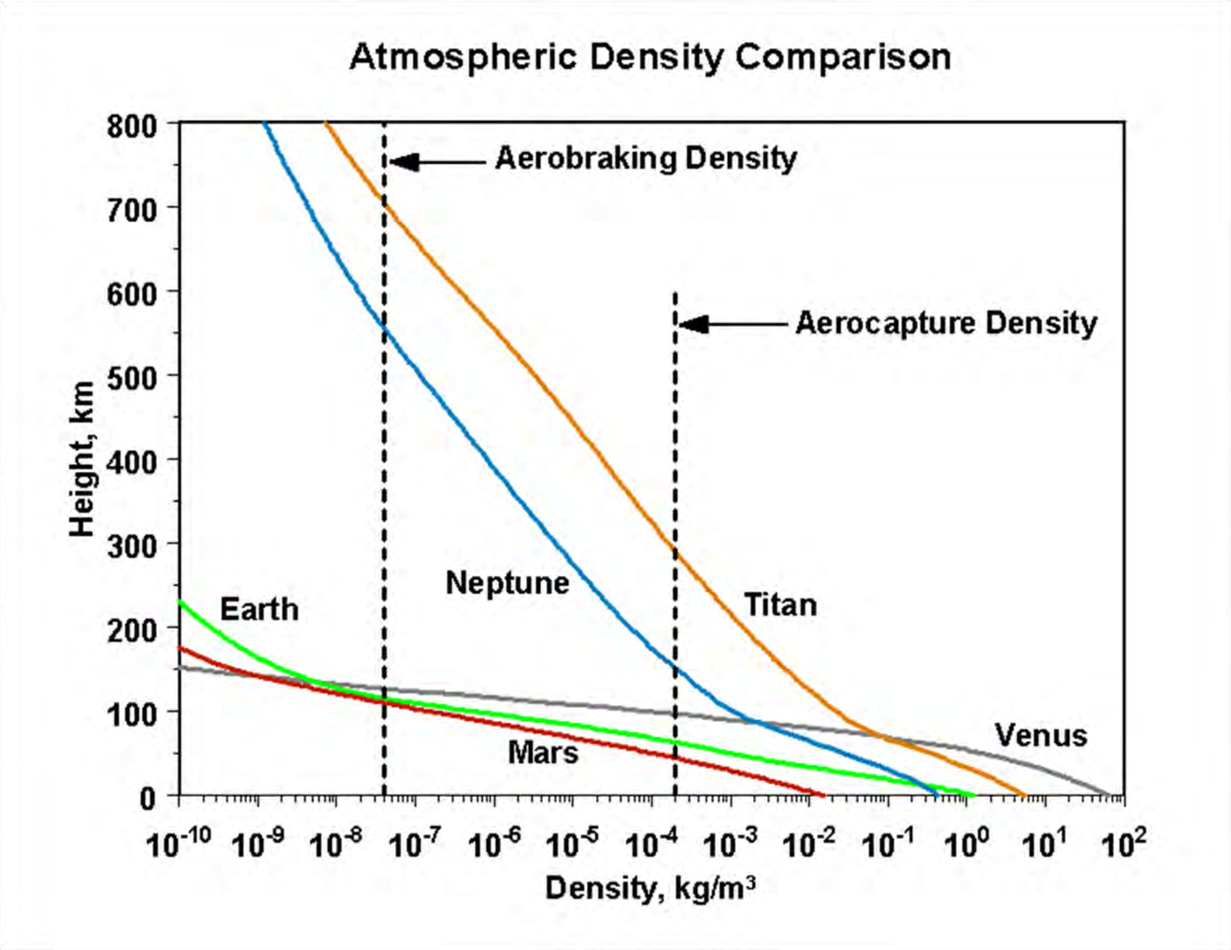
Pros	Cons
Little spacecraft design impact	Still need ~1/2 propulsive fuel load
Gradual adjustments; can pause and resume as needed (with fuel)	Hundreds of passes = more chance of failure
Operators make decisions	Months to start science
	Operational distance limited by light time (lag)
	At mercy of highly variable upper atmosphere

Pros	Cons
Uses very little fuel--significant mass savings for larger vehicles	Needs protective aeroshell
Establishes orbit quickly (single pass)	One-shot maneuver; 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	

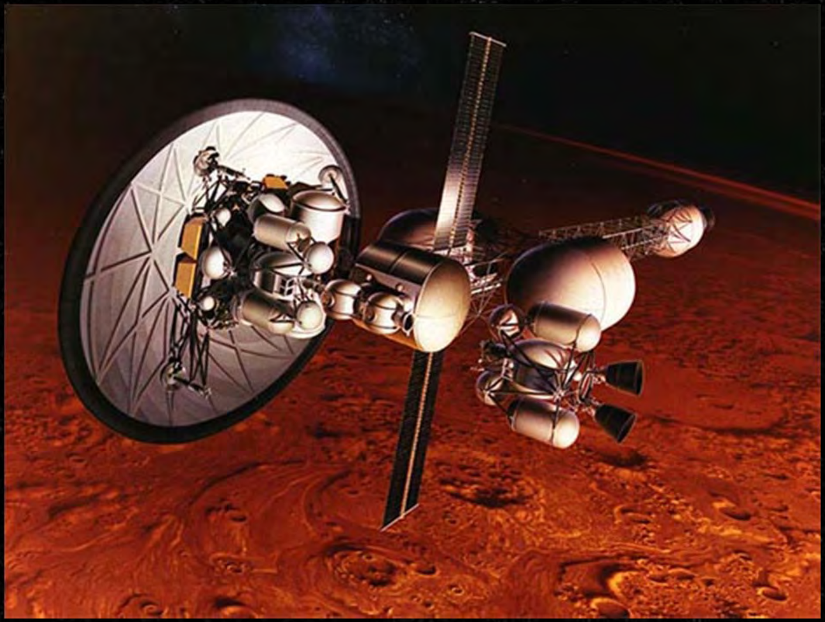
Characteristics of Hypersonic flow around a blunt object (Mach 5-10)

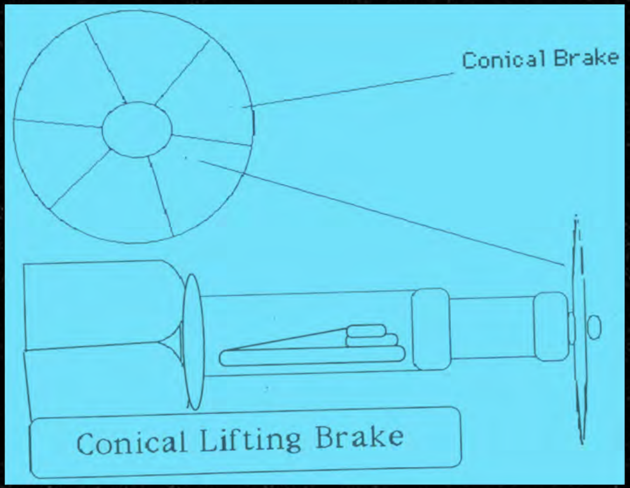


Planets Atmospheric Density Comparison



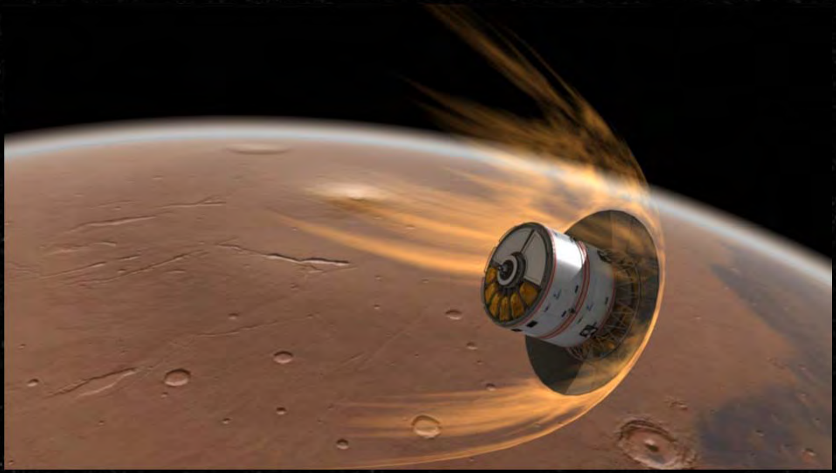
Aeroshell-Aerocapture Configuration

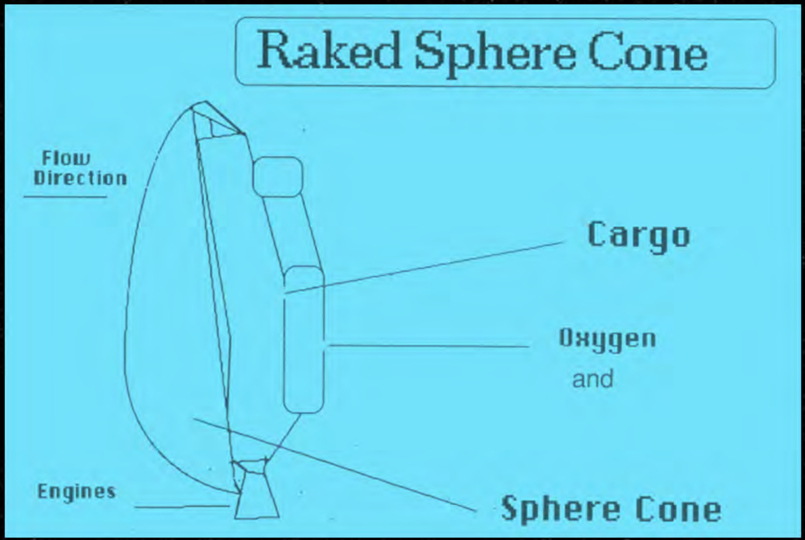




SHAPE	ADVANTAGES	DISADVANTAGES
Conical Lifting Brake	Low heating rates on all surfaces Low structural mass	Low L/D (.15-.30) Large structural volume/low cargo Complex and difficult to deploy

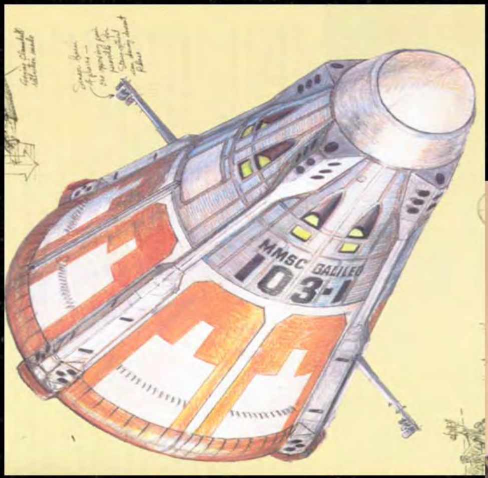
Aeroshell-Aerobraking Configuration

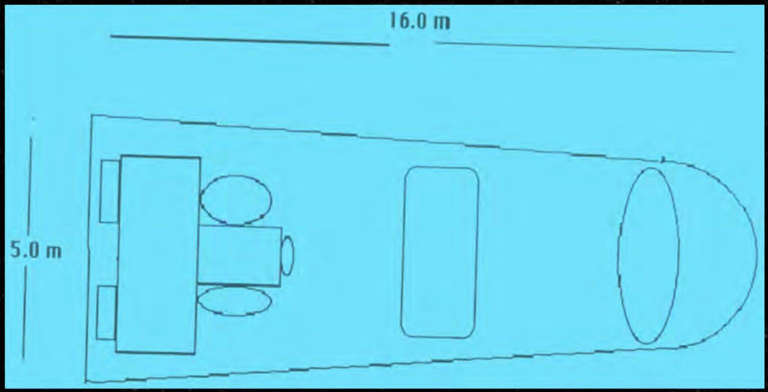




SHAPE	ADVANTAGES	DISADVANTAGES
Raked Sphere Cone	Low heating rates on all surfaces Low structural mass Some testing completed (AFE)	Medium L/D ratio (.25-.50) Large structural volume/low cargo Complex structurally

Aeroshell-Aerobraking Configuration



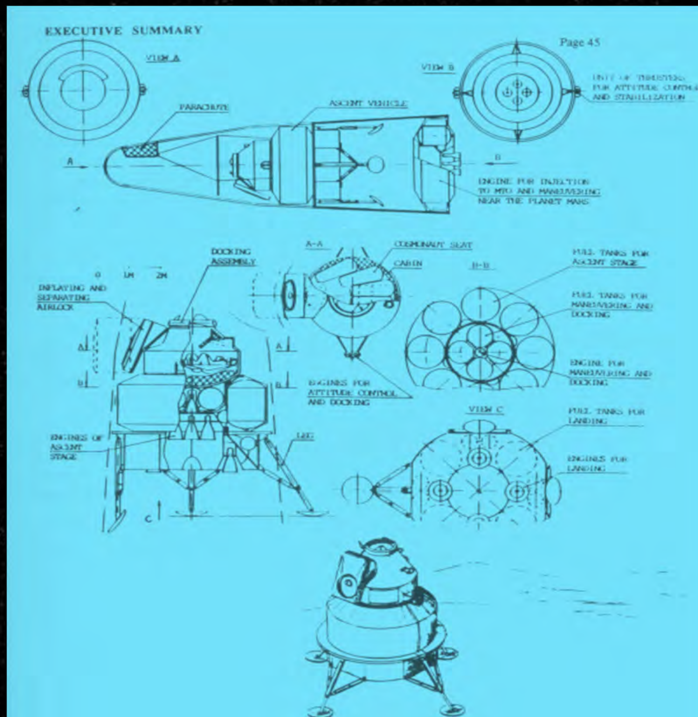


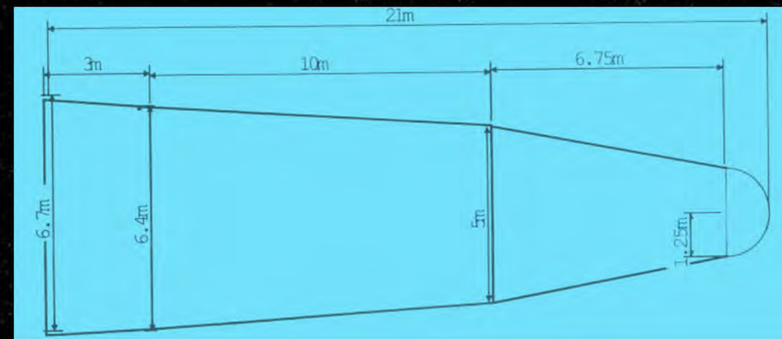
SHAPE	ADVANTAGES	DISADVANTAGES
Symmetric Conic	Moderate heating rates Moderate cargo volume Tested configuration/easy to deploy	Moderate L/D ratio (.50-.60) Moderately large aeroshell mass

Aeroshell-Aerobraking Configuration

SHAPE	ADVANTAGES	DISADVANTAGES
Symmetric Conic	Moderate heating rates Moderate cargo volume Tested configuration/easy to deploy	Moderate L/D ratio (.50-.60) Moderately large aeroshell mass

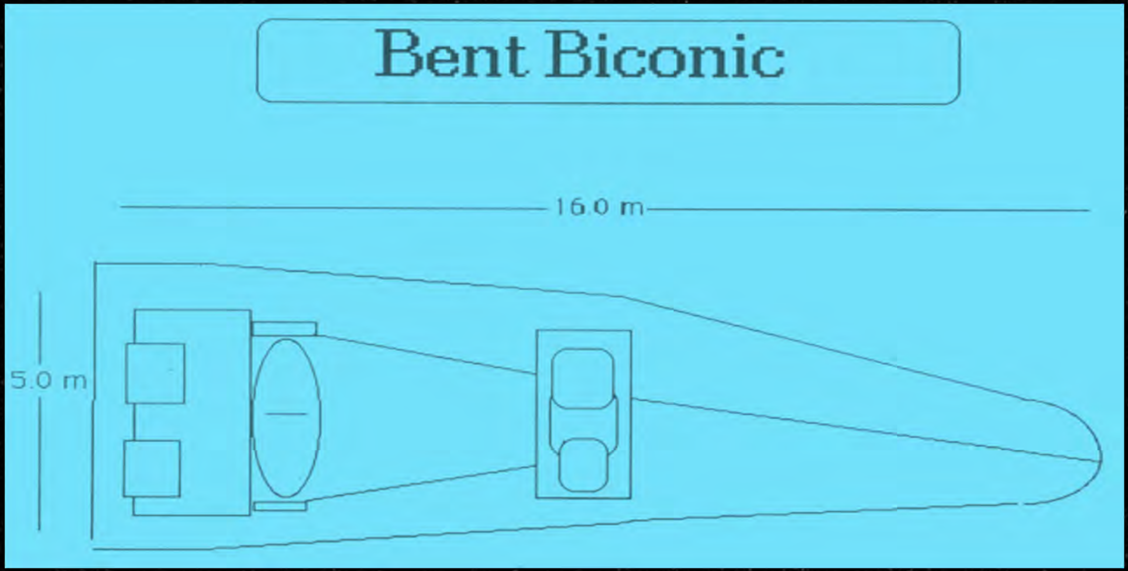
Aeroshell and Aerobrake Options





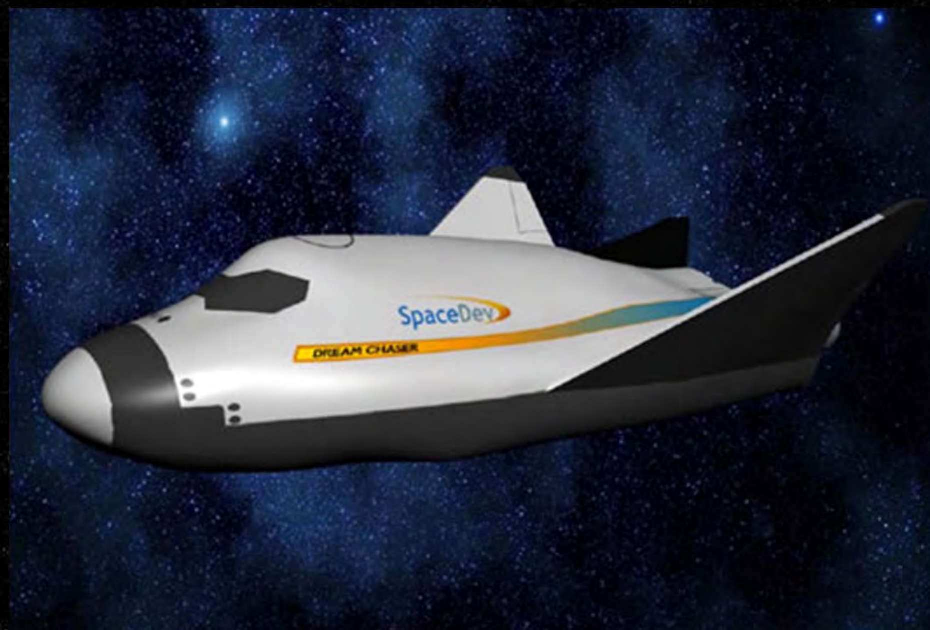
SHAPE	ADVANTAGES	DISADVANTAGES
Symmetric Biconic	Moderate heating rates Moderately high L/D ratio (.60-1.0) Large cargo volume Tested configuration/easy to deploy	Moderately large aeroshell mass

Aeroshell and Aerobrake Options



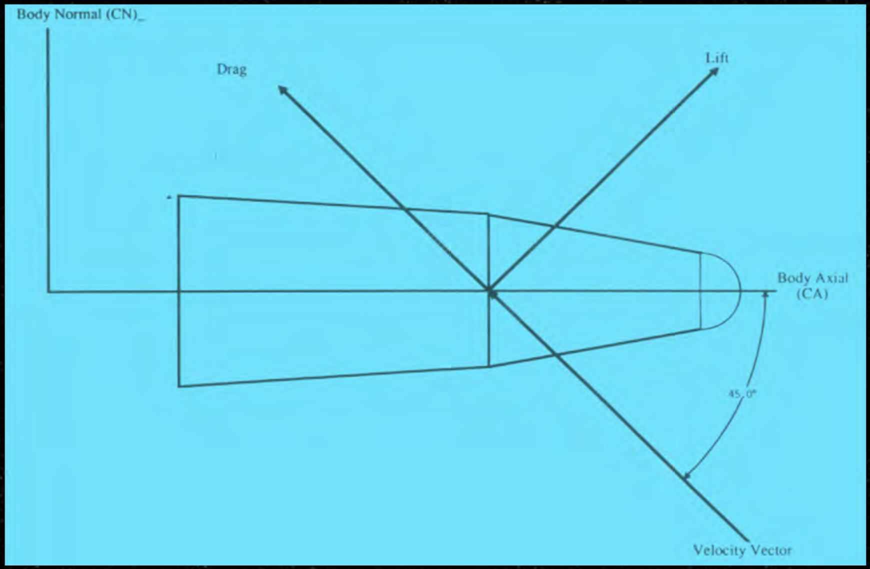
SHAPE	ADVANTAGES	DISADVANTAGES
Bent Biconic	High L/D ratio (1.0-1.5) Large cargo volume Easy to deploy	High heating rates Moderately large aeroshell mass Difficult for packing purposes

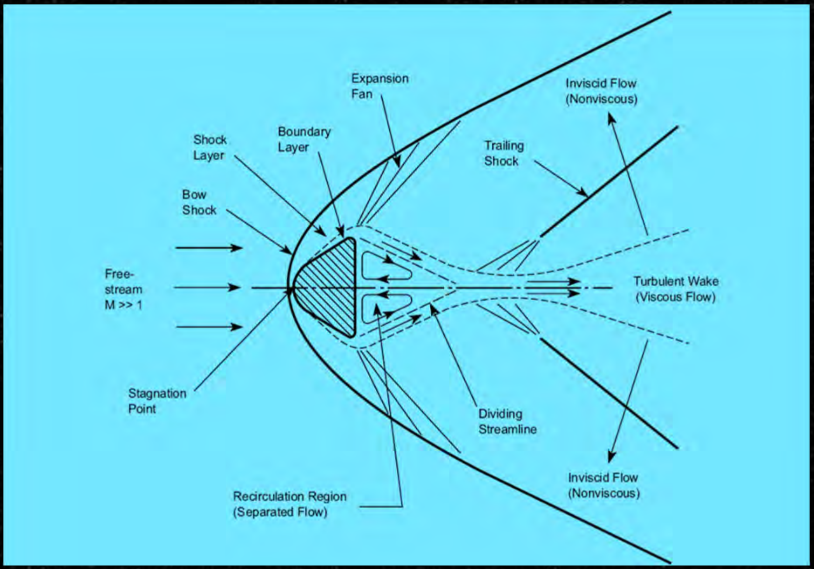
Aeroshell and Aerobrake Options



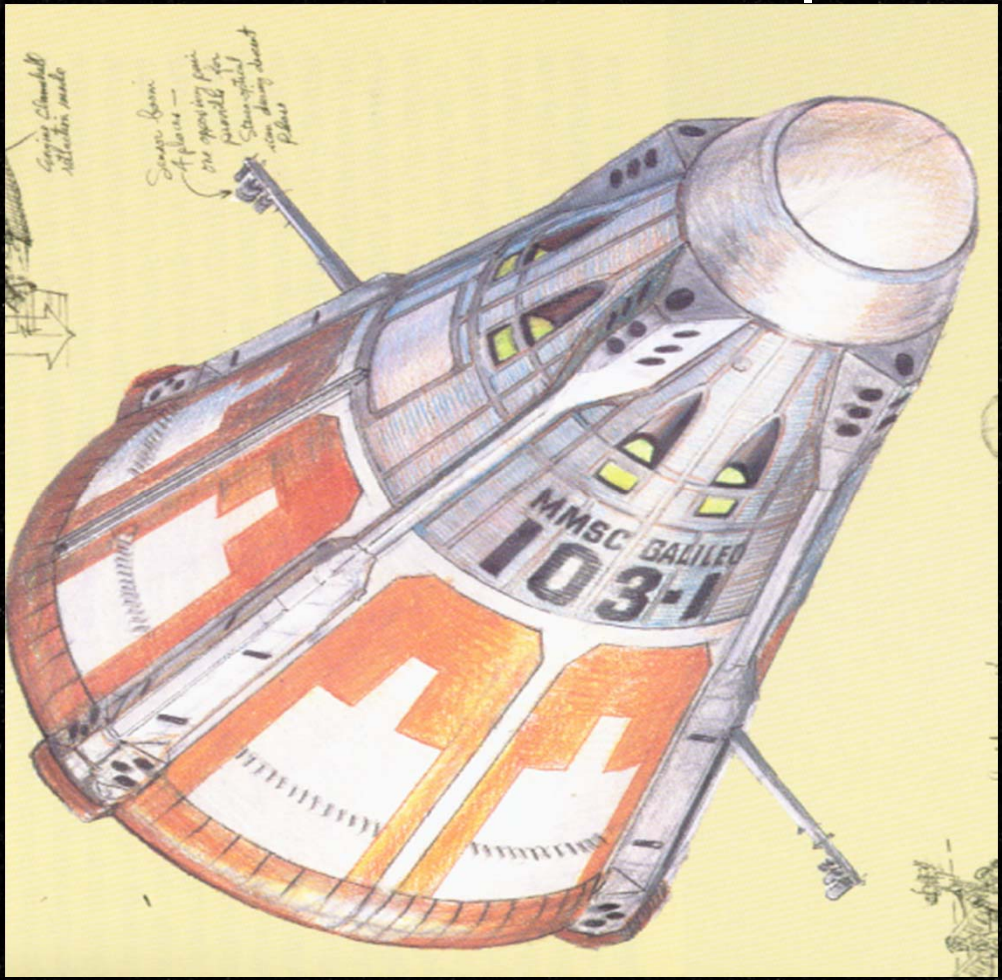
SHAPE	ADVANTAGES	DISADVANTAGES
Glider/Shuttle Configuration	High L/D ratio (1.5-2.5) Moderate cargo volume Easy to deploy Tested configuration	High heating rates Large aeroshell mass Packing is difficult

Aeroshell Coordinate System

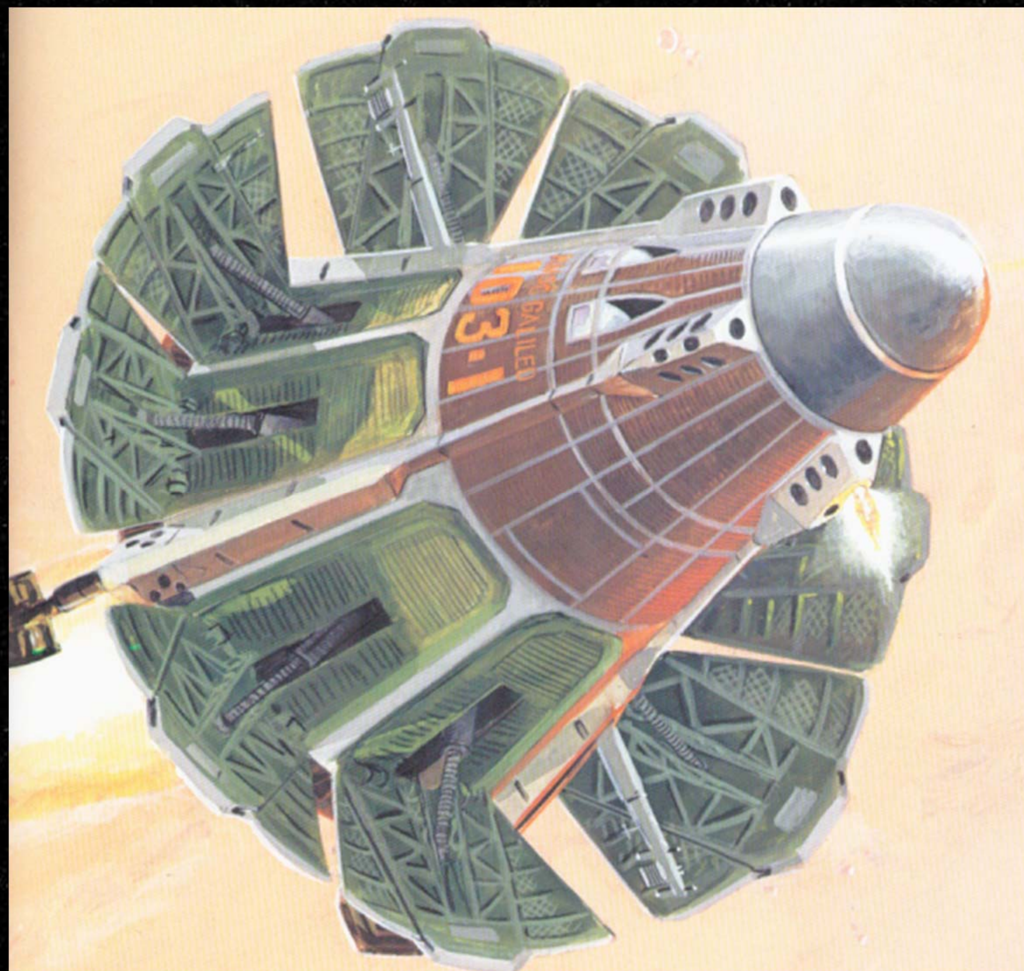




Aeroshell Concept



Aeroshell Concept



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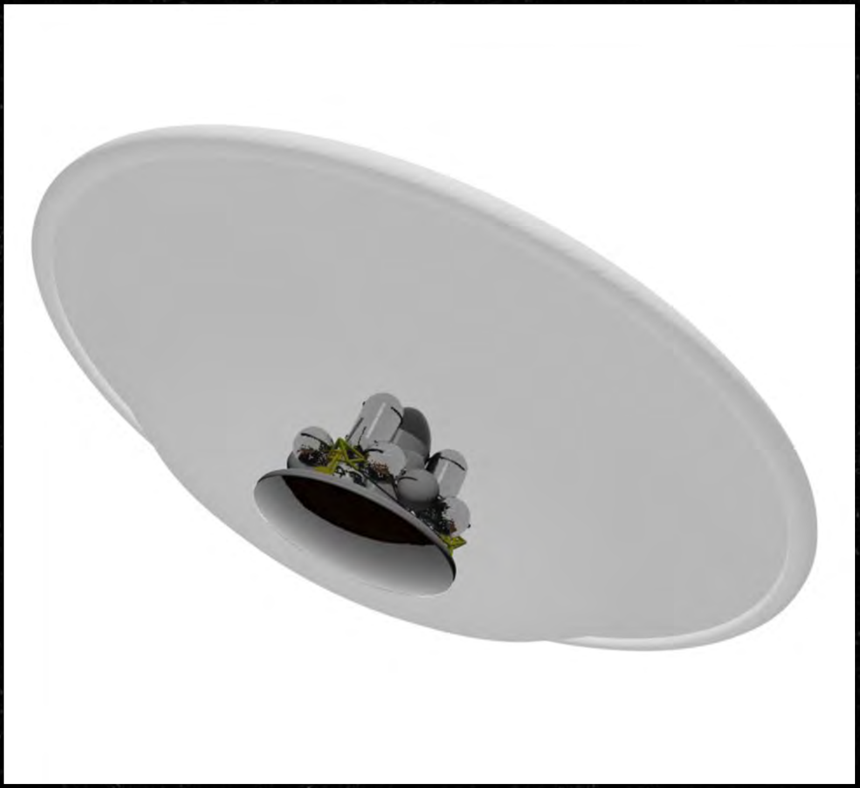
Aeroshell Ballute Concept



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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

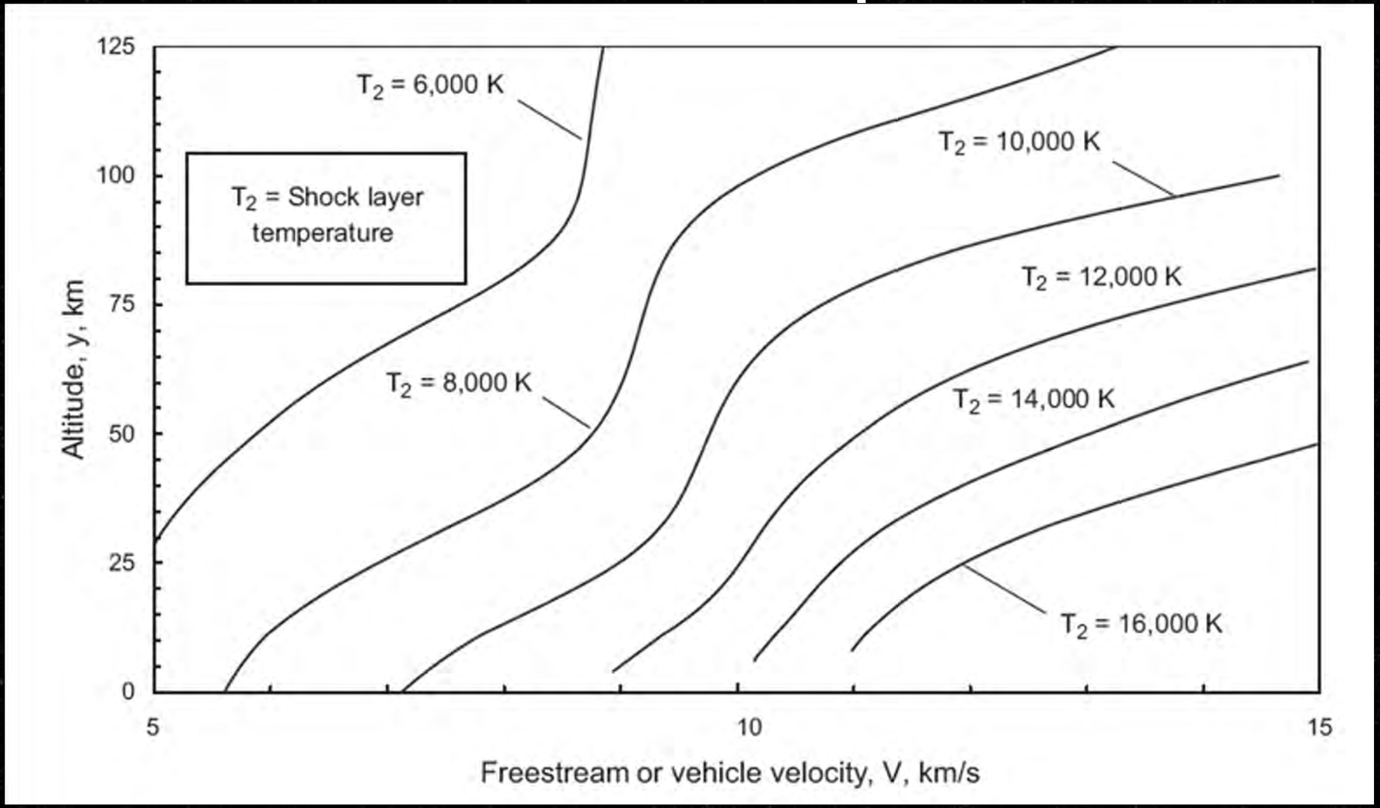
```
%---------------------------------------------------------
%Variation of Aerodynamic Coefficients with Angle of Attack
%Aerodynamic Coefficients vs. Angle of Attack
%for given aeroshell design shape
%(Symmetric Biconic)
%---------------------------------------------------------
%Clear workspace
clear attack Cdac Clac LDac Cdland Clland LDland
clear Cler Cder LDer cbac cbland cber
Wmtv=3000;
Wlan=1266;
Wert=200;
% Base, middle, and nose radii for blunt biconic
rnose=1.0;
rcone=2.0;
rbase=2.3;
rertb=1.2;
renos=0.1;
% Forward and rear nose angles
delta1=16;
delta2=4;
delter=20;
% Reference Area
Aref=pi*rbase^2;
for i=1:25;
    alpha=i-1;
    attack(i)=alpha;
%Mars Aerocapture coefficients
[Cda,Cla,LDa]=coeffs(delta1,delta2,rnose,rcone,rbase,alpha);
Cdac(i)=Cda;
Clac(i)=Cla;
LDac(i)=LDa;
[Cba,err]=ballistic(Wmtv,rbase, Cda);
cbac(i)=Cba;
%Descent coefficients
[Cdl,Cll,LDl]=coeffs(delta1,delta1,rnose,rcone,rcone,alpha);
Cdland(i)=Cdl;
CLland(1)=Cll;
LDlan(i)=LDl;
```

SYMMETRIC MATLAB

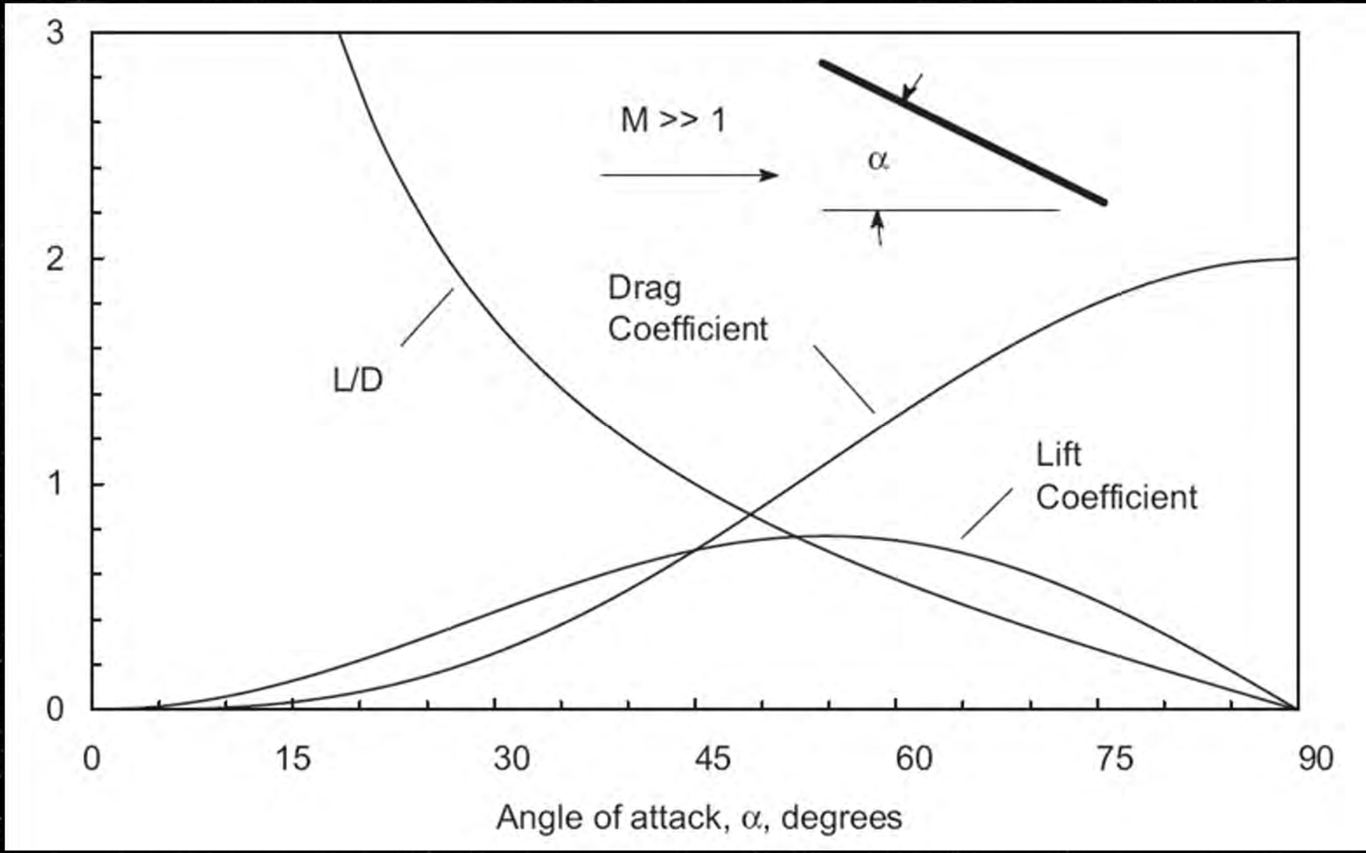
```
%Function calculates aerodynamic coefficient for a
%blunt, SYMMETRIC BICONIC aeroshell at arbitrary
%angle of attack given the following input parameters:
%dl = forward cone angle (in degrees)
%d2 = rear cone angle (in degrees)
%rn = nose radius
%rc = intermediate cone radius
%rb = base radius
%alpha = angle of attack (in degrees).
%The units on rn, rc, and rb must be consistent
%Outputs are dimensionless Cl, Cd, and L/D for the body.
%Inviscid, hypersonic Newtonian flow is assumed and skin
%friction drag is neglected.
%-----------------------------------------------------------
function [Cd,Cl, LonD] = coeffs (dl, d2, m, rc, rb, alpha)
%Trig relations
sial=sin(alpha*pi/180);
sial2=sin(2*alpha*pi/180);
coal=cos(alpha*pi/180);
sidl=sin(dl*pi/180);
codl=cos(dl*pi/180);
sid2=sin(d2*pi/180);
cod2=cos(d2*pi/180);
% Ratio of Specific Heats (Cp/Cv) behind shock
spcheats=1.1;
eps=(spcheats-1)/(spcheats+1);
%Normal and axial force ciefficients
%Note CN=Cl and CA=Cd at alpha = 0
CN1=(1-(m/rc)^2*codl^2)*codl^2*sial2;
CA1=(1-sidl^4)*(m/rc)^2+((1-(m/rc)^2*codl^2)*(2*sid^2*coal^2+codl^2*sial^2));
CN2=(1-(rc/rb)^2*cod2^2)*cod2^2*sial2;
CA2=(1-(rc/rb)^2*cod2^2)*((2*sid2^2*coal^2+cod2^2*sial^2));
Cdcone1=(CN1*sial+CA1*coal)*(rc/rb)^2;
Clcone1=(CN1*coal-CA1*sial)*(rc/rb)^2;
Cdcone2=CN2*sial+CA2*coal;
Clcone2=CN2*coal-CA2*sial;
Cd=Cdcone1+Cdcone2;
Cl=Clcone1+Clcone2;
LonD=Cl/Cd;
```

Project1.m | COEFFS.m | ALPHACOEFFS.m

MATLAB Graphs



MATLAB Graphs



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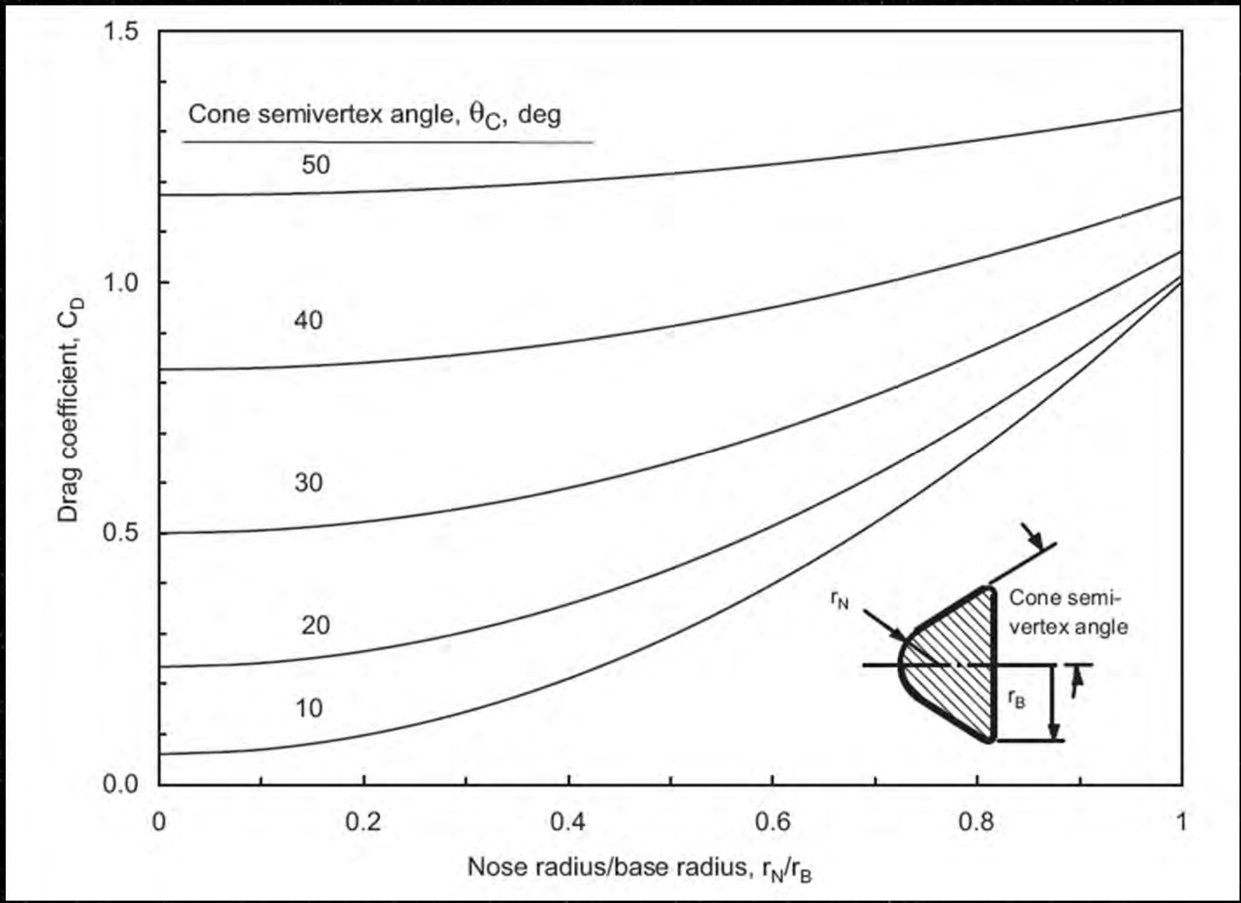

Aeroshell Design Constraints and Selected Design Point

Design Parameter	Symbol	Minimum	Maximum Acceptable	Selected Design Point
Forward Cone Angle	(δ1)	10º	25º	16º
Rear Cone Angle	(δ2)	>0º	(δ1)	4º
Nose Radius	(Rn)	.25m	1.5m	1.0m
Base Radius	(Rb)	N/A	2.5m	2.3m
Intermediate base Radius	(Rb1)	Rn	Rb	2.0m

Aeroshell Performance at Selected Design Point

Performance Parameter	Symbol	Relation to design parameters	Performance at Design Point
Lift to Drag Ratio	L/D	F(δ1, δ2, Rn)	0.6 (A/C), 0.5 (Lander)
Drag Coefficient	C_D	F(δ1, δ2, Rn)	0.28(A/C); 0.38 (Lander)
Ballistic Coefficient	C_β	F(W, δ1, δ2, Rn)	522Kg/m^2 (A/C);
Max Heating rate	q_{omax}	F(v, Rn, C_β)	20 W/cm^2 (A/C); 60 W/cm^2 (Lander)
Total integrated heating	Q_0	F(L/D, δ1, δ2, Rn)	6kJ/cm^2 (A/C); 33 kJ/cm^2 (Lander)

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.

Aeroshell and Aerobrake Options

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Symmetric Conic	Moderate heating rates Moderate cargo volume Tested configuration/easy to deploy	Moderate L/D ratio (.50-.60) Moderately large aeroshell mass
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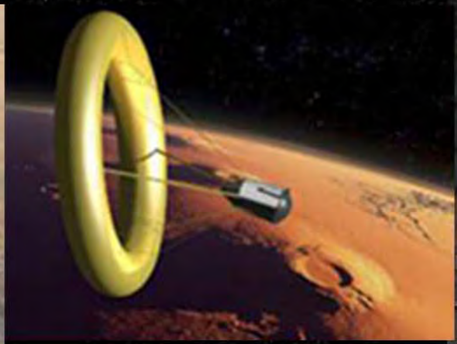
Glider/Shuttle Configuration	High L/D ratio (1.5-2.5) Moderate cargo volume Easy to deploy Tested configuration	High heating rates Large aeroshell mass Packing is difficult

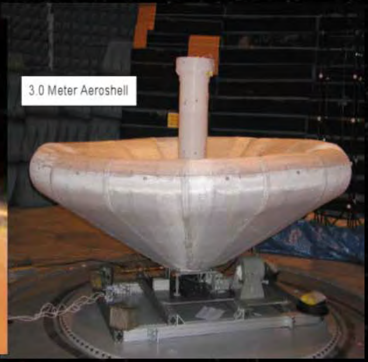
Inflatable Aerodecelators

- Inflatable Aeroshell
- Ballutes
- Hypercones

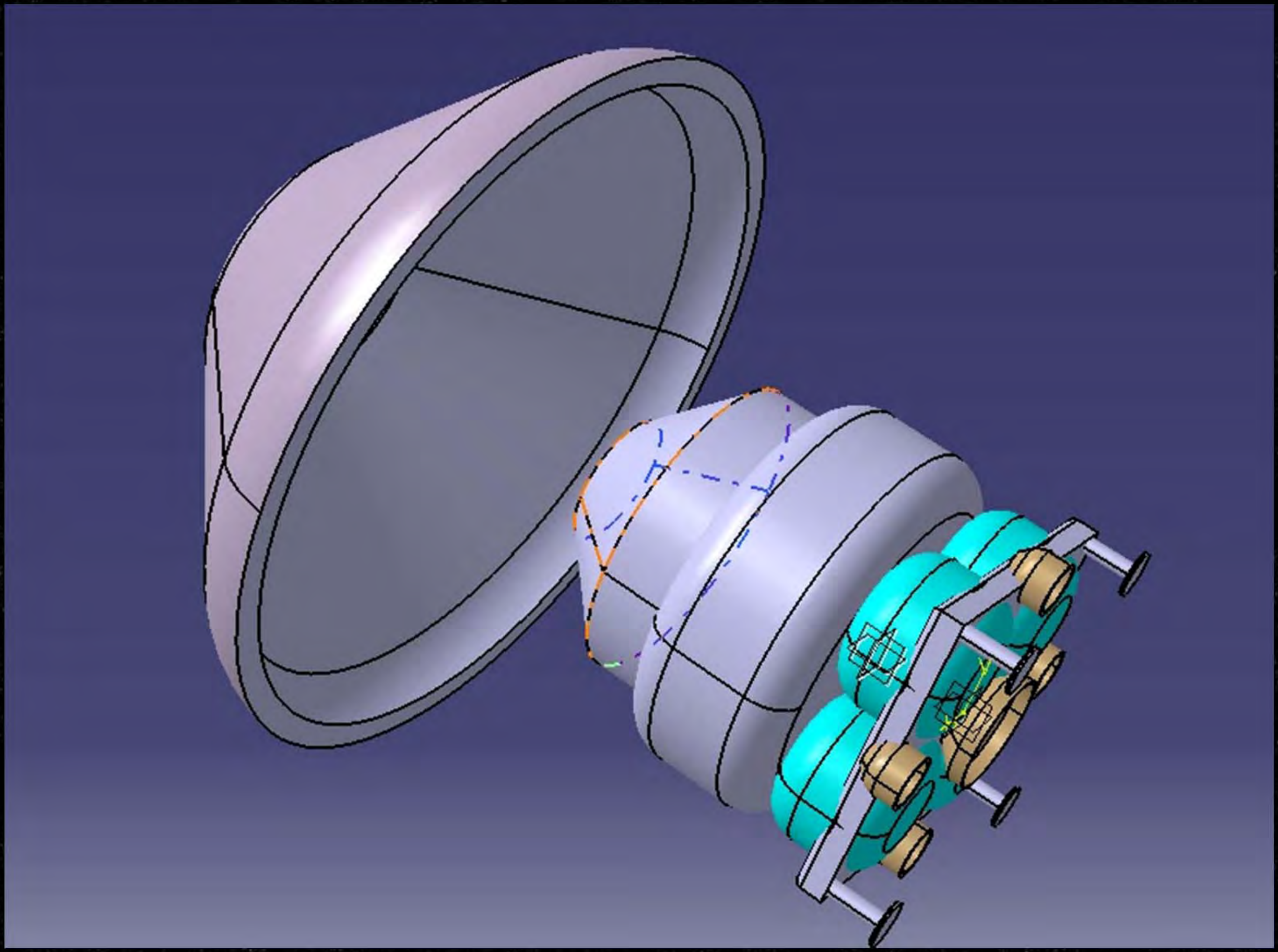
Aerodecelators

- 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

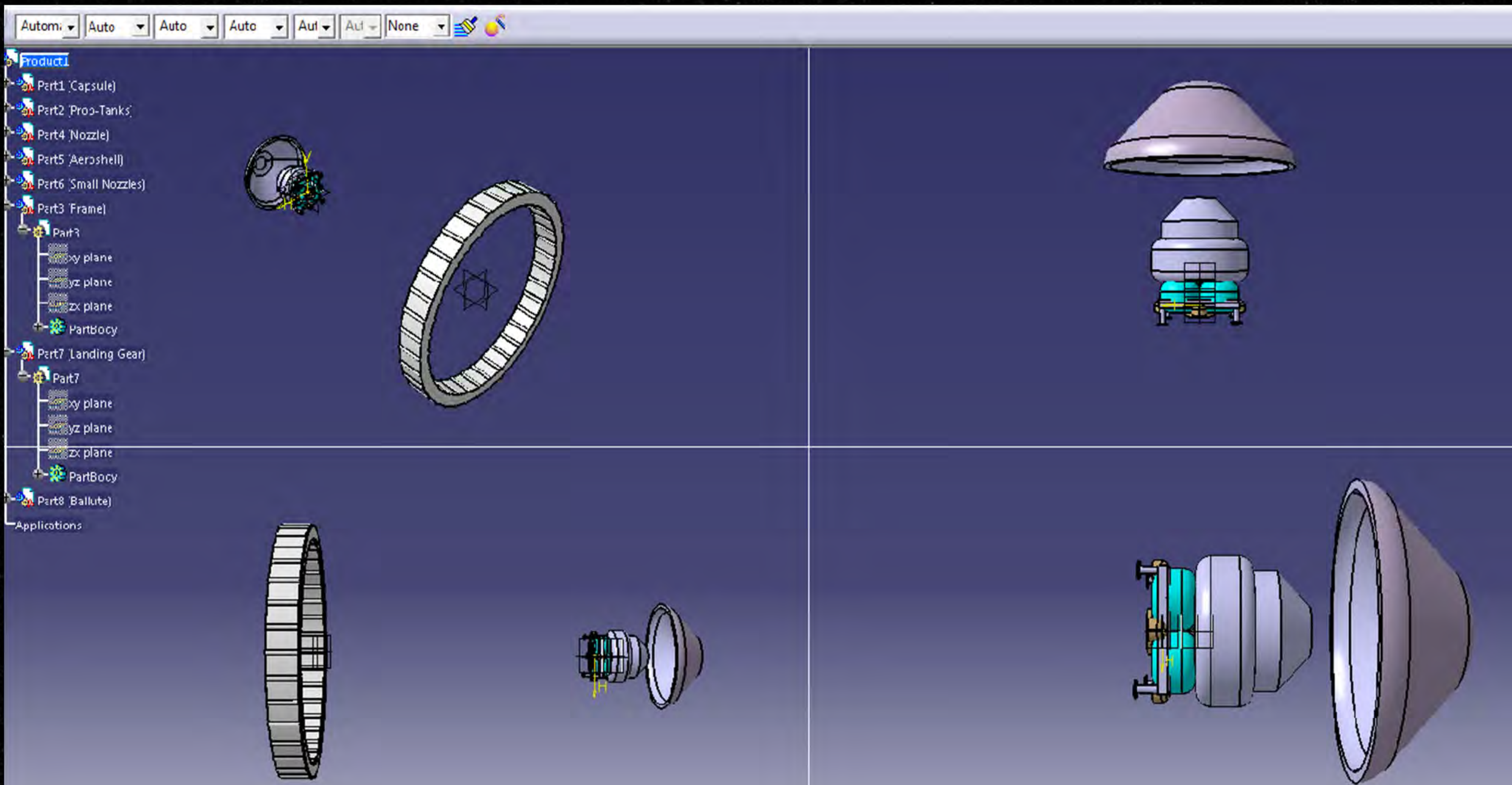




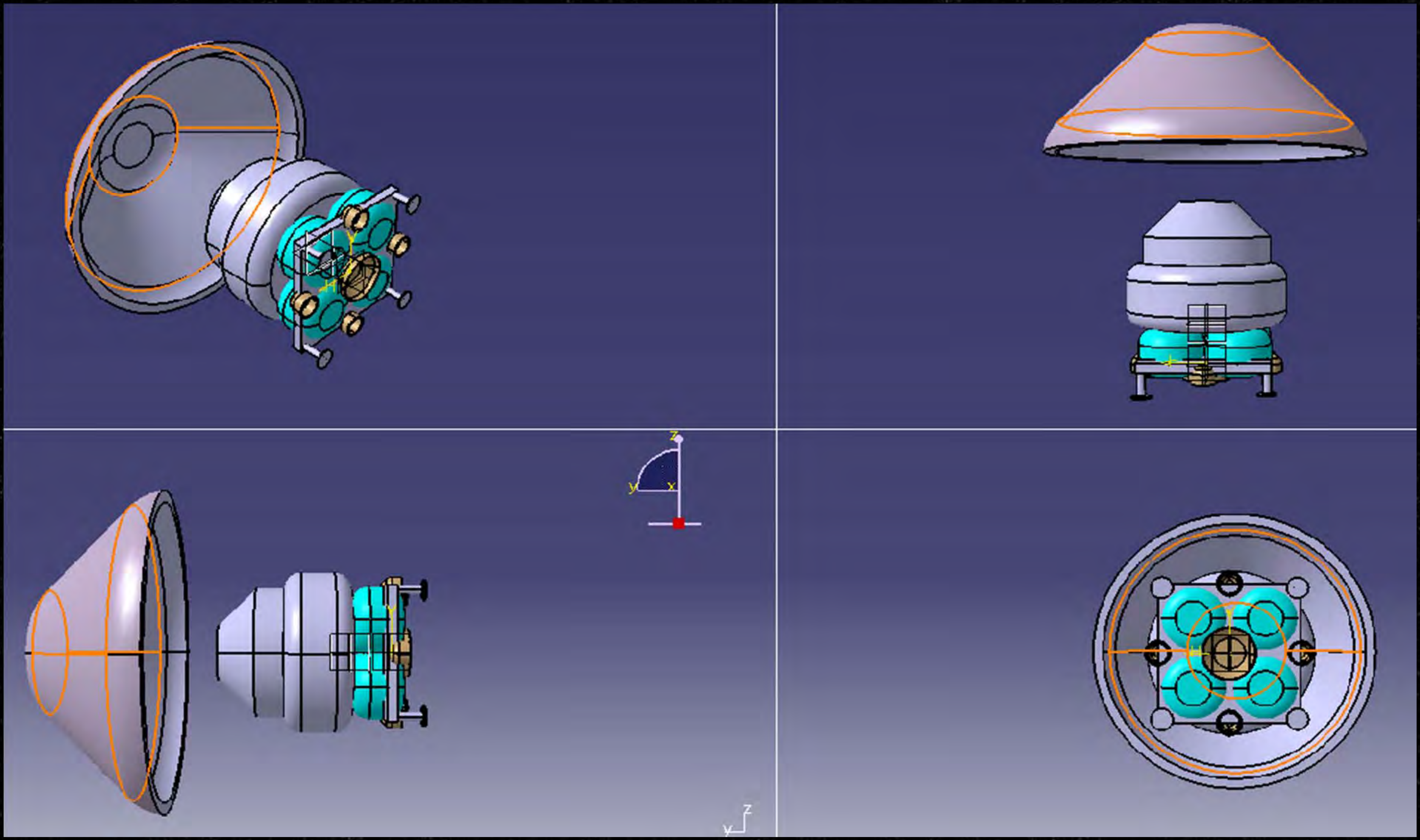
Inflatable Aeroshell



Inflatable Aeroshell



Inflatable Aeroshell



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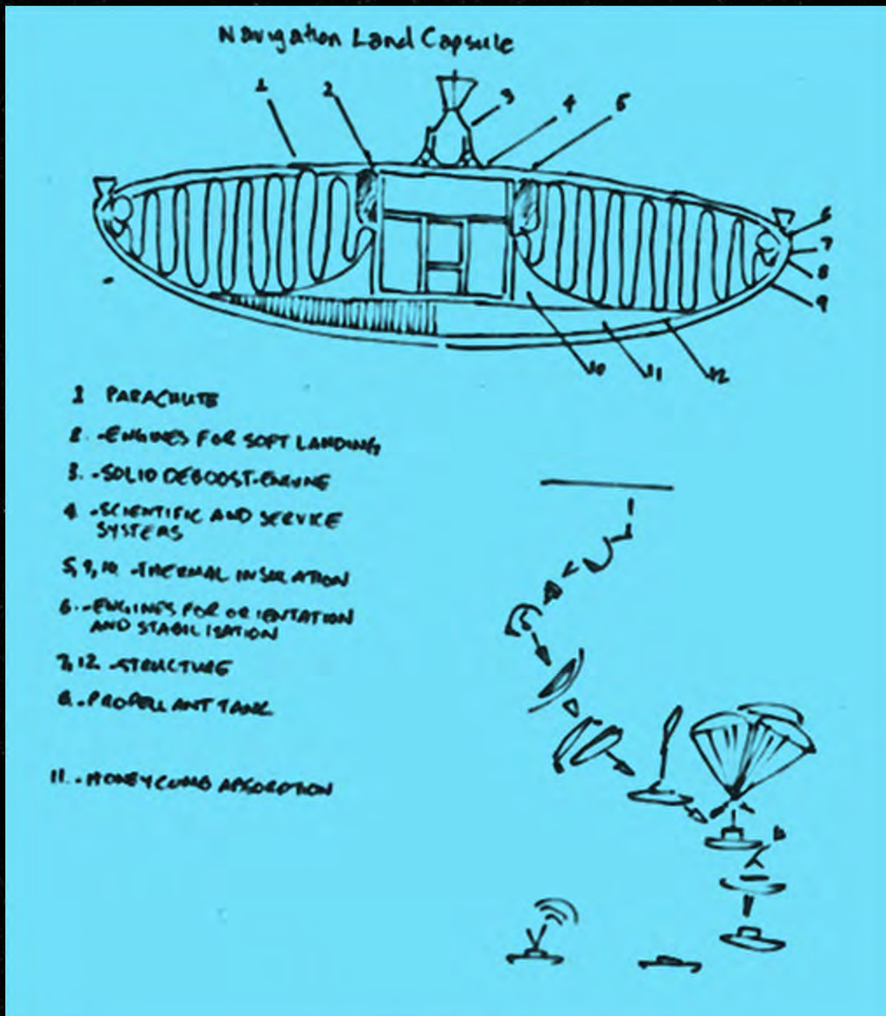
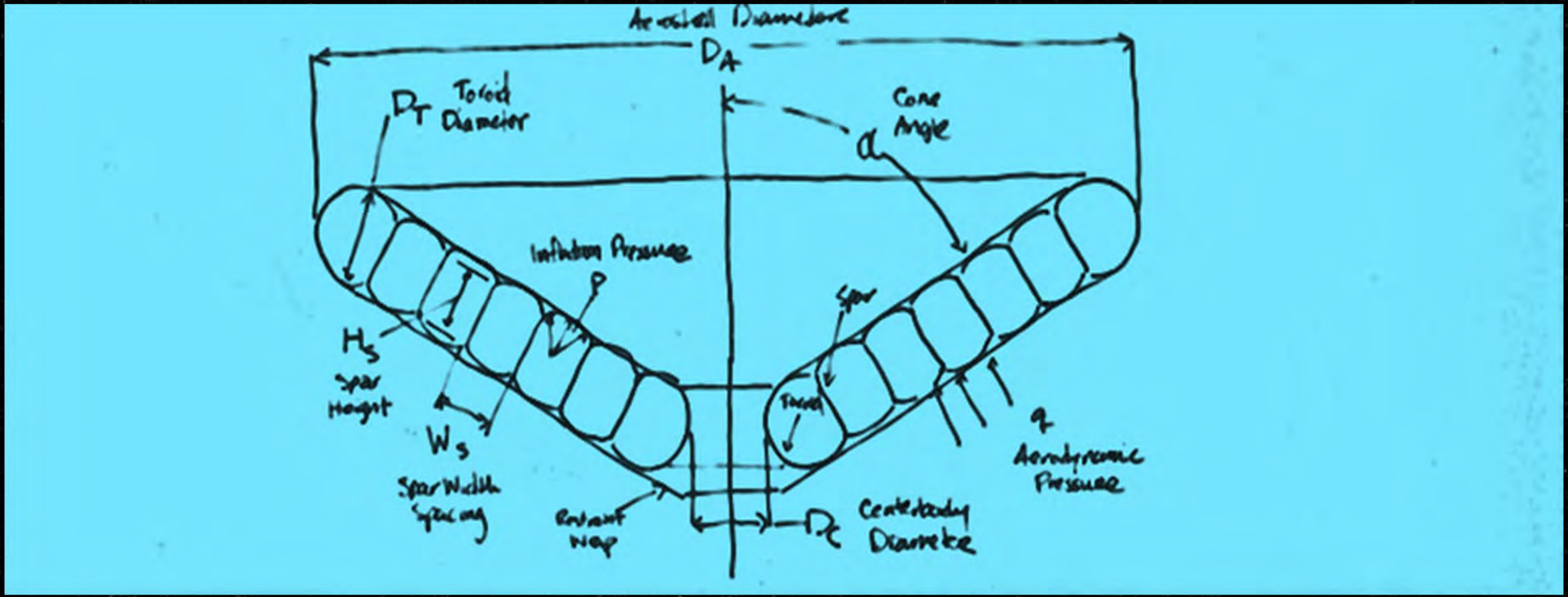
Navigation Landing Capsule



- 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

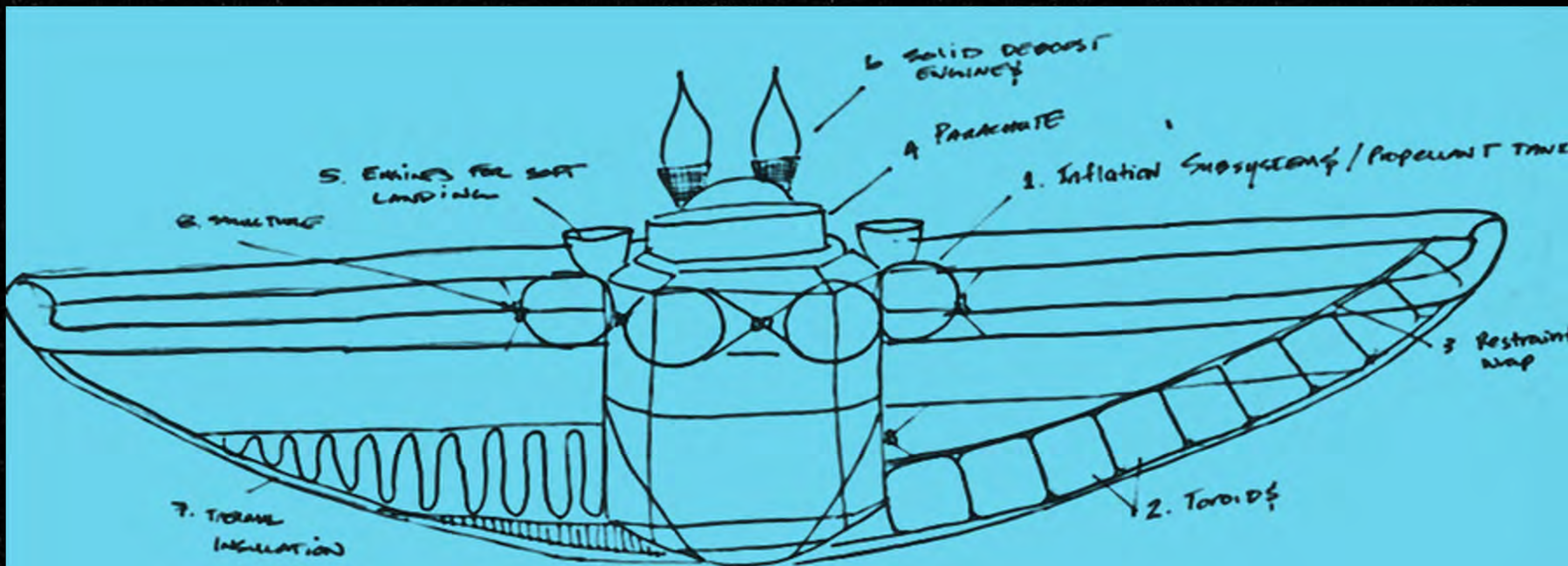
1. Toroid Fabric Loads
2. Spar Fabric Loads
3. Restraint Wrap Loads

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

$$N_{MAX} = \frac{PW_S}{2}\left[1 + \frac{1}{1 - \frac{H_S cos(\propto)}{D_C + D_T + W_S sin(\propto)}}\right] \approx PW_S$$

$$N_{MAX} = \frac{m_c a}{2\pi D_c cos(\alpha)}$$

Attachable Inflatable Aeroshell

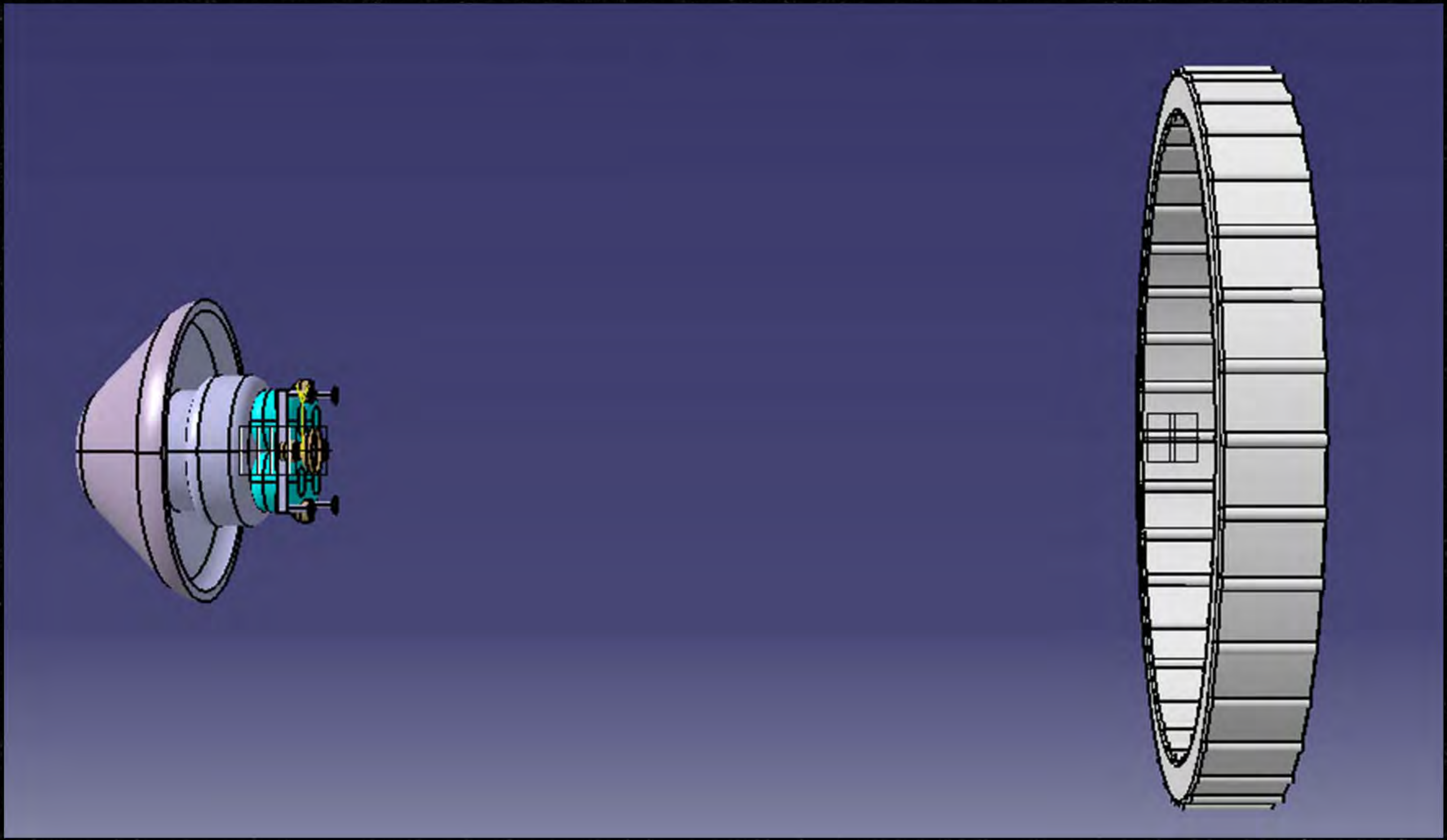


- Inflatable Aeroshell Cross-Section

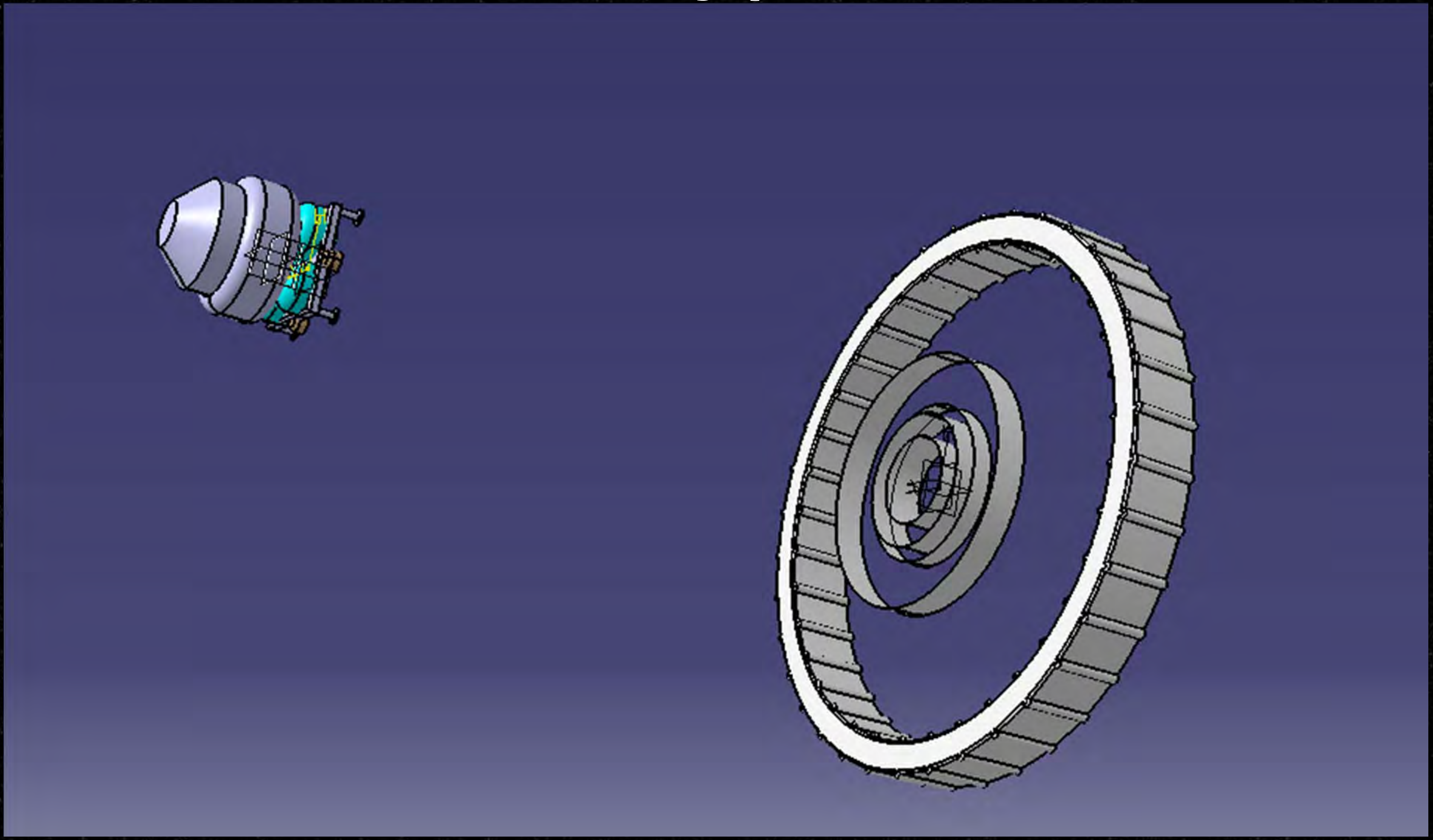
1. Inflation Subsystems/Propulsion Tanks
2. Inflatable Toroids are laced together and contained within a retraint wrap
3. Restraint Wrap (dry Kevlar fabric for structural loads, layers of Nextel cloth for thermal protection and Kapton layers to act as gas barrier)
4. Parachute
5. Engines for Soft Landing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

Hypercone

Inflatable Hypercone



Inflatable Hypercone

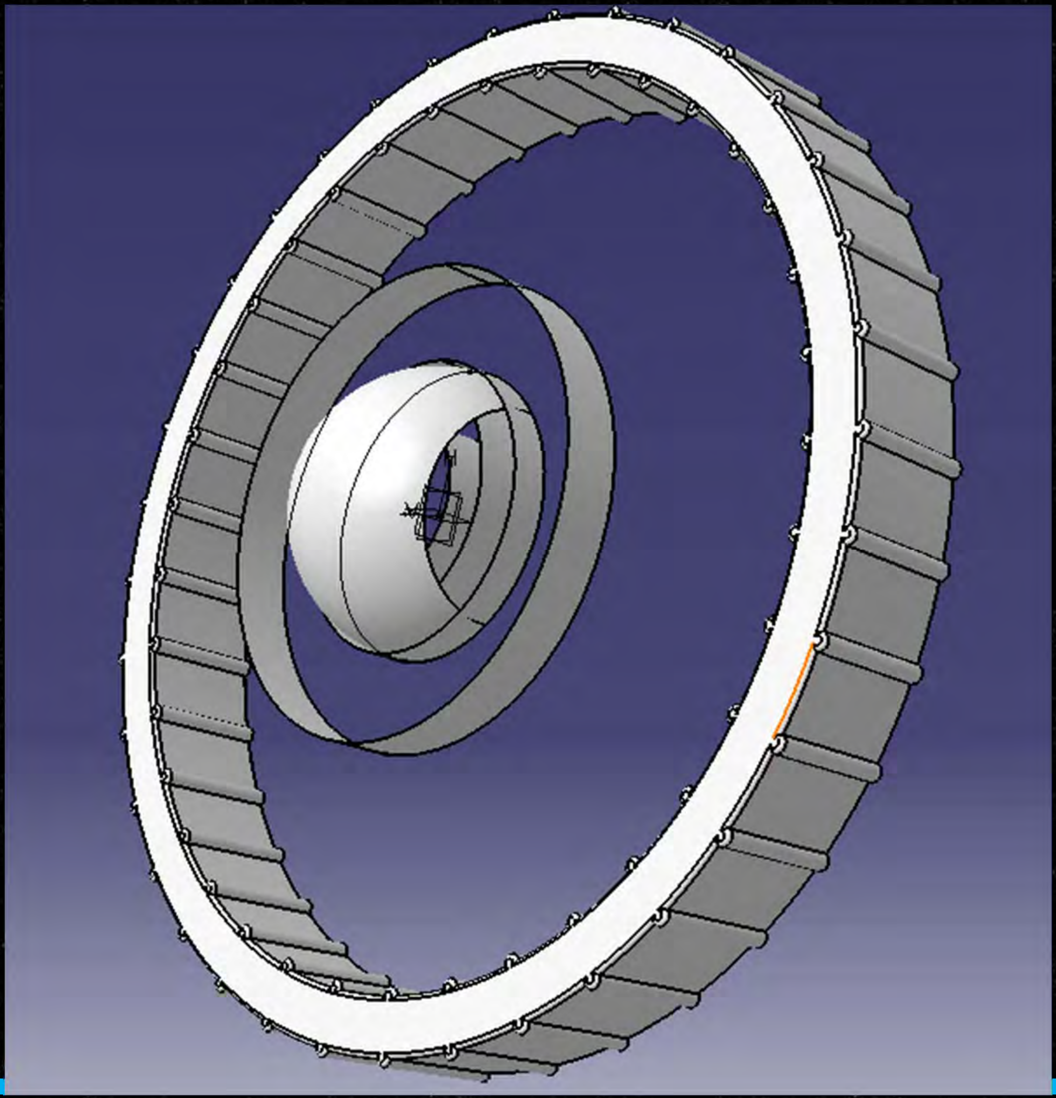


Hypercone

- Donut-shape Hypercone would be 30-40 meters in diameter
  - Inflatable supersonic decelerator-only CGI –would delerate 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

Ballute

Inflatable Ballute



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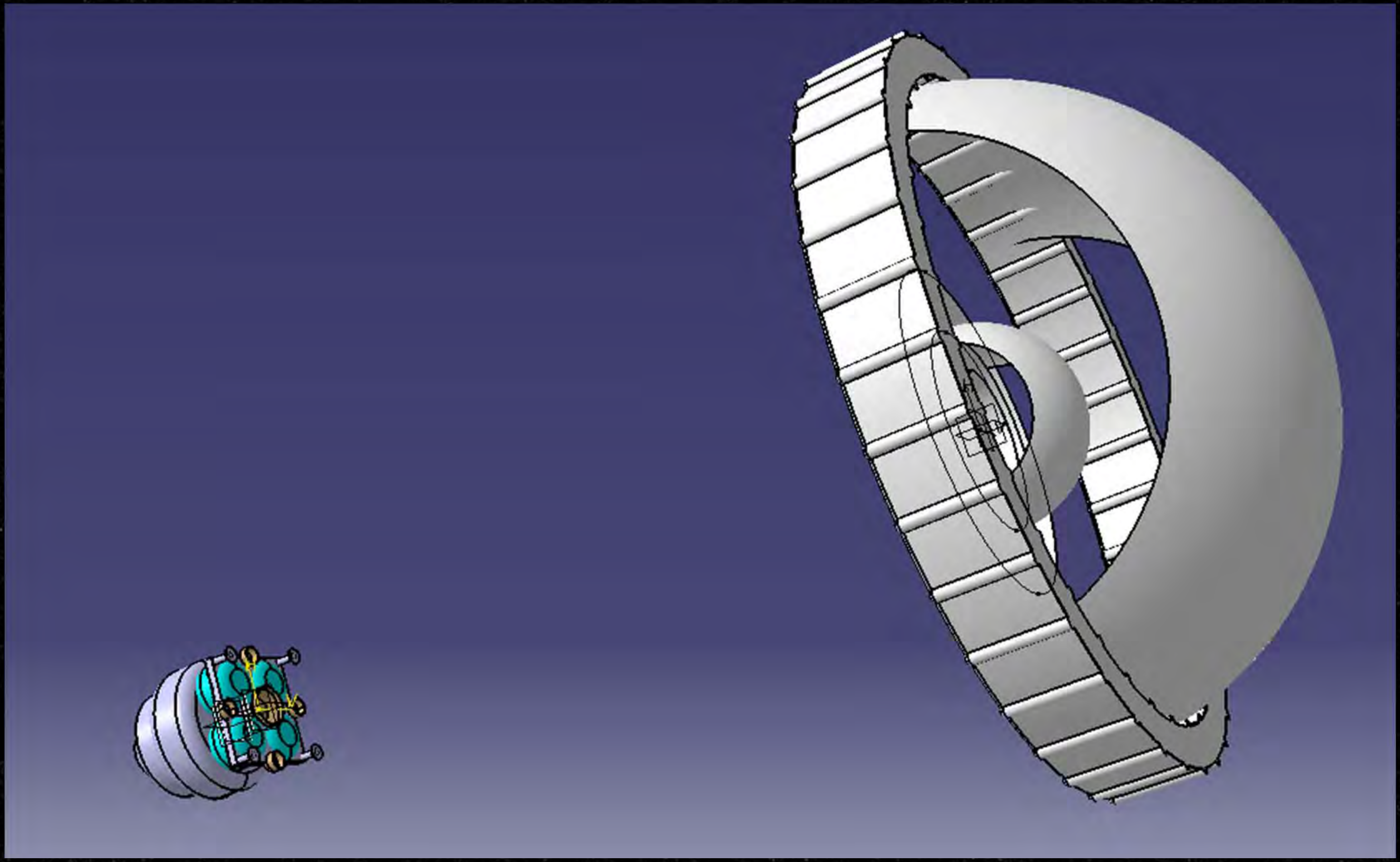
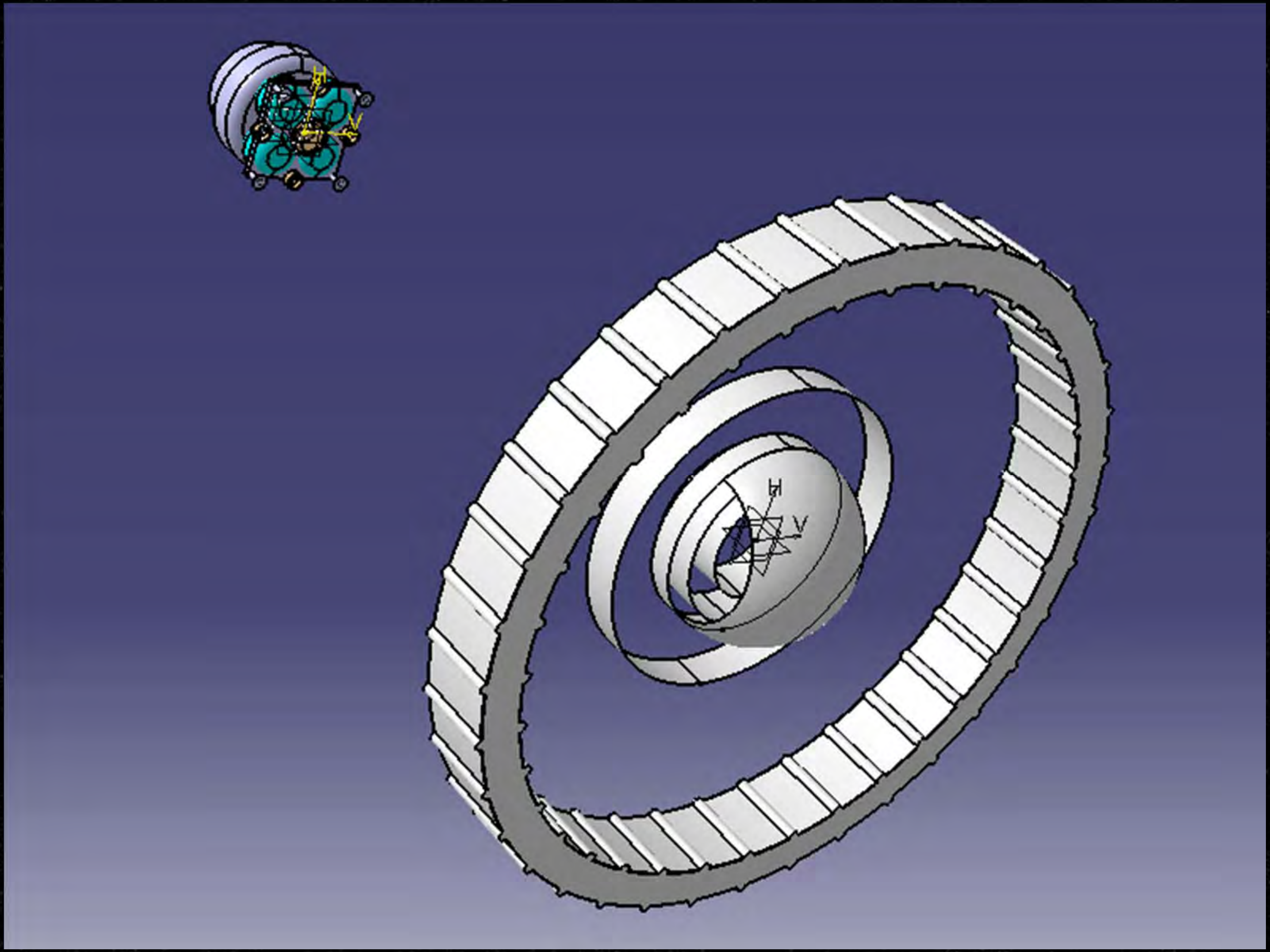
Inflatable Ballute



Inflatable Ballute



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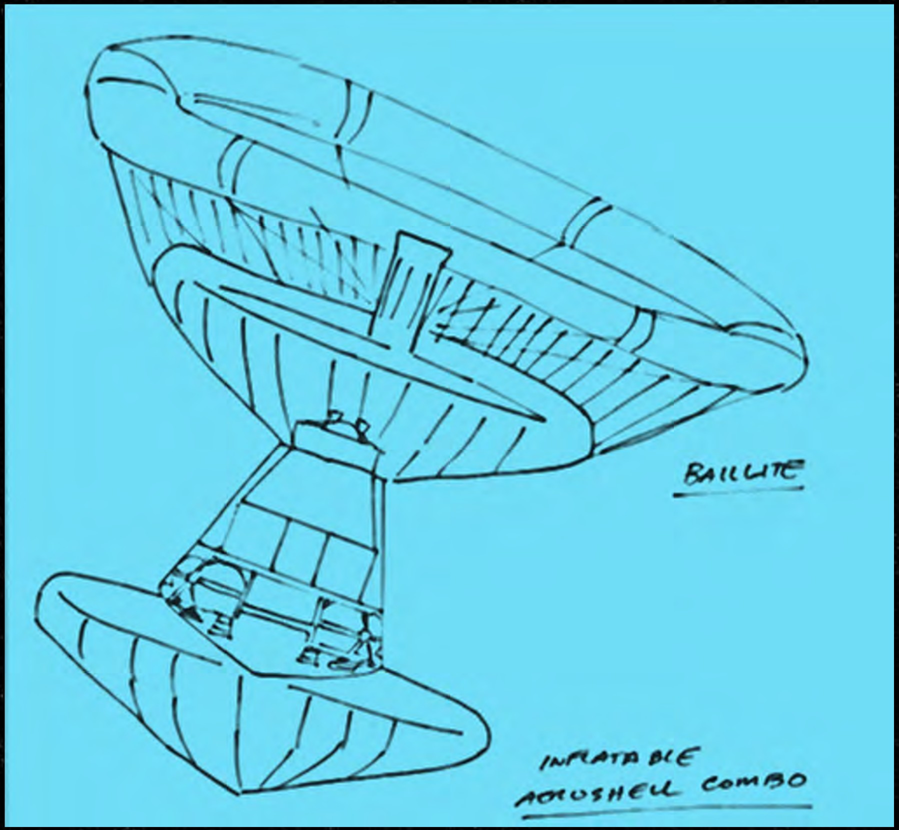
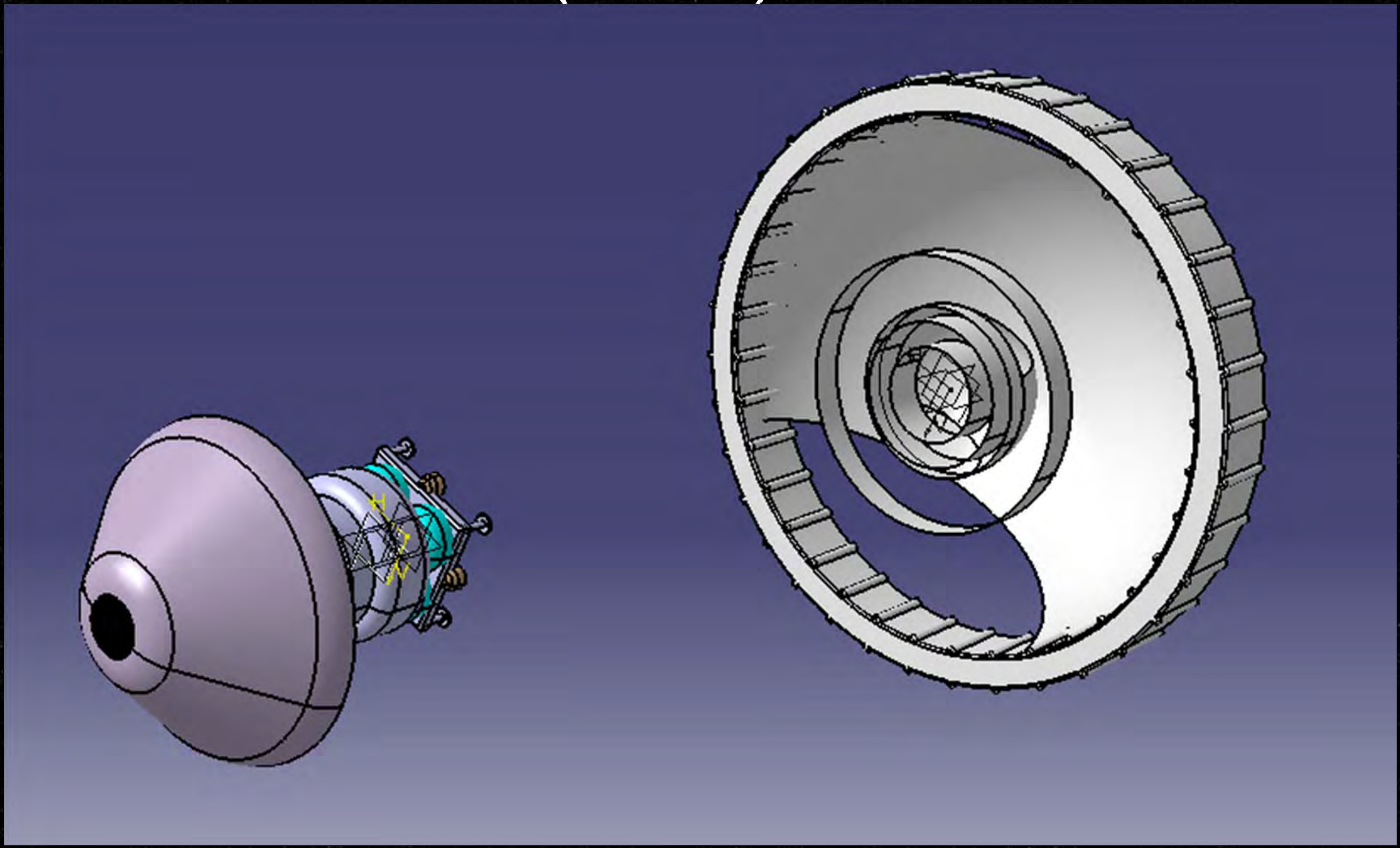
Ballutes-Ultra Lightweight Ballute (ULWB)

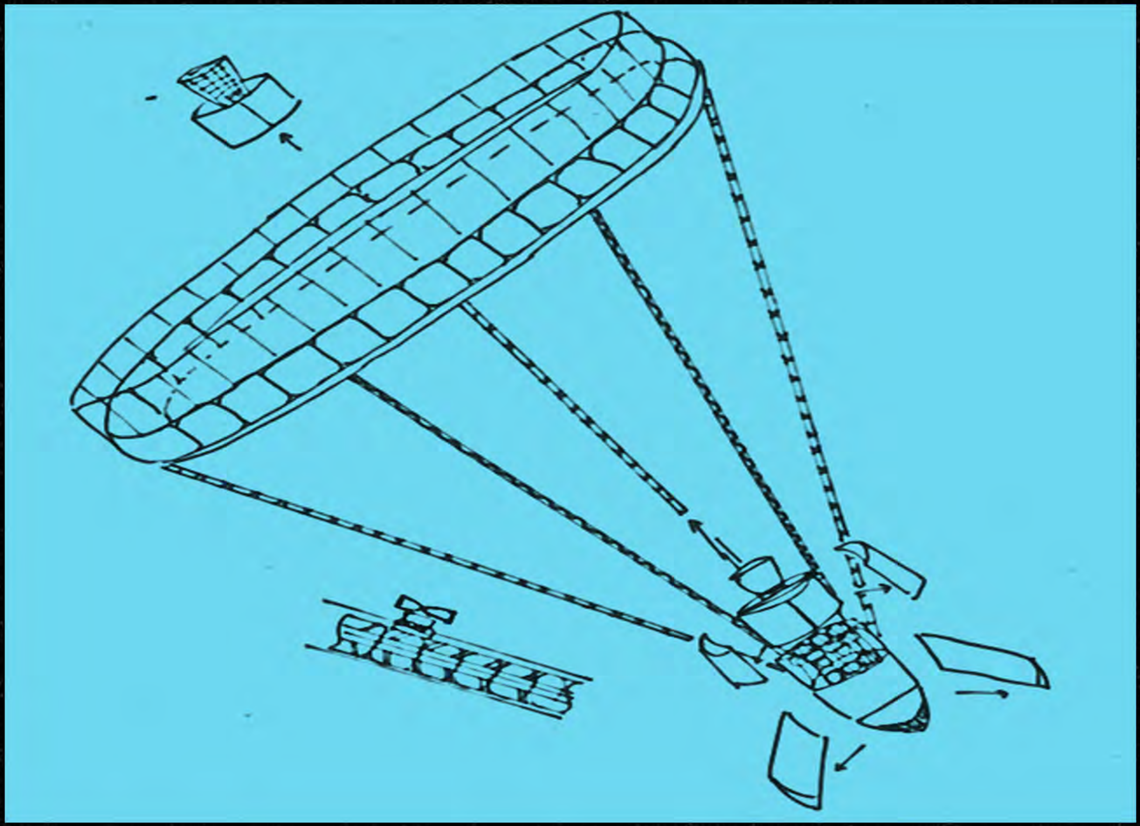
- A Deceleration solution similar to the Hypercone
  - The large drag area of the ballute enables the vehicle to decellerate even in a Martian atmosphere and it allows more payload to be carrried by the vehicle because of its lightweight construction



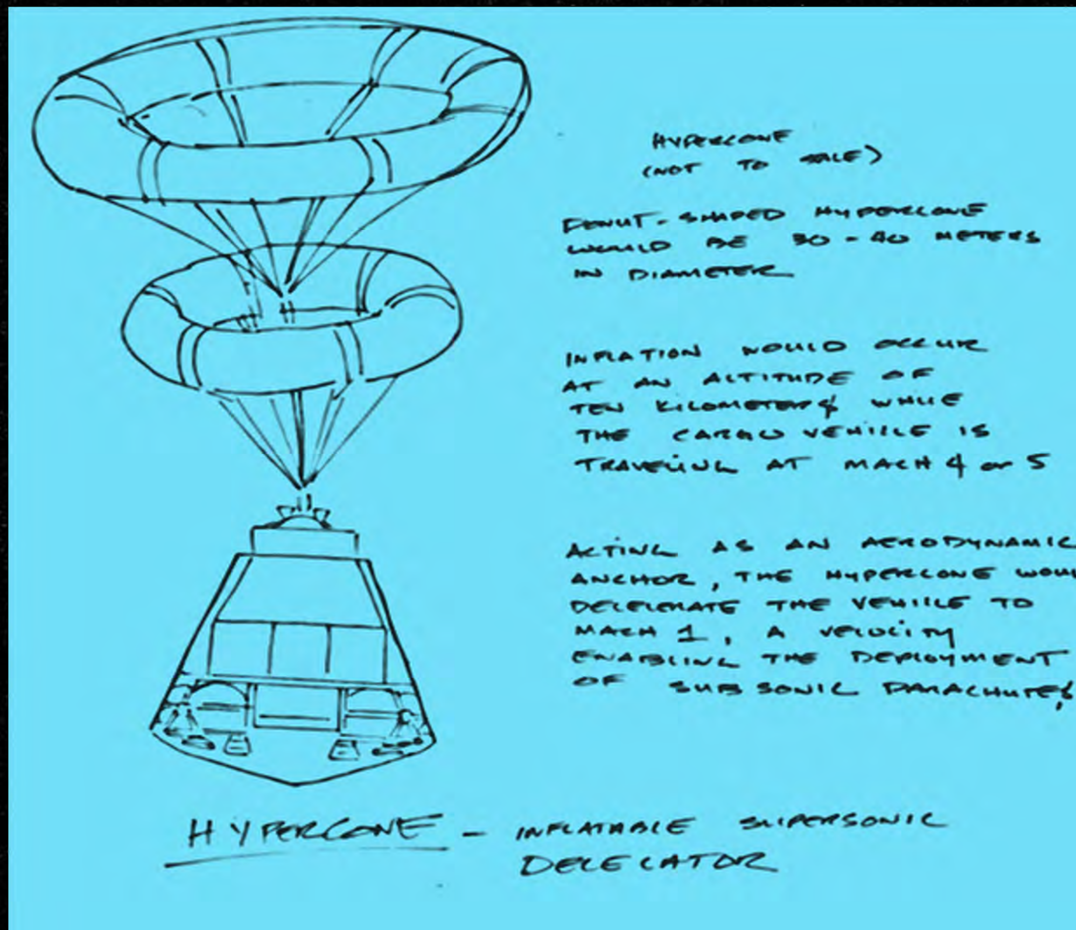
Inflatable Aeroshell & Ballutes-Ultra Lightweight Ballute (ULWB) Combo



Ballute = Balloon + Parachute Concept



Hypercone



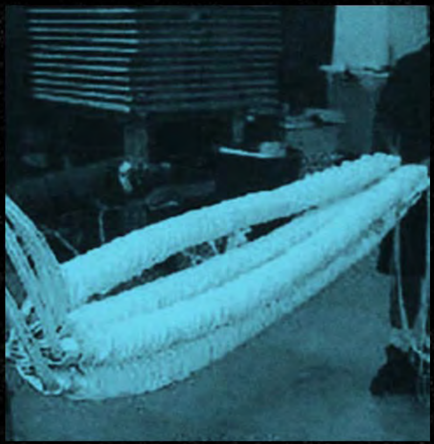
HYPERCONE
(NOT TO SCALE)
DONUT-SHAPED HYPERCONE WOULD BE 30-40 METERS IN DIAMETER
INFLATION WOULD OCCUR AT AN ALTITUDE OF TEN KILOMETERS WHILE THE CARGO VEHICLE IS TRAVELING AT MACH 4 or 5
ACTING AS AN AERODYNAMIC ANCHOR, THE HYPERCONE WOUL DECELERATE THE VEHICLE TO MACH 1, A VELOCITY ENABLING THE DEPLOYMENT OF SUBSONIC PARACHUTES
HYPERCONE - INFLATABLE SUPERSONIC DECELATOR

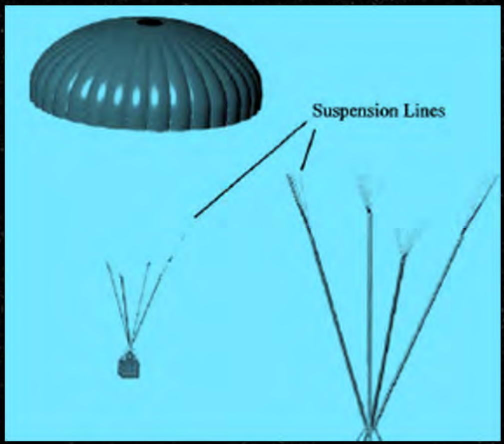
Pros & Cons

- Spar with Rim Inflatable Baseline Configuration
  - Pros: Efficient Structure; Efficient gas usage; Good Heat Transfer; Potential for Shape-morphing; Inflatable Components Thermally Portected
  - 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: Manufactoring 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

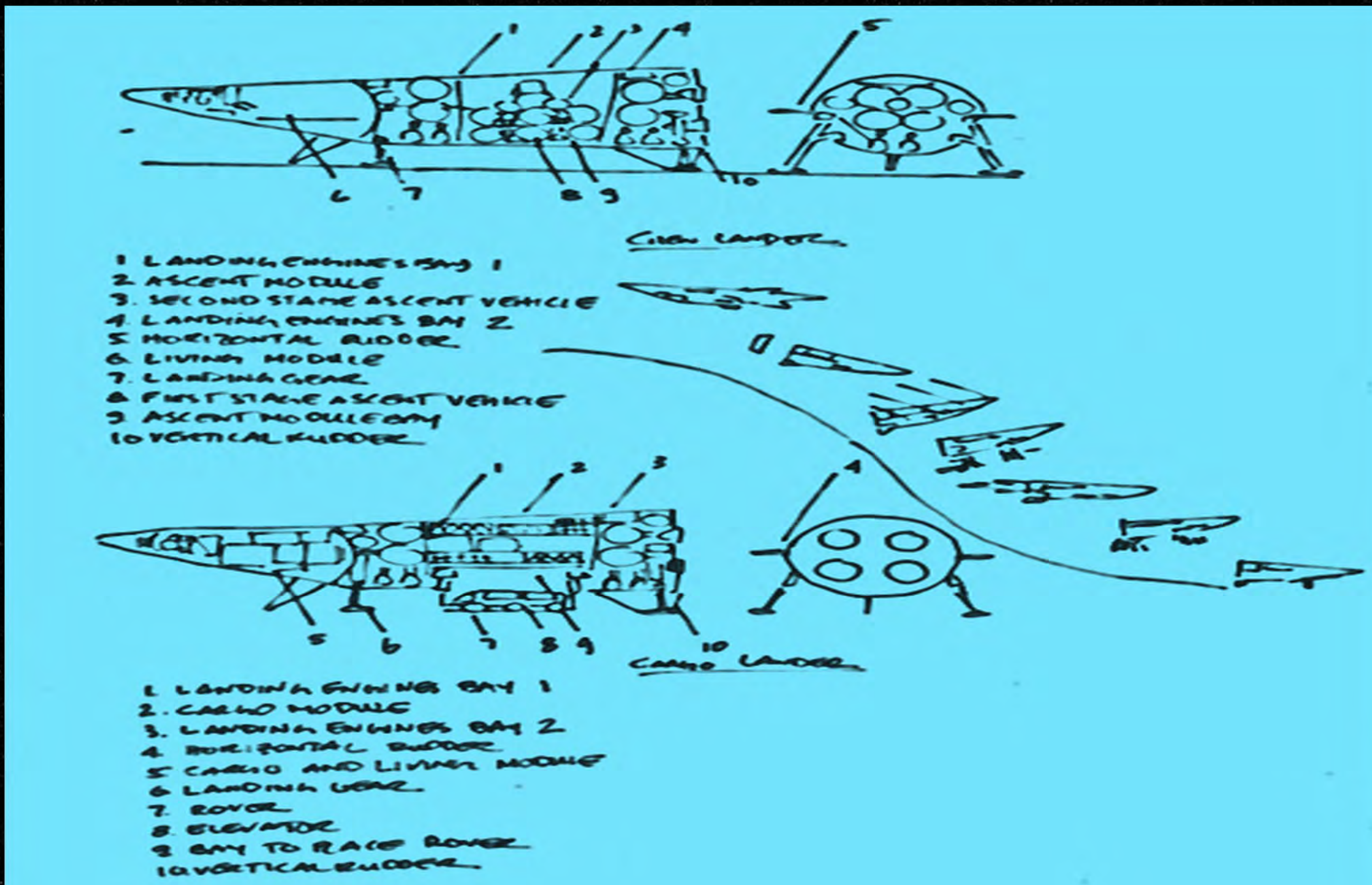
Challenges

- 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.

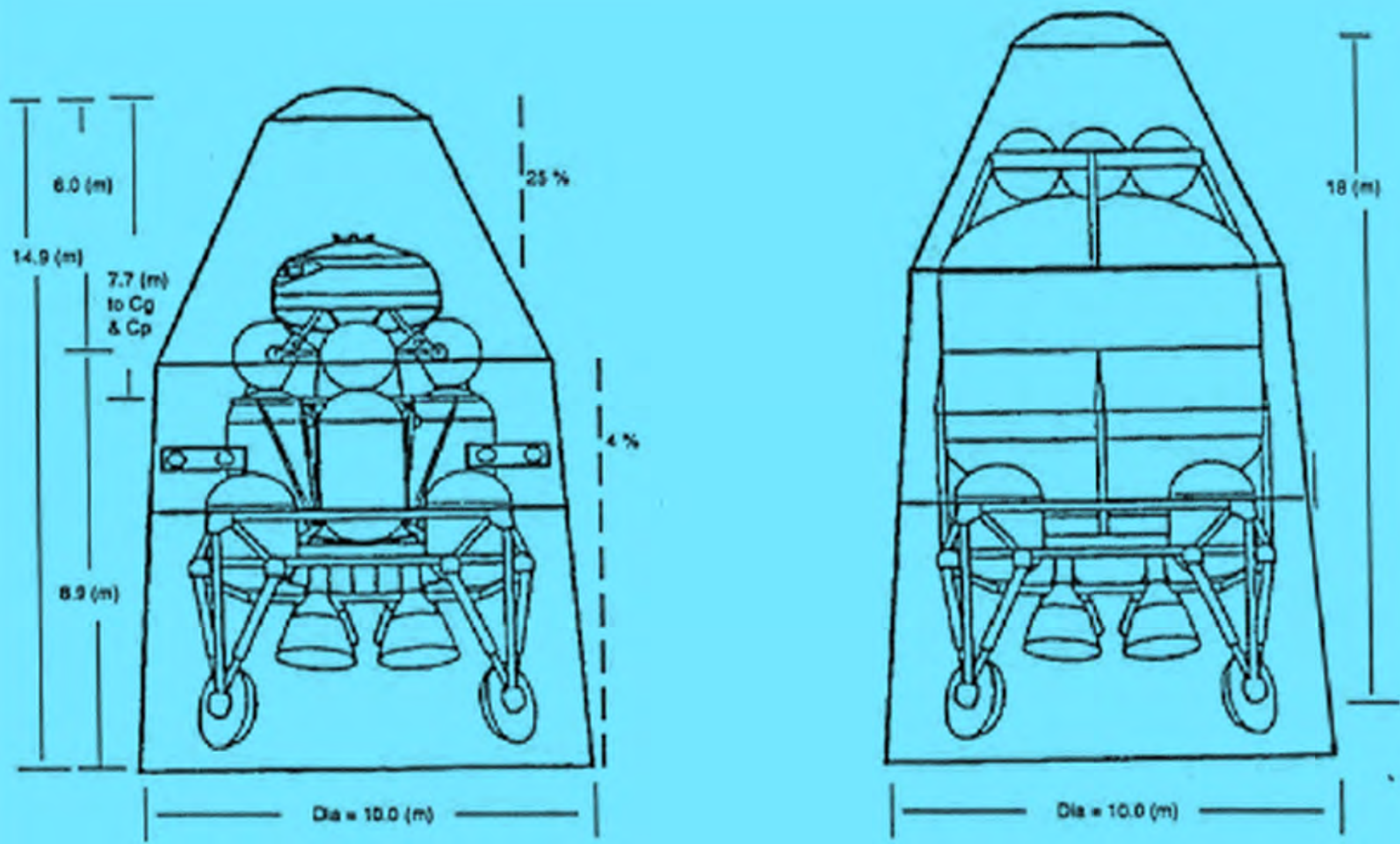




Biconical Crew/Cargo Lander



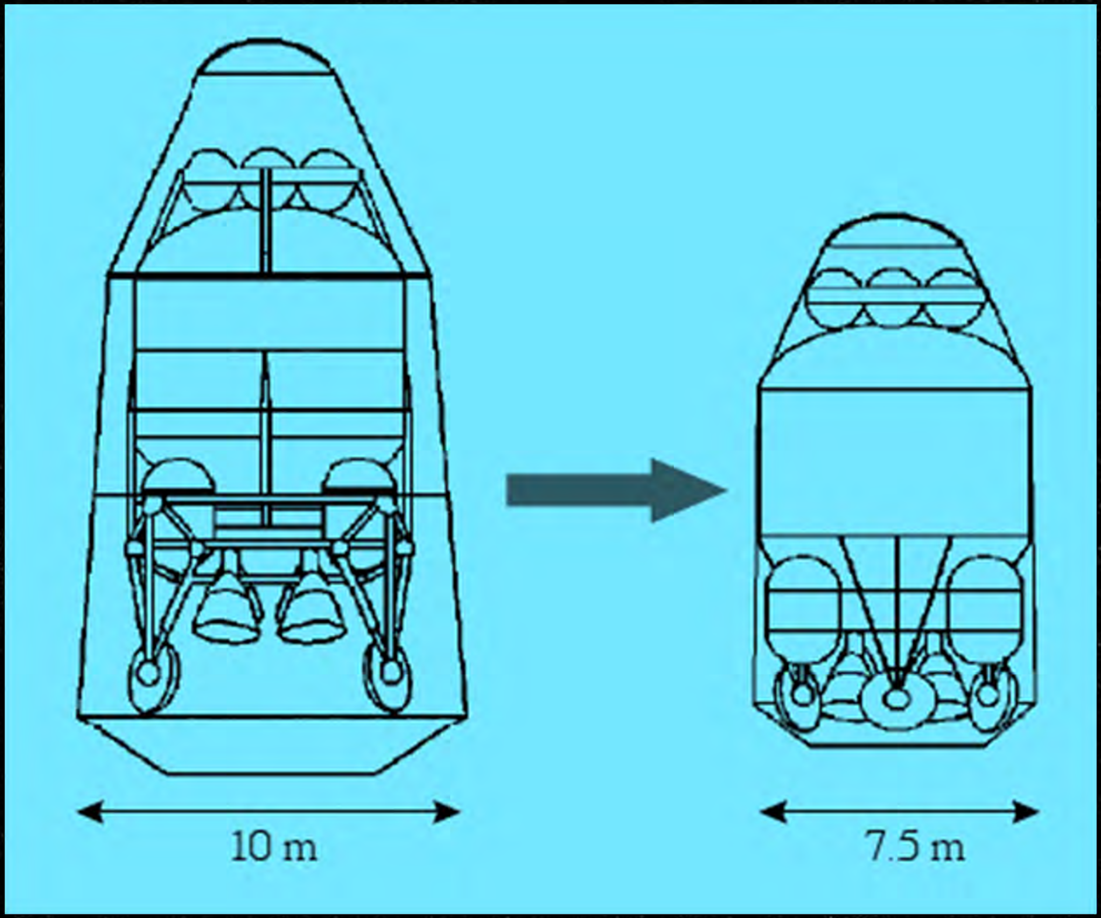
DRM1 Biconic Aeroshell Dimensions for Mars Lander and Surface Habitat Modules



Reference Biconic: 10 (m) Dia by 15 (m) length. 1/D = 0.65 At 25° Angle of Attack

Extended Center Section Biconic 10 (m) Dia by 18 (m) length.

DRM3 Biconic Aeroshell Dimensions for Mars Habitat Module



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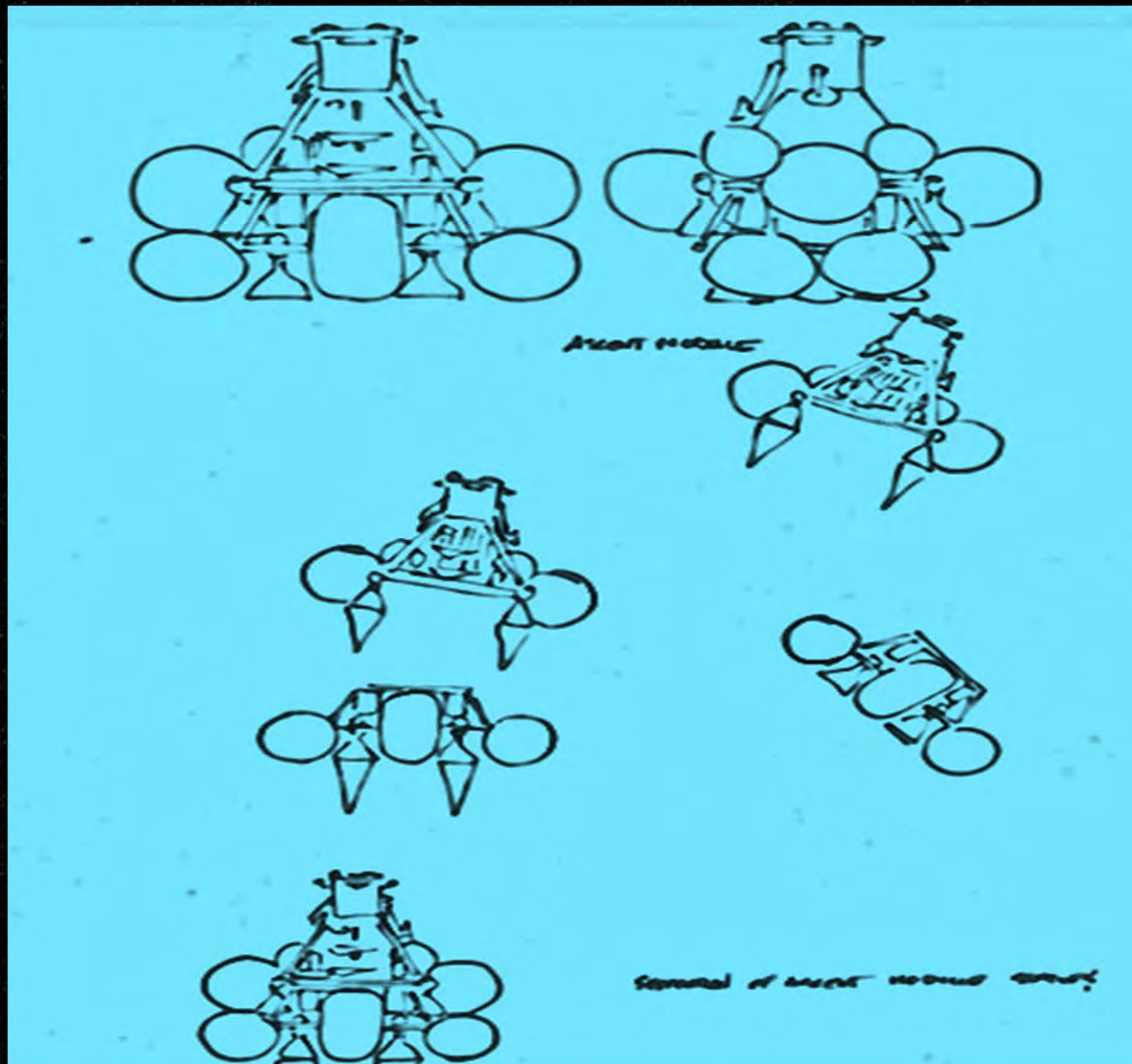
Two Stage Ascent Module



Nomenclature

A	= reference area of entry vehicle
a	= acceleration
C_D	= drag coefficient
C_L	= lift coefficient
D	= drag
g	= acceleration of gravity
h_∞	= freestream enthalpy
L	= lift
m	= vehicle mass
R_o	= planetary radius
rn	= nose radius
V	= flight velocity (m/s)
W	= vehicle weight
α	= angle of attack
γ	= flight path angle
Λ	= sweepback angle
ρ	= free stream density (kg/m^3)
$\Delta\gamma_E$	= flight path entry angle

Major References

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