IPPW5-short course lecture 4 Atmospheric reentry

EADS Astrium Space Transportation

J. MOULIN, J.M. BOUILLY

23-24 June 2007

All the space you need

EADS astrium

Objectives of this short course

- To focus on design of vehicle or mission of interplanetary mission,
- To present mainly the system aspects fo the atmospheric entry or re-entry.
- <u>This course is in interface with other presentations :</u>
- To introduce the main notions and concepts with more physics than mathematics.
- To illustrate with some missions

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

What is reentry?

- It is a phase during which a vehicle cross the atmosphere of planet or satellite (Venus, earth, mars, Jupiter, Titan,…) in order to decrease its kinetic and potential energies.

- This kinetic energy is mainly transformed in thermal and radiative powers which are transferred to the vehicle and to atmosphere surrounding the vehicle

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

CLASSES OF VEHICLES

VEHICLE

BALLISTIC BODY :

HUYGENS, BEAGLE 2, ...

→ No CONTROL, open loop

LIFTING BODY :

shuttle, CRV, ARD, ...

→ CONTROLLED :

VIKING, AFE shape

The majority of interplanetary vehicles do not have any main propulsion system

→ They mainly use the aerodynamic forces to decelerate and to manage the re-entry trajectory.

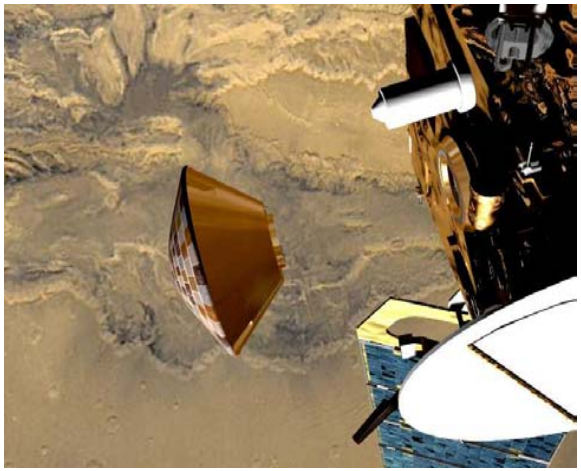
Small thrusters can be used for the landing (in controlled/none controlled mode)

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Examples of ballistic bodies

Pathfinder (Mars, USA)

Huygens probe

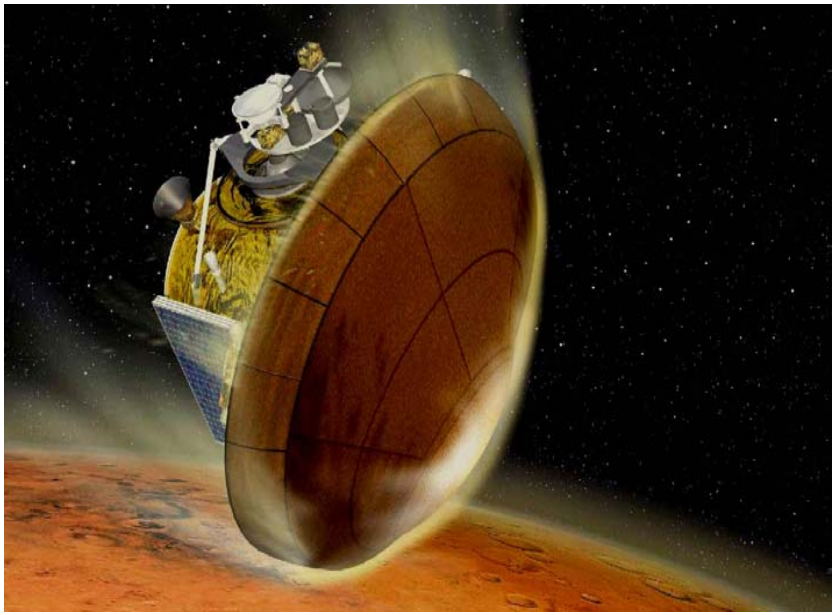


Beagle 2 (ESA courtesy)

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

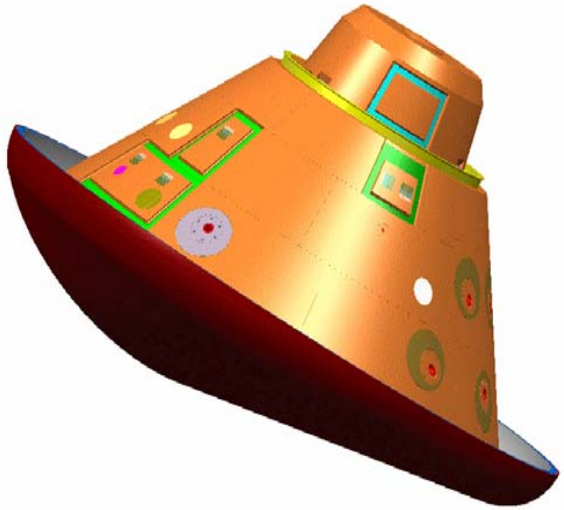
AEROCAPTURE (lifting body)

- Mars Sample Return



CNES courtesy

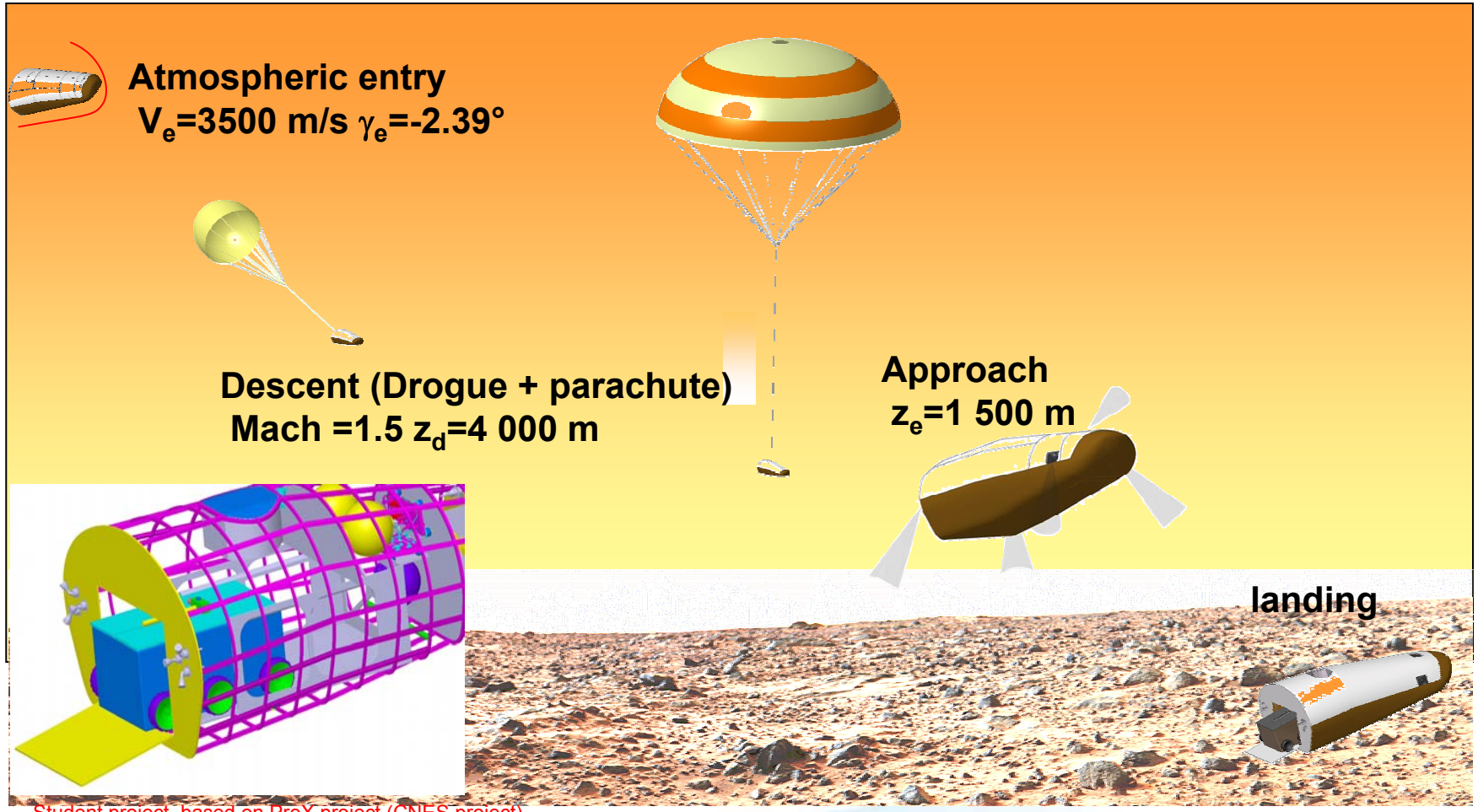
- Aerocapture demonstrator



ASTRIUM ST proposal
based on ARD heritage

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Mars mission with lifting body



Student project based on PreX project (CNES project)
Alexandre Tellier, ESTACA 2003

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

3 Main requirements for operational vehicles

A good compromise should be between

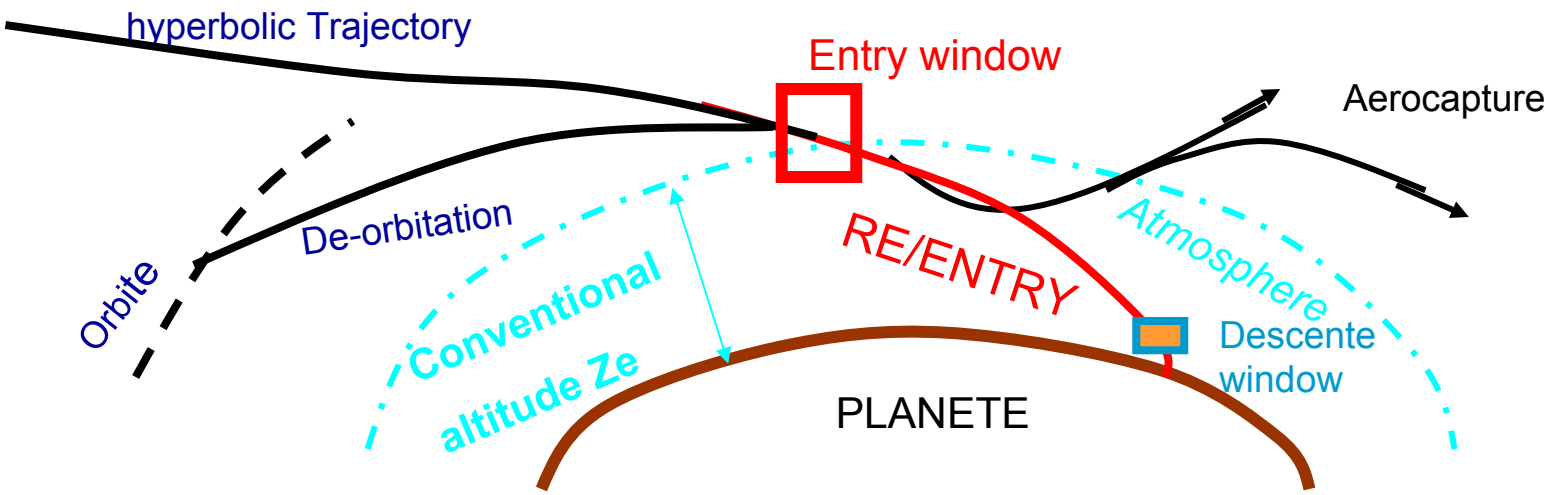
- ⇨Deceleration
  - limited by the structure and the pay-load of the vehicle
- ⇨Heating
  - Heat flux
  - Heat load
- ⇨Accuracy
  - On board navigation & control capabilities
  - Mainly fonction of the trajectory and of vehicle concept

while mastering vehicle attitude

Additionnal requirements for entry experimental vehicle

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

ENTRY PHASE I/F



Initial orbital trajectory, manœuver (orientation , ΔV)

ENTRY

ENTRY WINDOW

Partial : aerobracking or aerocapture

complete

end of entry

landing

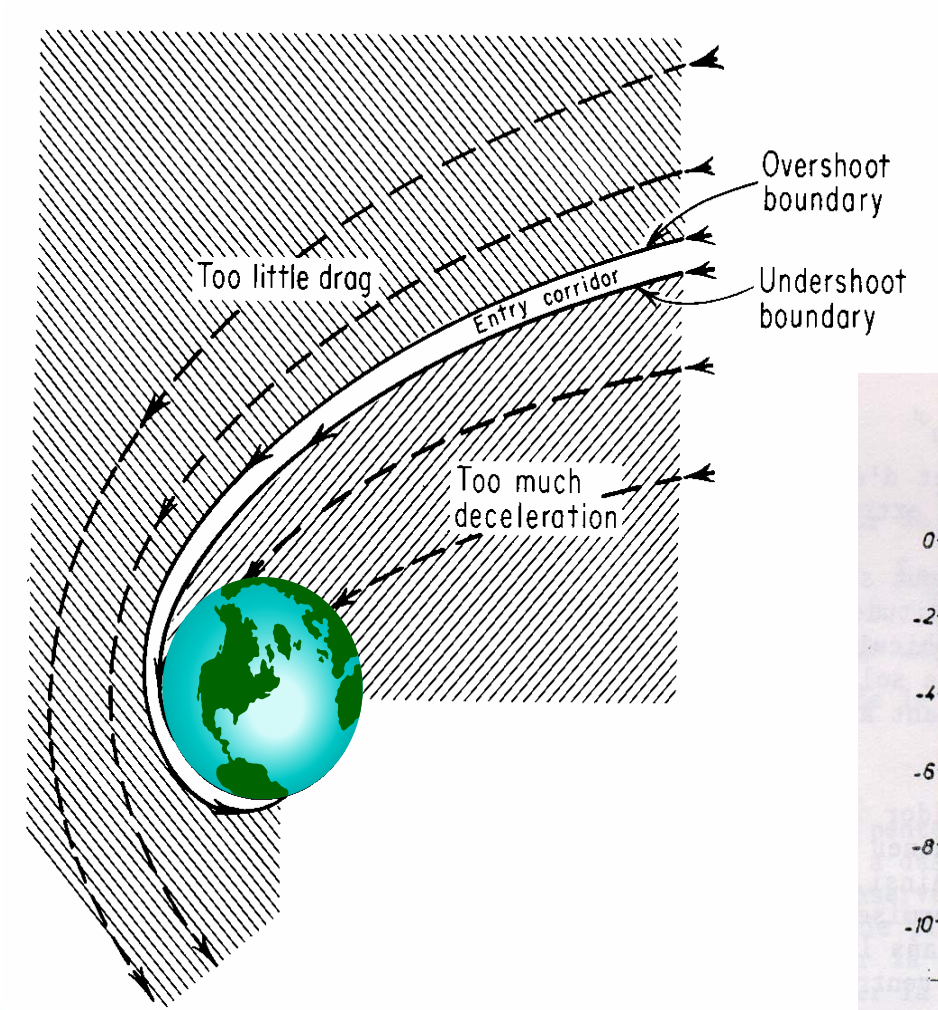
Manœuver for energy management

Descent under parachute

Descent window

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Entry corridor

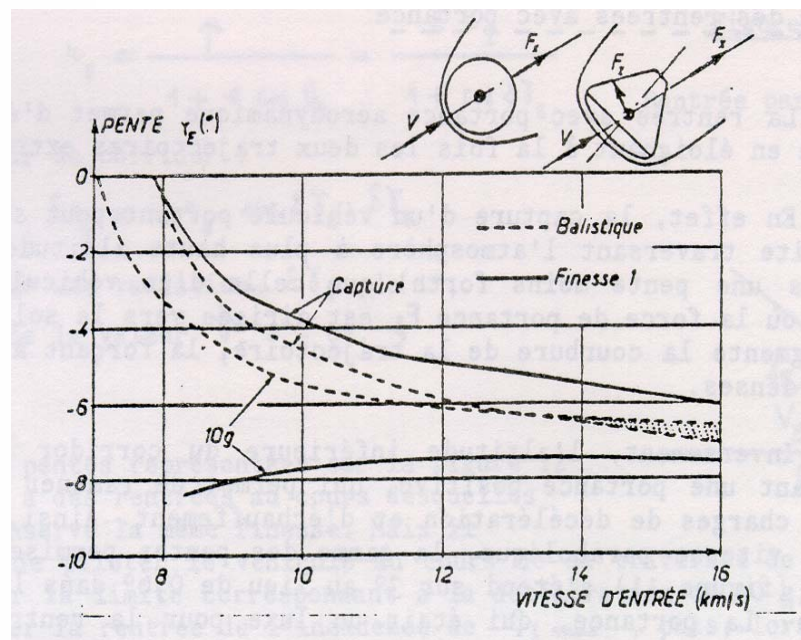


Entry Relative Velocity Ve

Entry relative flight path angle γe

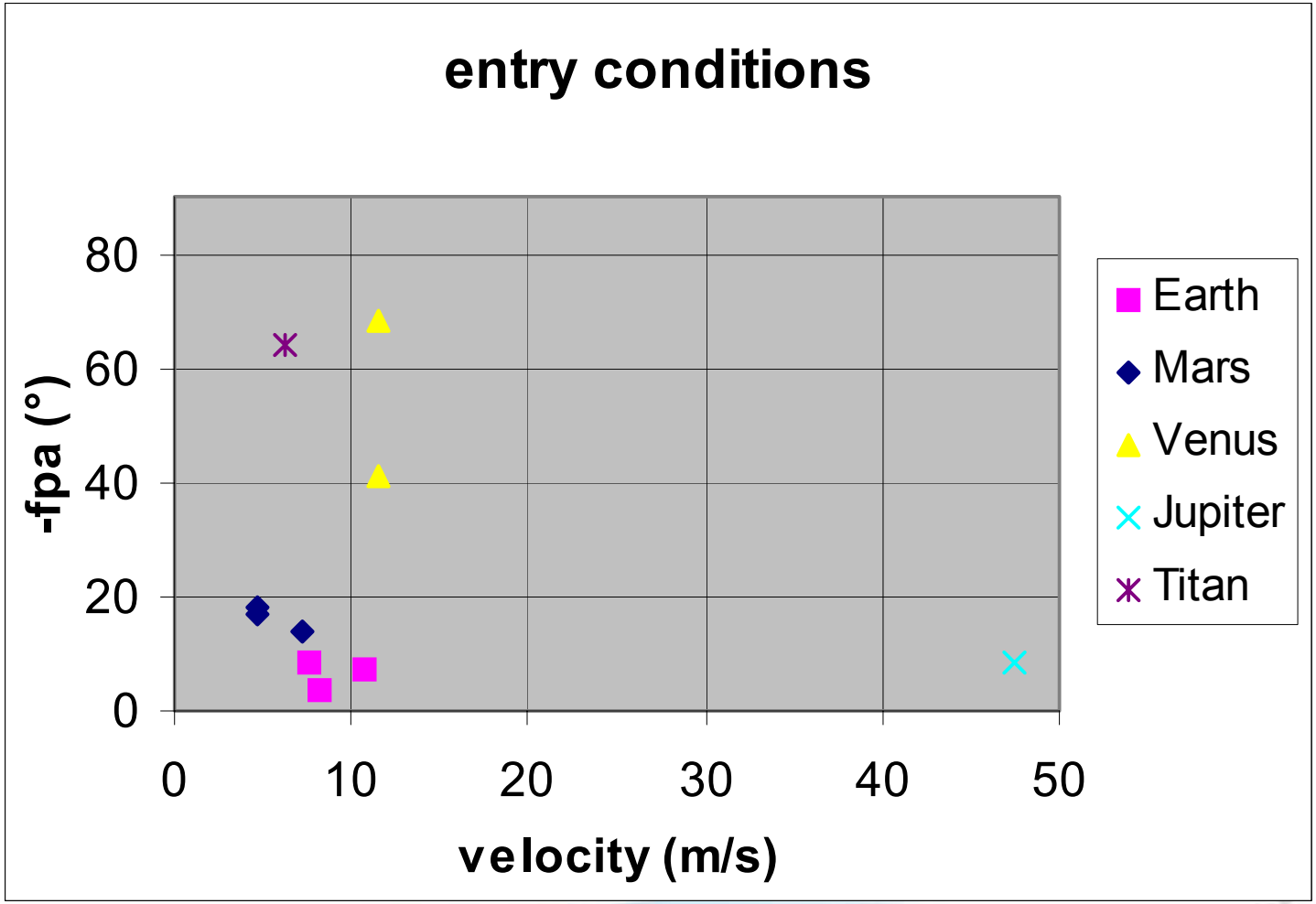
Ze

Key parameters of the entry



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Typical entry I/F parameters



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

IMPACTS OF THE ATMOSPHERE

CHEMICAL COMPOSITION :

==> influence on real gas effect

DUST

==> mechanical erosion

THERMODYNAMIC PARAMETERS (p, ρ,T) = F(z)

==> important dispersions on ρ , impact on aérodynamic et aérothermic

Wind :

- quasi-static component

==> influence on trajectory and guidance

- turbulence Wt

==> influence on stability and control,

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerodynamics (1/5)

Lift = Fl = ½ρV² S C_L

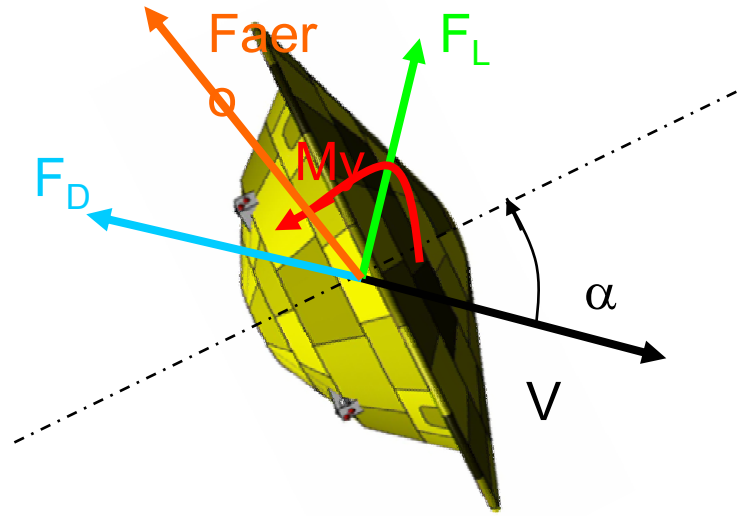
Drag = Fd = ½ρV² S C_D

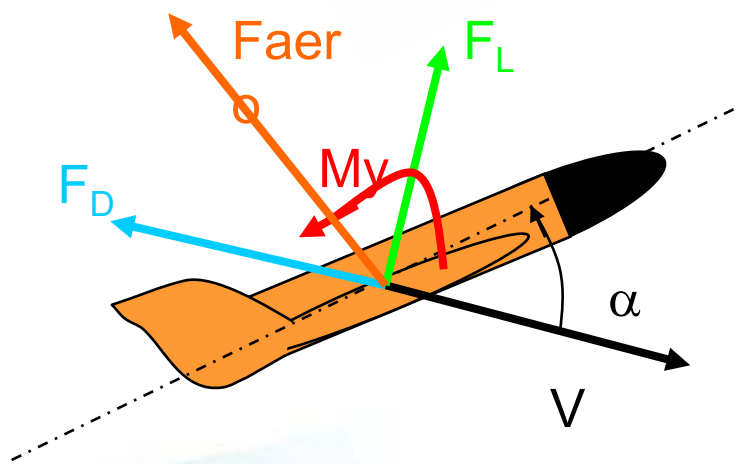
Pitching moment : My = ½ρV² S L Cm

Lift to Drag ratio : L/D = Lift / Drag

Dynamic Pressure Pdyn = ½ρV²
α = angle of attack
V = aerodynamic velocity

C_L, C_D, Cm = f(α,Mach, ...)
L/D = C_L/ C_D = f(α,Mach)



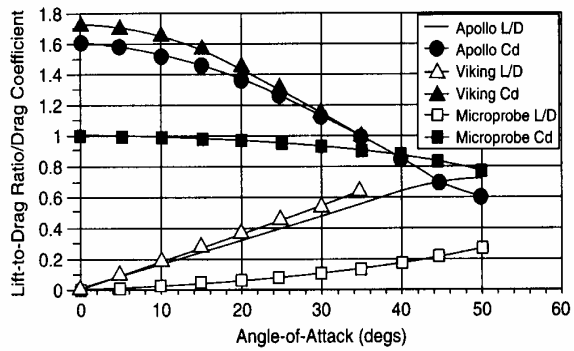


This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerodynamics (2/5)

L/D versus AoA for different types of vehicles

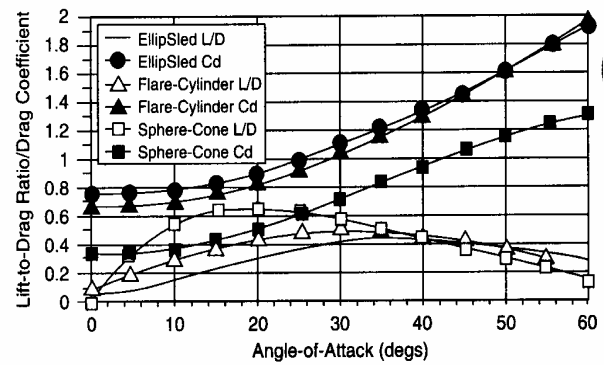
a. Low L/D
(0 – 0.5)



Capsule

Apollo	L/D = 0,3	α=20°
Viking	L/D = 0,17	α=10°
MicroProbe	L/D = 0,02	α=10°

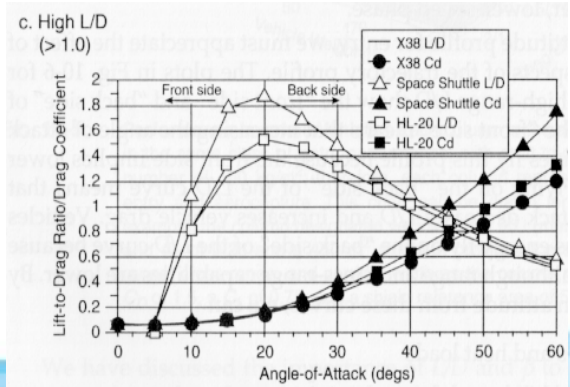
b. Mid L/D
(0.5 – 1.0)



Biconic

EllipSled	L/D = 0,40	α =45°
Cylindre-cône	L/D = 0,5	α =35°
Sphère-cône	L/D = 0,6	α =20°

c. High L/D
(> 1.0)



spaceplane

HL-20	L/D = 1,5	α =20°
X-38	L/D = 1,4	α =20°
Navette spatiale	L/D = 1,9	α =20°

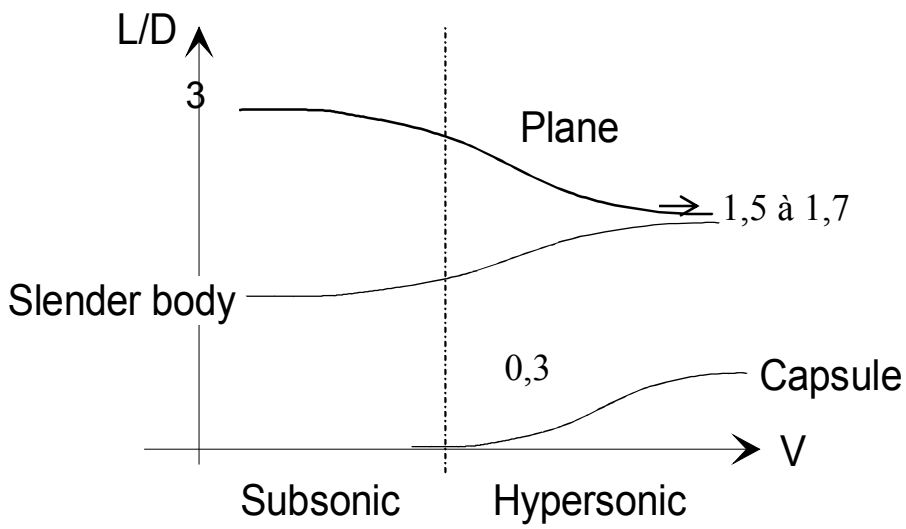
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerodynamics (3/5)

Hypersonic & subsonic L/D

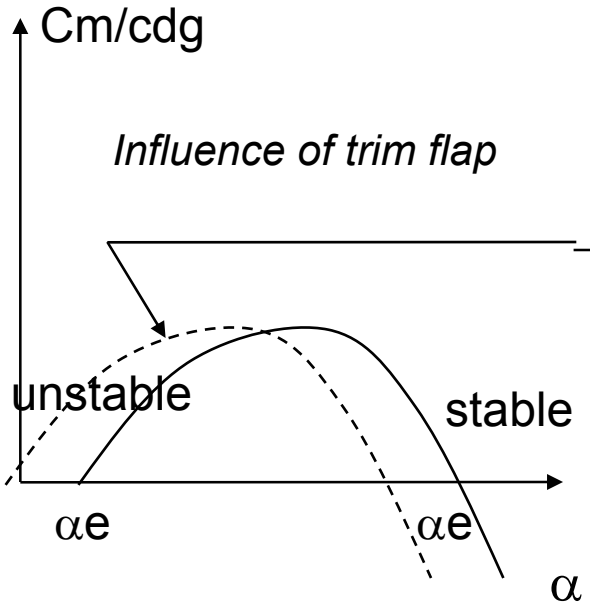
The subsonic L/D induces the landing capability

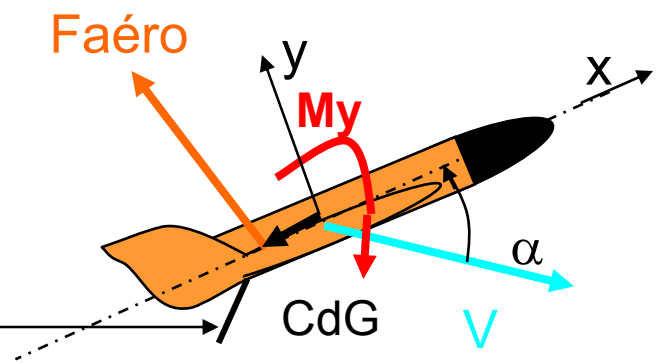
Le hypersonic L/D drives the down range and the cross range

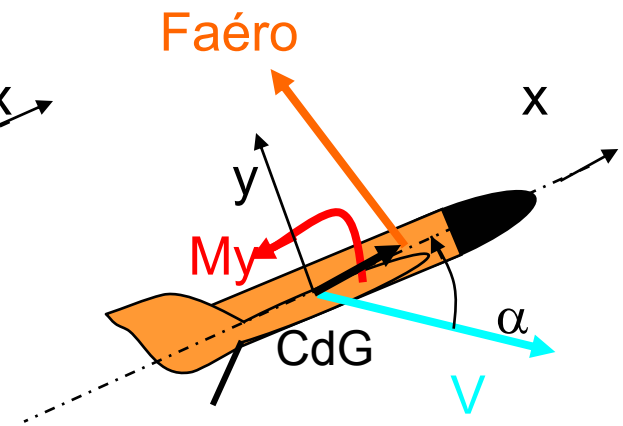


This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerodynamics (4/5)







aerodynamic stable

Xcp-Xcdg < 0

Aerodynamic unstable

Xcp-Xcdg > 0

with Xcp = Center of pressure and $\partial Cn/\partial\alpha > 0$

Cm(αe) = 0 => αe = trim AoA ==> **trim L/D**

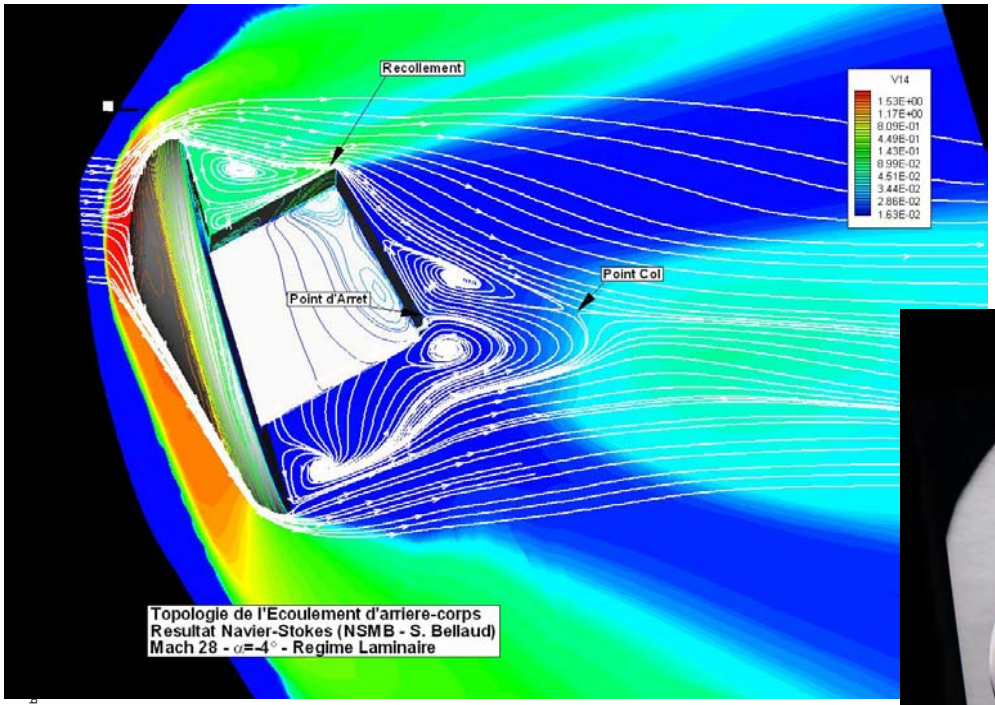
==> **major importance of the mass centering of the vehicle**

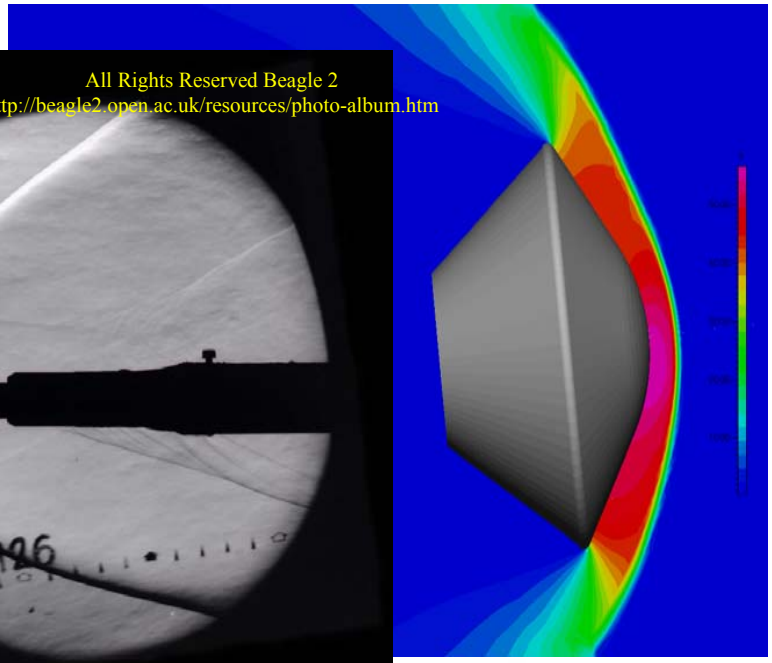
∂Cm/$\partial\alpha$ > 0 = > unstable** equilibrium **∂Cm/$\partial\alpha$ < 0 = > stable equilibrium

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerodynamics (5/5)

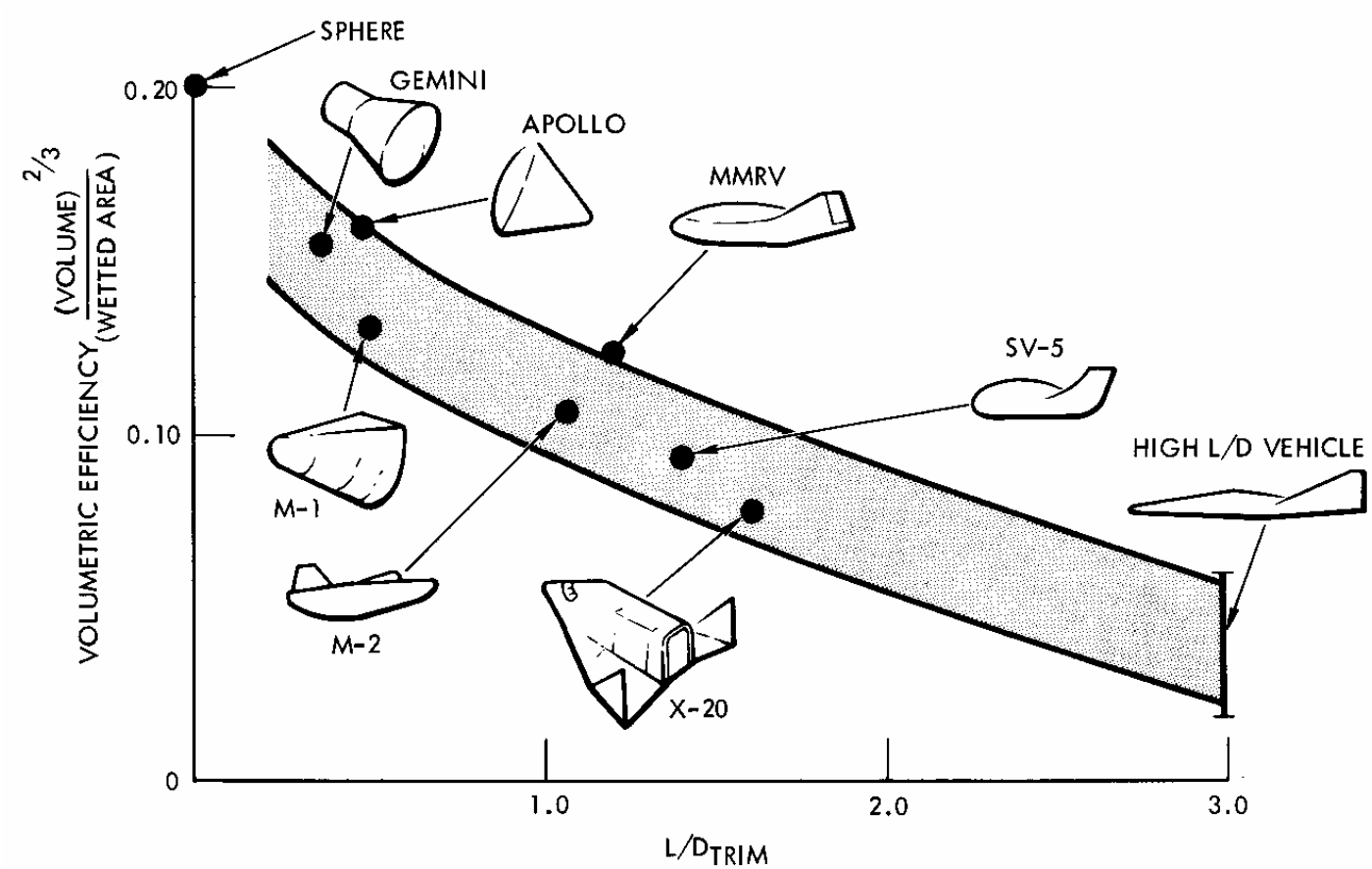
Aerodynamic charaterisation





This document is the property of Astrium. It shall not b

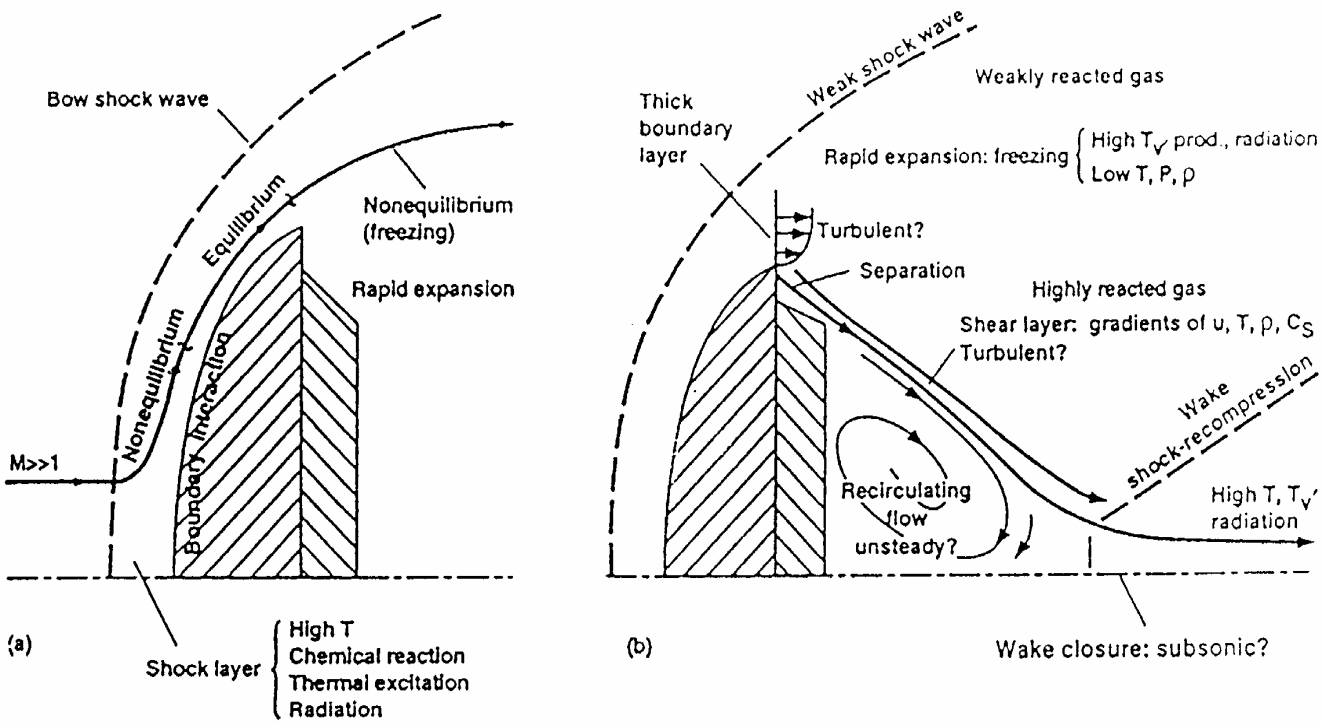
Volumic efficiency



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerothermodynamics (1/3)

Physical Phenomena



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerothermodynamics (2/3)

Convective heat flux (Fay - Riddell)

$$\phi = 1{,}705.10^{-4}\sqrt{\frac{\rho}{R_N}}V^3$$

Φ = stagnation heat flux (w/m2)

Rn = nose radius (m)

V = aerodynamic velocity (m/s)

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Aerothermodynamics (3/3)

Thermal behaviour on skin

convection+radiation of gas+ablation heat = skin radiation + blocage+ conduction

In first appproach , $\Phi = \varepsilon\sigma T^4$ with $\sigma = 5.67\ 10^{-8}$ and ε = f(matériaux)

➔Radiative equilibrium heat flux (first assessment of temperature mapping)

Interaction of the material properties

- if ablative ➔ flux ↘

(*product of pyrolyse ➔ recombination chemistry in the flow field, blocage)*

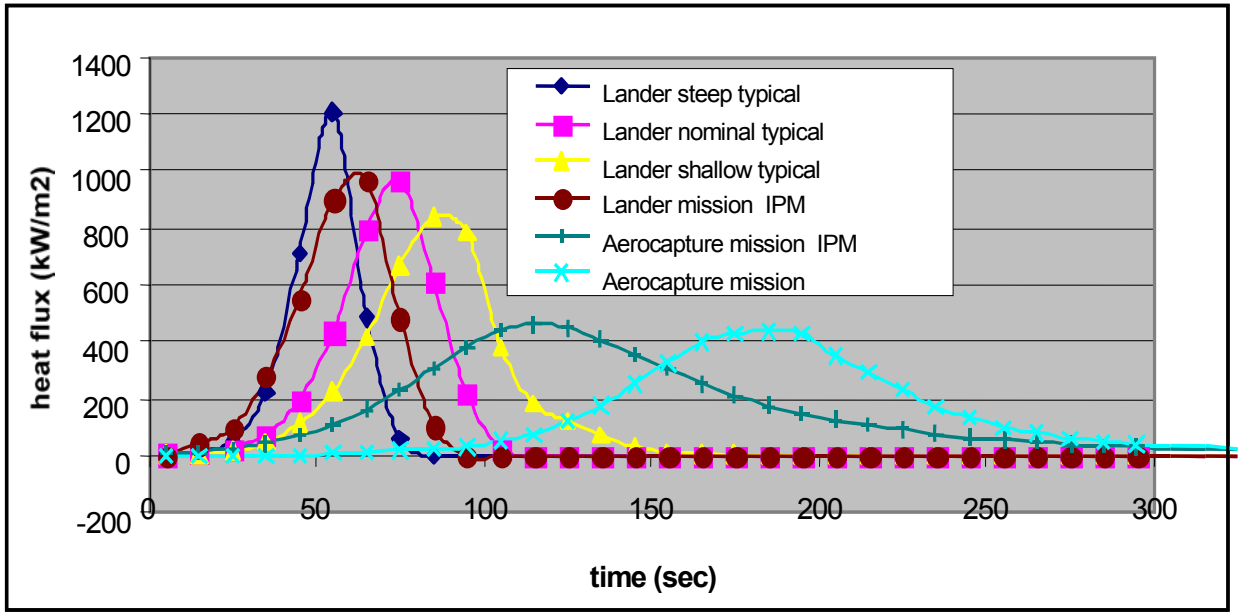
- if catalytic ➔ chemical reaction is boosted ➔ flux ↗

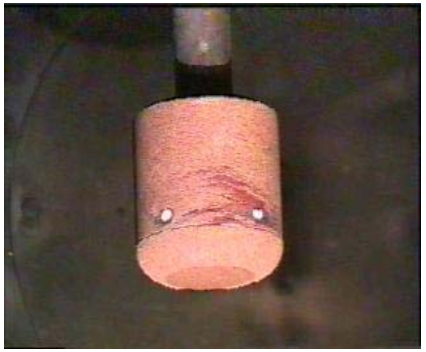
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Thermal protection tests : example on « Norcoat liege »

Tests Conditions :

- **stagnation point**
- **atmosphère CO_2**
- **representative heat flux profiles for various missions**





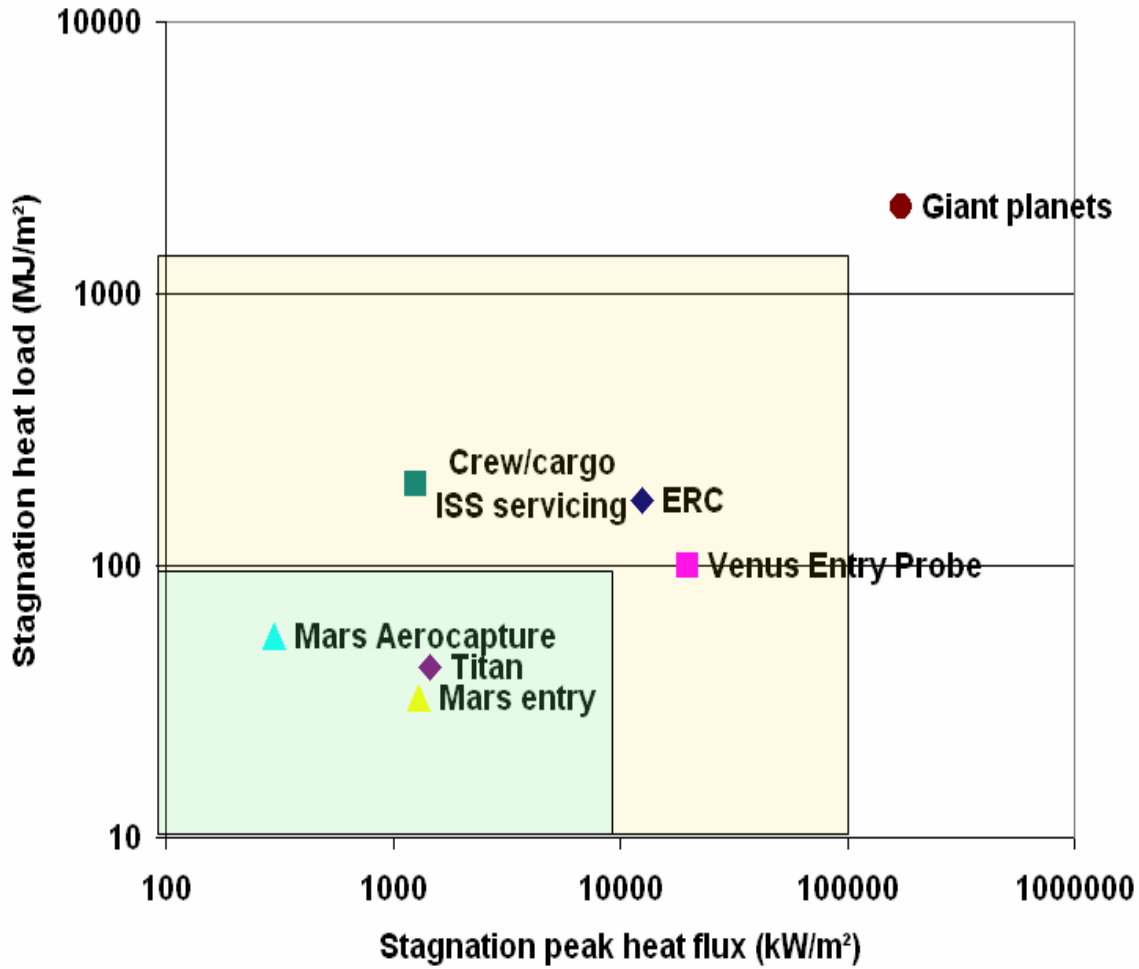
Comete facility

ablation < 1 mm

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Typical orders of magnitude for identified missions

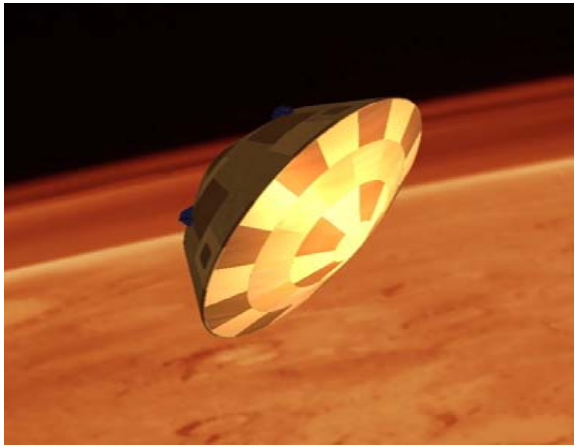
Different categories of missions, requiring different classes of materials

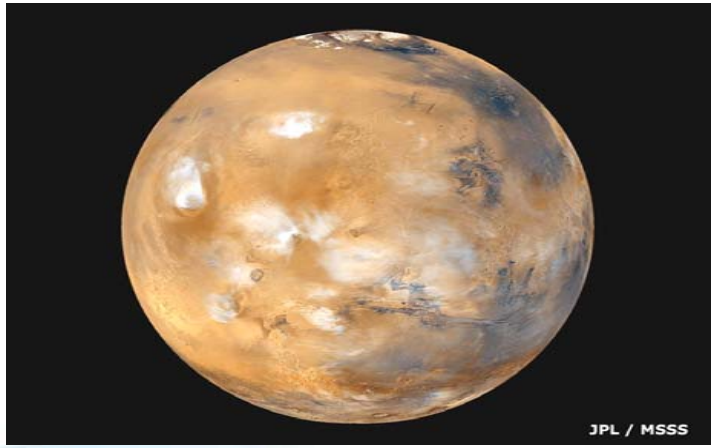


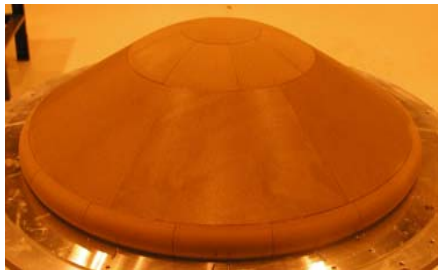
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Review of envisioned missions
Planetary exploration - Mars

- Entry : 1000-1600 kW/m²
  25-40 MJ/m²
- Aerocapture : 200-400 kW/m²
  45-65 MJ/m²
- CO2 and dust particles
- Planetary protection
- Norcoat-Liege experience fully applicable







Beagle 2 TPS

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Review of envisioned missions
Planetary exploration - Venus

- Similarity to small Pioneer-Venus probes
- Heat flux : ~20000 kW/m²
- Heat load : ~ 100±20 MJ/m²
- CO2 atmosphere
- Carbon / Phenolic is the first proposed concept
- Interest of solutions developed for Sample Return Capsules

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Review of envisioned missions
Planetary exploration - Titan

HUYGENS values

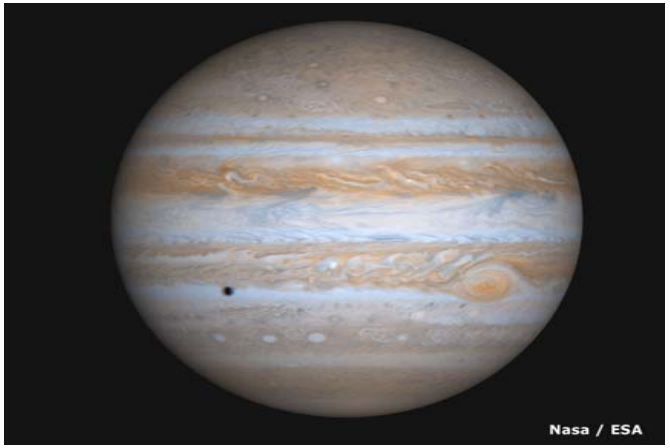
- Heat flux : 1300-1600 kW/m²
- Heat load : 40-45 MJ/m²
- CH4 + N2 atmosphere
- High radiation

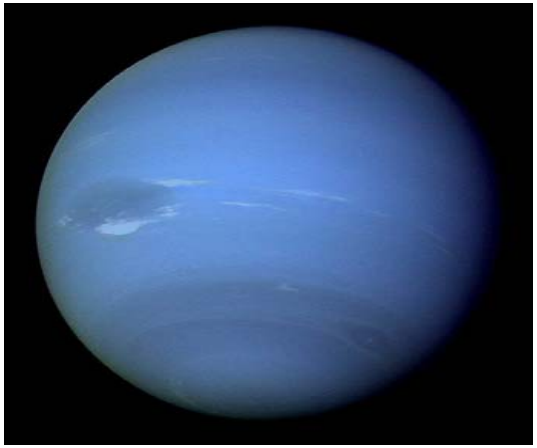
- Experience of available materials is applicable (AQ60, also Norcoat-Liege)

- Transparency in the UV range is no longer a concern

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Review of envisioned missions
Planetary exploration – Giant planets





- Very demanding environment
- Heat flux 170 000 kW/m²
  Heat load 2000 MJ/m²
- Any material behaves as an ablator
- Dense carbon/phenolic is the basic solution
- C/C or C/SiC probably less suitable
- Qualification is of concern

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Ballistic reentry trajectories (L/D = 0) (1/3)

Major assumptions

- $\rho = \rho_0 e^{-bz}$ (z in m) with ρ_0 = 1.225 kg/m3 et b = 0.14 10-3 (SI, on Earth)
- aerodynamic >> weight force
- if $\frac{L}{D} = 0 \Rightarrow \gamma = Cste$
- Then $V = V_E e^{-\lambda\rho}$ with $\lambda = \frac{\beta}{2b\sin\gamma_E}$ $\beta = \frac{SCx}{m} = ballistic-ratio$

and S = reference area , m = vehicle mass

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Ballistic reentry trajectories (L/D = 0) (2/3)

parameters / Maximum	ρ_M	Z_M	$\frac{V_M}{V_E}$	$Pdyn$	$deceleration$	$Flux$
$Pdyn$	$\frac{1}{2\lambda}$	$\frac{1}{b}\log\frac{\rho_0}{\rho_M}$	$e^{-\frac{1}{2}}=0{,}606$	$k=0{,}184$	$k=0{,}184$	$k=3{,}804.10^{-5}$
$Flux=\phi$ $\phi=1{,}705.10^{-4}\sqrt{\frac{\rho}{R_N}}V^3$	$\frac{1}{6\lambda}$	$\frac{1}{b}\log\frac{\rho_0}{\rho_M}$	$e^{-\frac{1}{6}}=0{,}846$	$k=3{,}71.10^{-2}$	$k=3{,}71.10^{-2}$	$k=5{,}97.10^{-5}$
				$kV_E^2\frac{b\sin\gamma_E}{\beta}$	$-kV_E^2 b\sin\gamma_E$	$kV_E^3\sqrt{\frac{b\sin\gamma_E}{\beta R_N}}$

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Ballistic reentry trajectories (L/D = 0) (3/3)

❑ Consequences

$$Z_{flux_\max} > Z_{pdyn_\max} \qquad \text{(or } Z_{décélération_\max} \text{)}$$

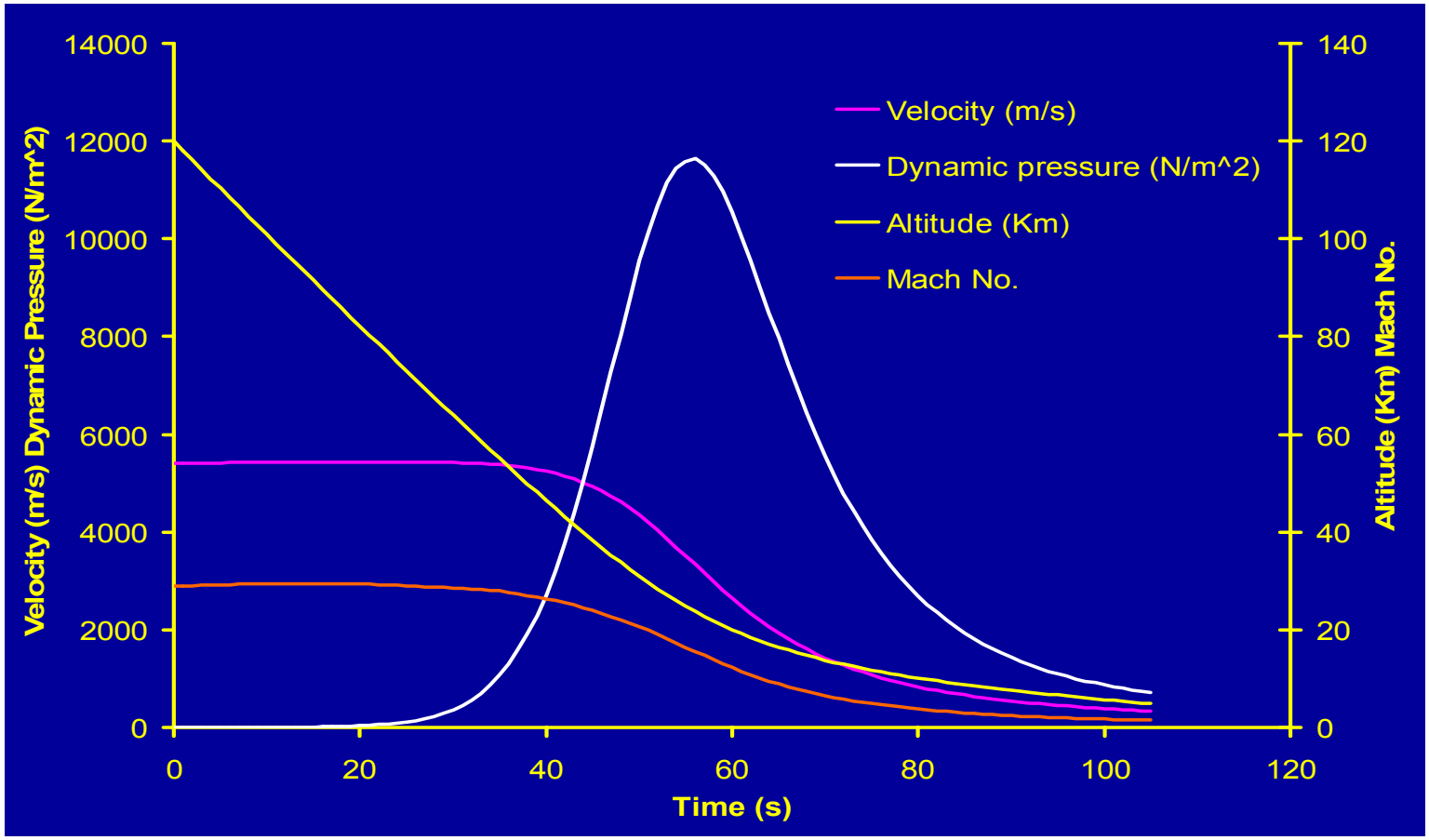
⇨ **The maximal deceleration depends only on reentry conditions at 120km atmosphere boundary (V_E, γ_E) and on the characteristics of atmosphere (b)**

⇨ **it does not depend on the ballistic coefficient**

⇨ **The heat flux depends on all the parameters (V_E, γ_E, β, b)**

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Mission description

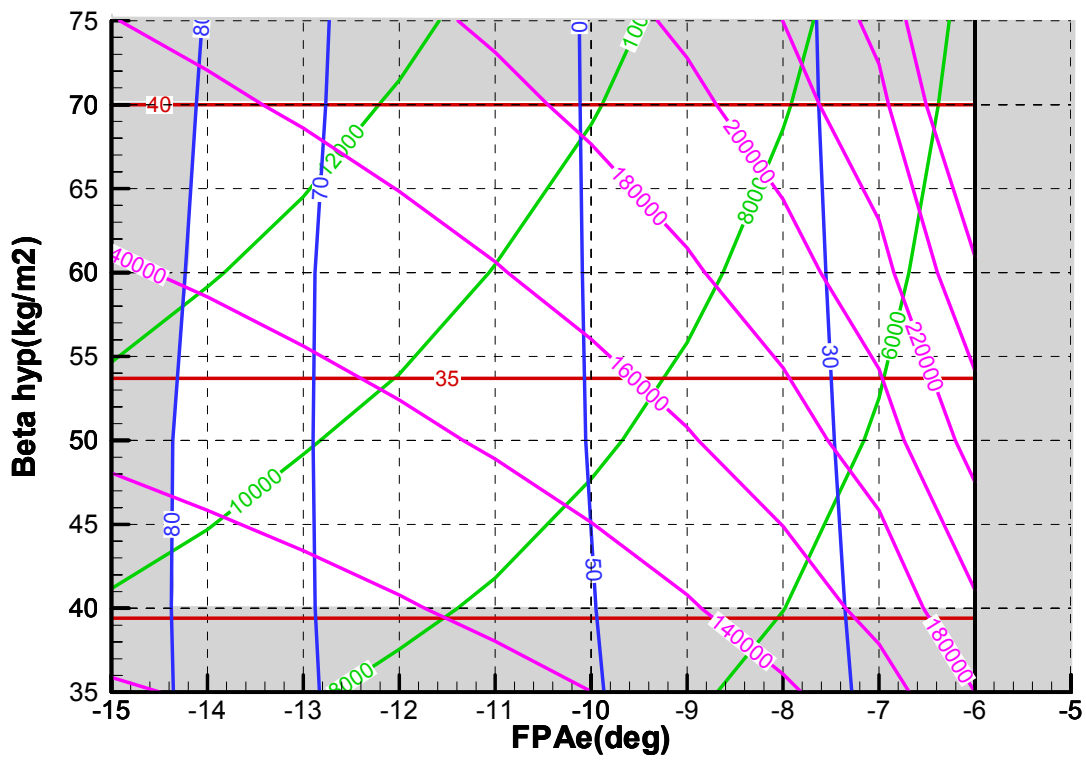


All Rights Reserved Beagle 2
http://beagle2.open.ac.uk/resources/photo-album.htm

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Illustration of flight domain assessment Case : AURORA EVD

- **FPAe limits :**
  - min = -6°
    - min value not to escape
  - max = -14°
    - max. acceleration acceptable wrt to probe structure => ≈ 80g's
- **β_{hyp} limits :**
  - max = 70 kg/m²
    - wrt max. impact velocity acceptable => 40m/s
  - min = 40 kg/m²
    - seems to be a reasonable technology limit (TBC)
- **First flight domain obtained**
  - 40 kg/m² < β_{hyp} < 70 kg/m²
  - -14° < FPAe < -6° (without margins)



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Ballistic reentry flight management

Flight stability

The motion about the CoG is driven by the following equations

$$[I]\frac{d\vec{\Omega}}{dt} + \vec{\Omega} \wedge [I]\vec{\Omega} = \sum \vec{M}_a$$

With $[I]$ *inertia matrix,* $\vec{\Omega}$ *rotation vector,* $\vec{M}_a$ *aerodynamic torques*

By considering only planar angular motion this system of equations becomes

$$\alpha'' + 2Amq\alpha' + Am_\alpha \alpha = 0$$

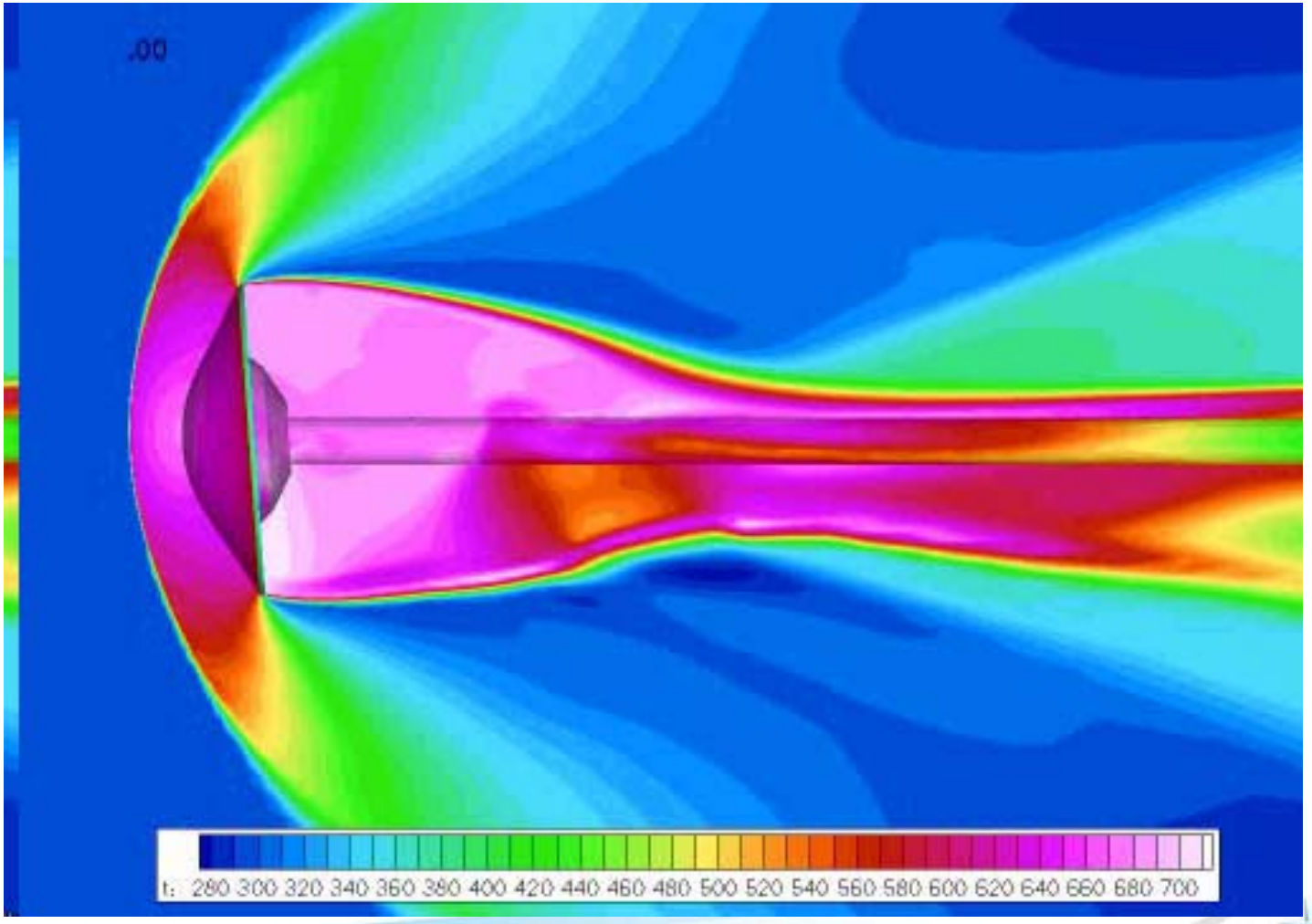
With a dynamic term $Amq = f(Cmq, Cm_\alpha)$ *,*

and a static term $Am_\alpha = f(x_{CoG} - x_{cp}, Cn_\alpha) = f(Cm_\alpha)$

- ⇨ Prime importance of Cmq for damping
- ⇨ Prime importance of Xcog/Xcp relative location

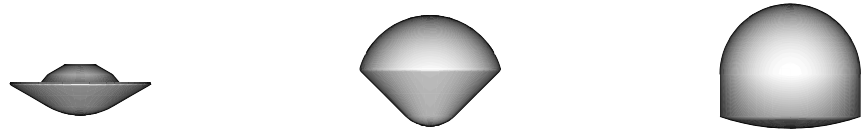
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Dynamic stability of capsules :Huygens shape



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

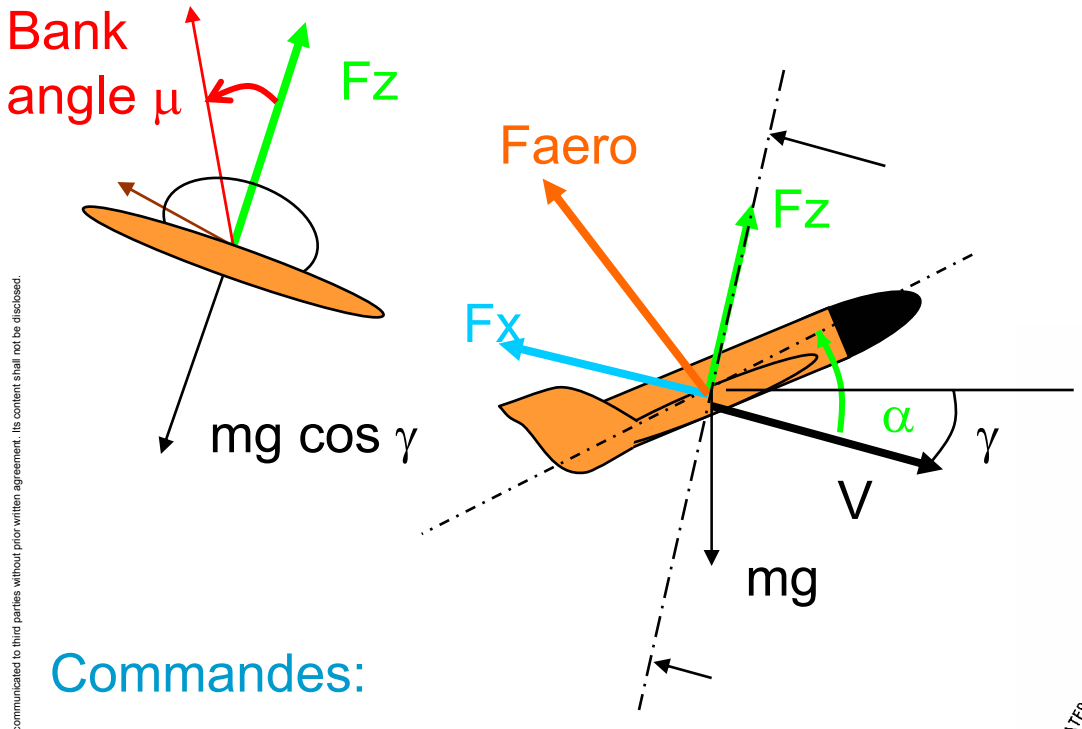
Illustration of criteria for shape selection
Case : AURORA EVD

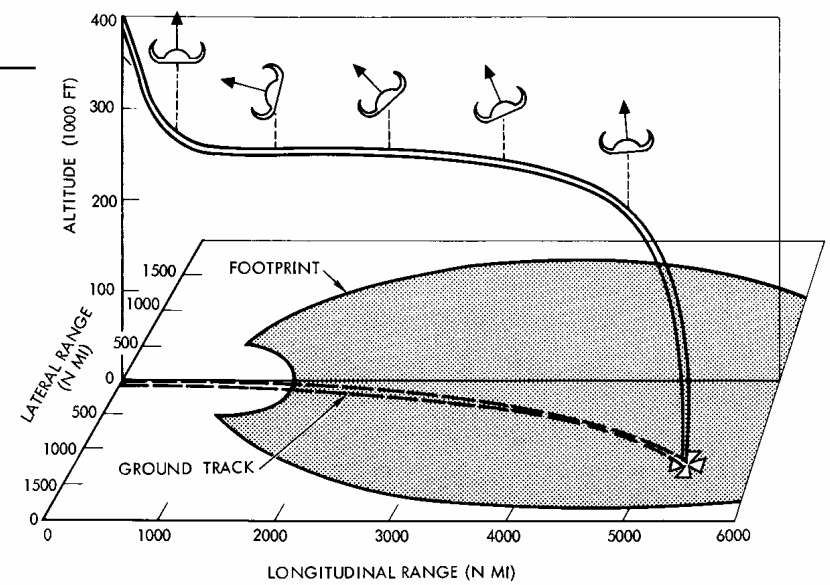


		"HUYGENS"	"MARS MICROPROBE"	"ISTC"
Probe Stability	High altitude stability for	XG/D < 23,02%	XG/D < 40.87%	XG/D < 23.94%
	Hypersonic single stable position for	XG/D < 3.5%	XG/D < 27%	XG/D < 32%
	Transonic stability	Dynamically unstable but may reach a ~12° limit cycle for XG/D=17% (TBC)	Dynamically stable for XG/D=26.55%, CoG=centre of hemispherical afterbody	Dynamically stable for XG/D=38.7% due to its hemispherical afterbody (TBC)
	Subsonic stability	dyn. unstable (TBC)	dyn. stable	dyn. unstable (TBC)
TPS design	Heat Flux	max Qt=9.2 MW/m²	max Qt=10.7 MW/m²	max Qt=8.2 MW/m²
	Heat Load (TPS sizing)	max H.L.=173 MJ/m²	max H.L.=227 MJ/m²	max H.L.=114 MJ/m²
Landing Phase	Conditions at impact	compliant with 30 m/s < Vi < 40 m/s range for mass ranging between **48.3 kg < M < 84.6 kg**	compliant with 30 m/s < Vi < 40 m/s range for mass ranging between **33 kg < M < 57.7 kg**	compliant with 30 m/s < Vi < 40 m/s range for mass ranging between **55 kg < M < 96.2 kg**

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

How to control a gliding vehicle in hypersonic regime





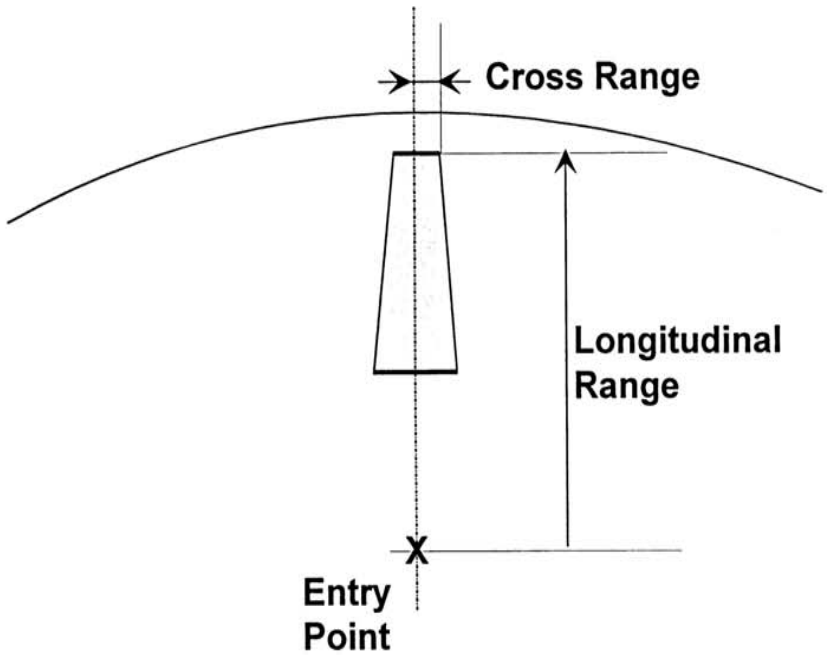
Commandes:

AoA= α : allows to manage aerodynamic forces F_L et F_D , and then the down range

Bank angle = μ : allows to manage the cross range

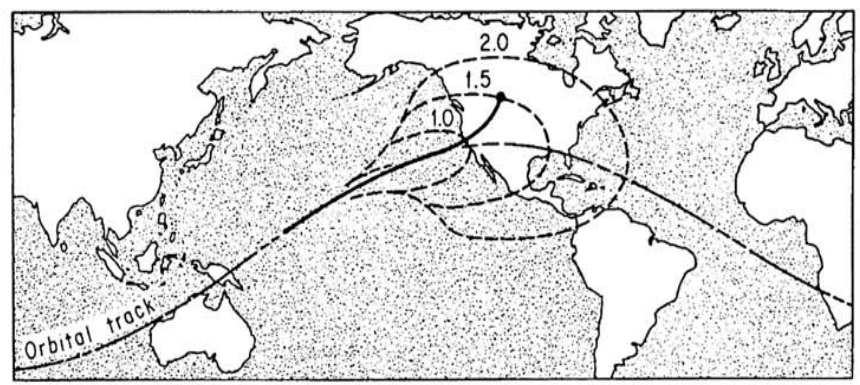
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Down range and cross range



Down range = K_1 (L/D)

Cross range = K_2 (L/D)²
with $K_2 \approx 1300$ km



This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Domain boundaries

- (1): limit of the control capability, gliding equilibrium

$$C_1 = (g\cos\gamma - \frac{V^2}{R}) - \frac{SC_L(\alpha, M)}{2m}\cos\mu\,\rho V^2$$

- (2): thermal limit, iso flux

$$C_2 = k\sqrt{\frac{\rho}{R_N}}V^3$$

- (3): deceleration limit,

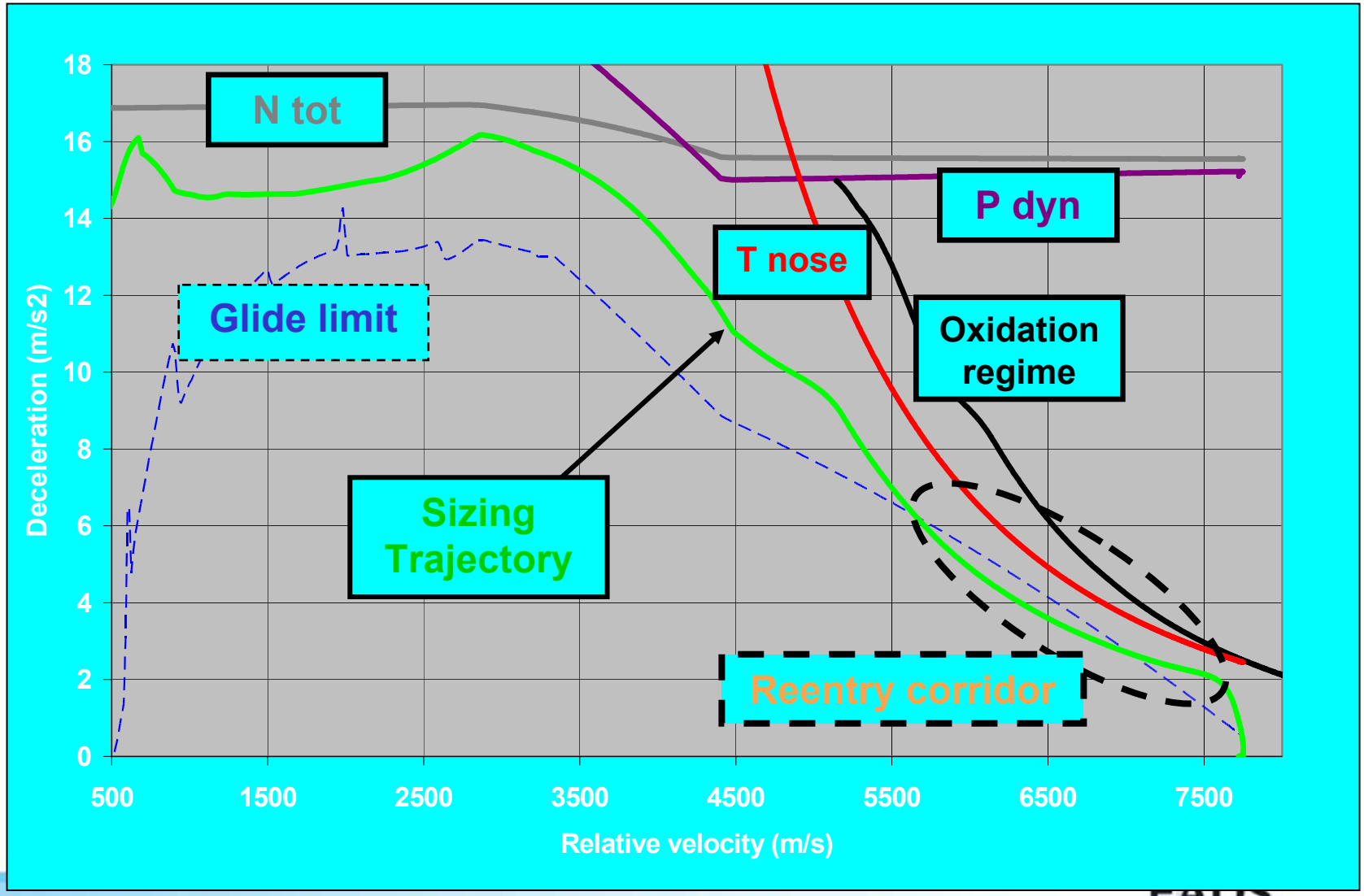
$$C_3 = g\sin\gamma - \frac{SCx(\alpha, M)}{2m}\rho V^2$$

- (4): dynamic pressure limit

$$C_4 = \frac{1}{2}\rho V^2$$

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

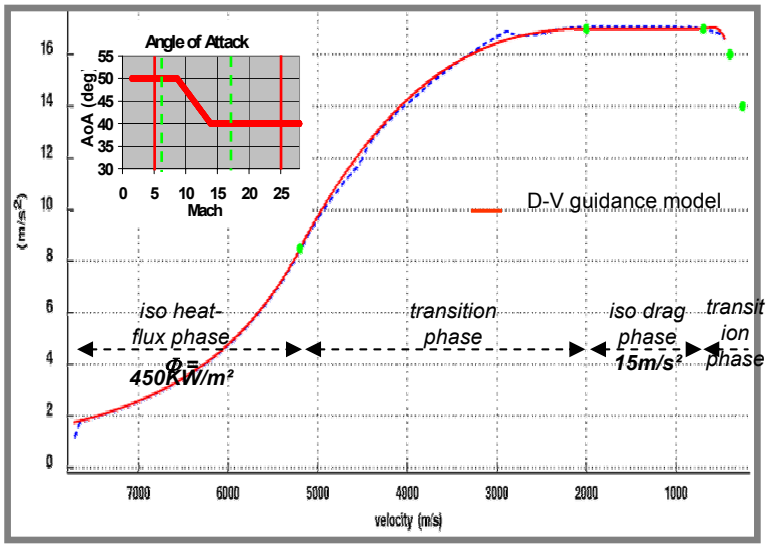
Example of Flight envelope : PreX case on Earth



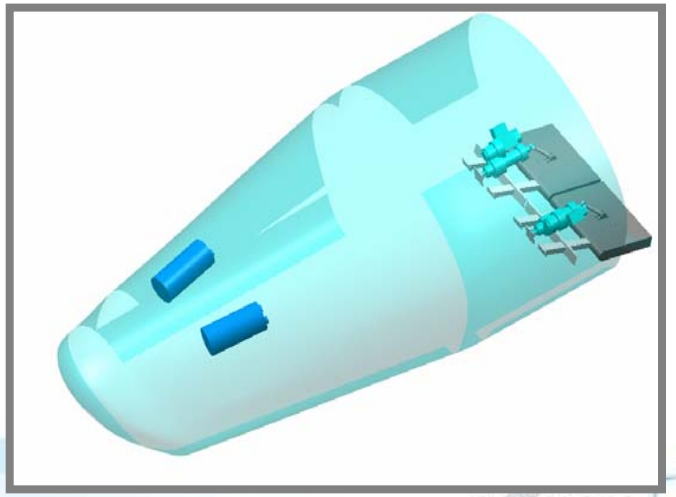
This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Examples of GNC function on PreX

- **The Guidance and Navigation Functions**
  - ⇨ **Principles directly derived from ARD flight proven experience (flight perfomed in 1998)**
    - Navigation : IMU (+GPS) & Drag Derived Altitude algorithm
    - Guidance : velocity vs. Drag profile



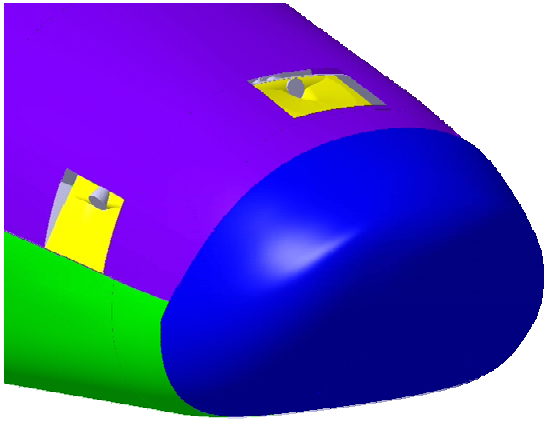
- **The Flight Control function :**
  - ⇨ **Reaction Control System (RCS)**
    - Ariane 5 H/W
  - ⇨ **Flap Control System (FCS)**
    - X-38 background

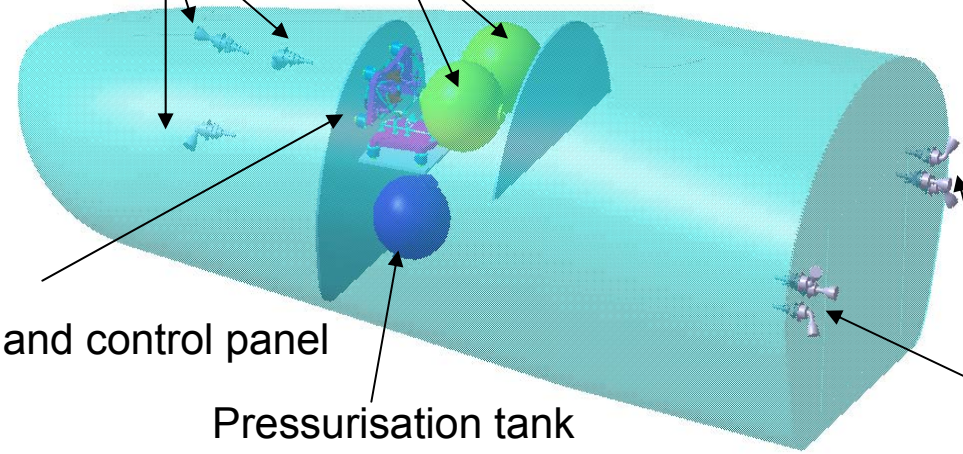


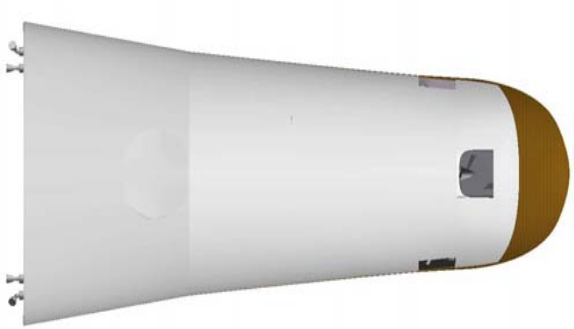
FCS

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Example of Control means : RCS



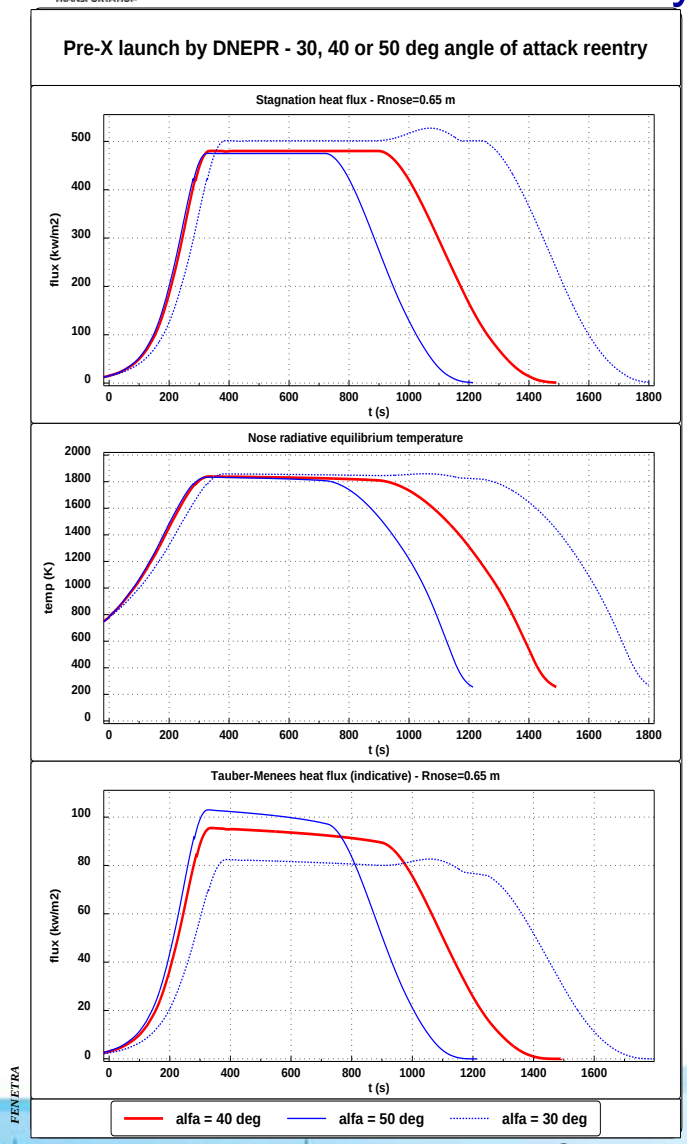


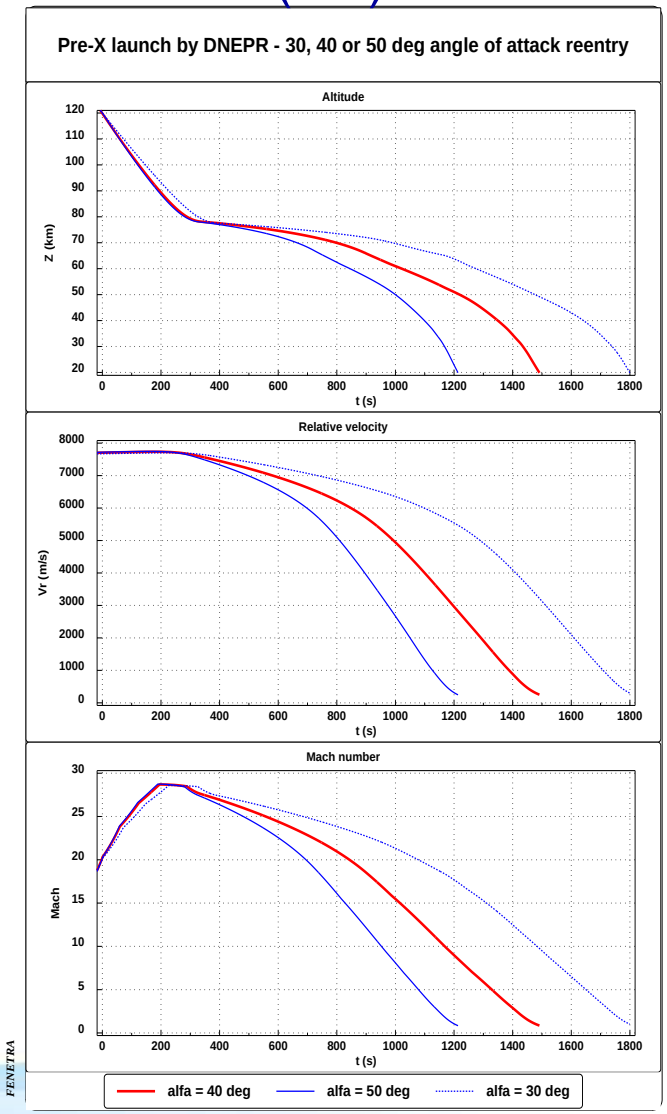


Student project based on PreX project (CNES project)
Alexandre Tellier, ESTACA 2003

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Examples of Re-entry gliding trajectories : Sensitivity to AOA law (1/2)



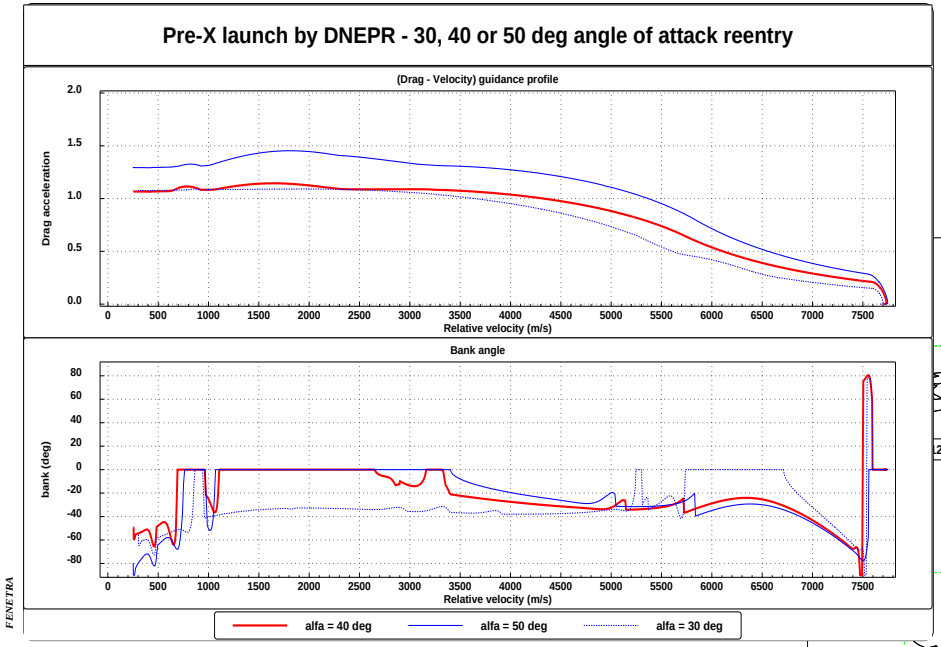


This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

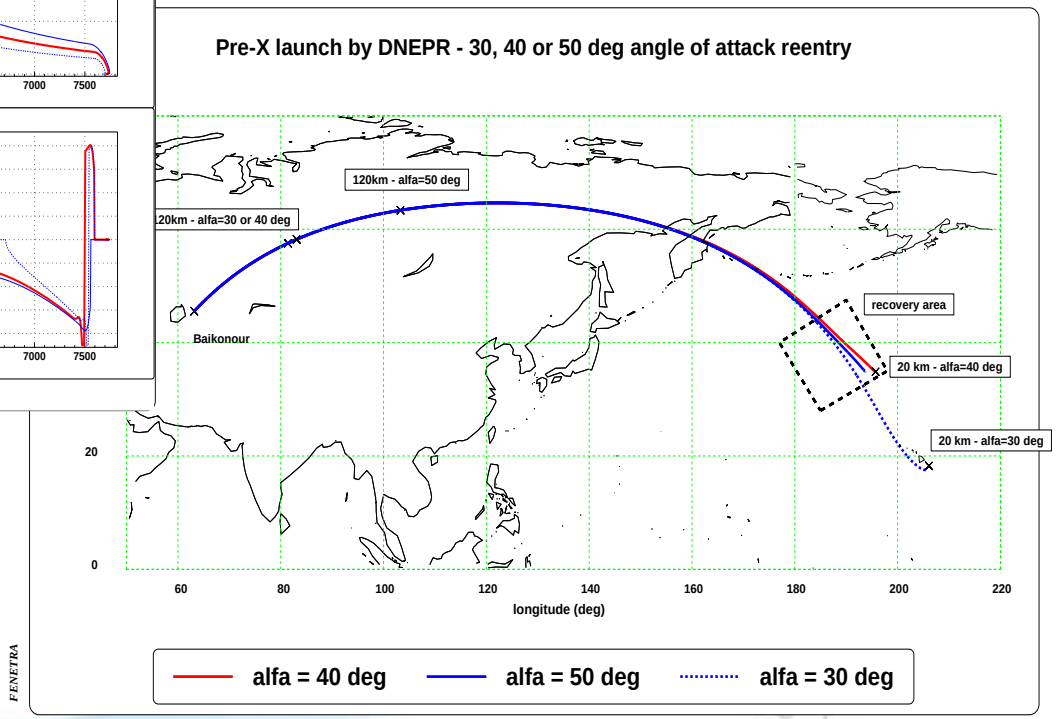
This document is the property of EADS SPACE Transportation and shall not be communicated to third parties and/or reproduced without prior written agreement. Its contents shall not be disclosed. © - EADS SPACE Transportation - 2004

This document is the property of EADS SPACE Transportation and shall not be communicated to third parties and/or reproduced without prior written agreement. Its contents shall not be disclosed. © - EADS SPACE Transportation - 2004

Examples of Re-entry gliding trajectories : Sensitivity to AOA law (2/2)



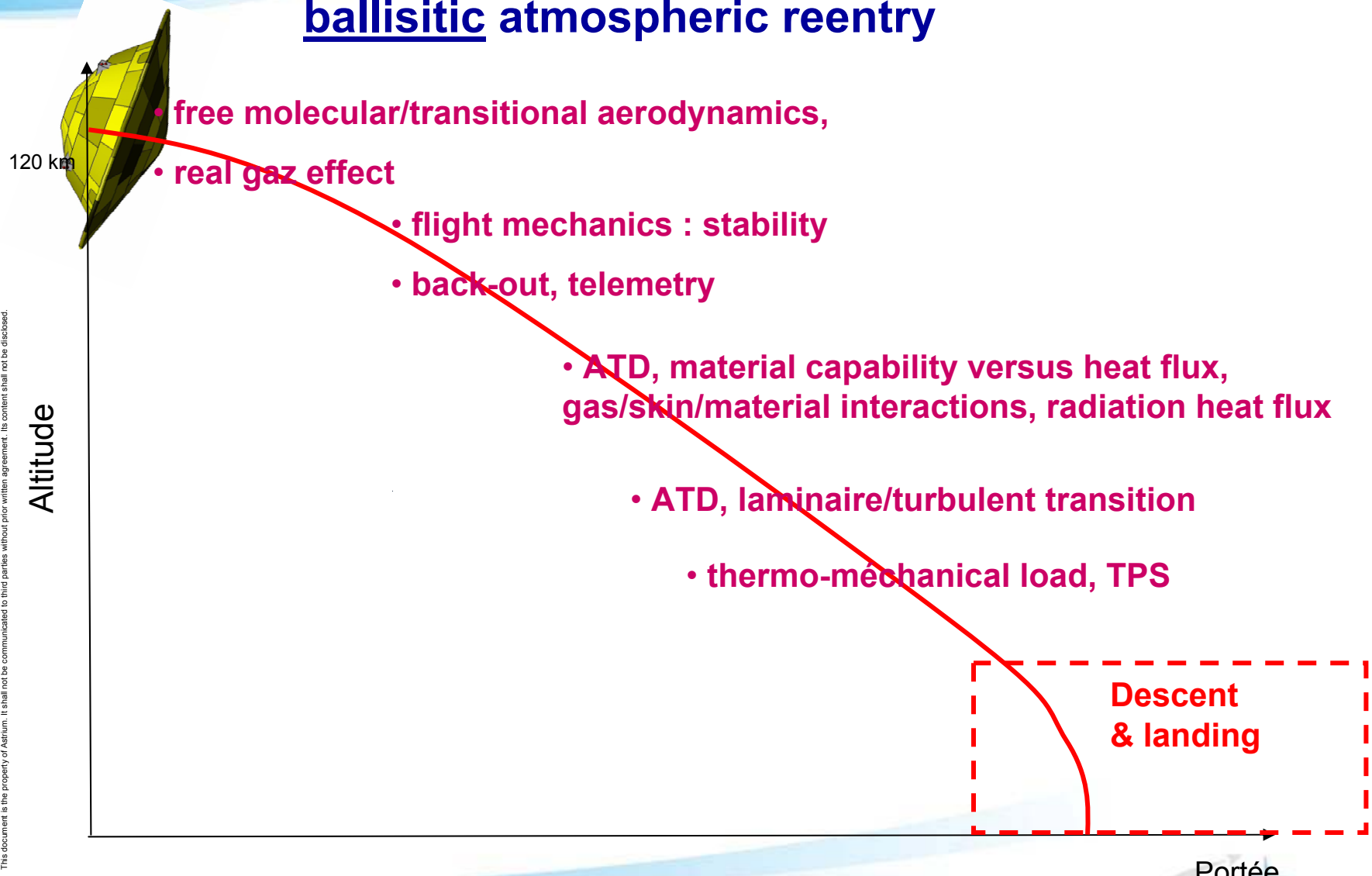
This document is the property of EADS SPACE Transportation and shall not be communicated to third parties and/or reproduced without prior written agreement.
Its contents shall not be disclosed. © - EADS SPACE Transportation - 2004



This document is the property of EADS SPACE Transportation and shall not be communicated to third parties and/or reproduced without prior written agreement.
Its contents shall not be disclosed. © - EADS SPACE Transportation - 2004

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Main problems to handel during ballisitic atmospheric reentry



- free molecular/transitional aerodynamics,
- real gaz effect
- flight mechanics : stability
- back-out, telemetry
- ATD, material capability versus heat flux, gas/skin/material interactions, radiation heat flux
- ATD, laminaire/turbulent transition
- thermo-mechanical load, TPS

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

Main problems to handel during gliding atmospheric reentry

- plume effects,
- aerodynamic flap efficiency

- management of the boundary of the flight domaine (coupling structure and TPS)

- Navigation
- Guidance
- Control

Altitude

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.

References:

- Planetary mission entry vehicules, quick reference Guide (V2.1), Nasa Ames research center, space technology division
- Cours de l'ENSAE 1988, Aerodynamique hypersonique, James LUNEAU
- Thermal Protection System Technology and Facility Needs for demanding Future Planetary missions, *Bernie LAUB & Dr Ethiraj VENKATAPATHY, IPPW4, Lisbon, 6-9 oct 2003*
- Ablative thermal protections for planetary entry : an overview, recent results and future needs, *J. M BOUILLY, F. LELEU, 4th international Symposium on atmospheric re-entry vehicles and systems, Arcachon, 21-23 mars 2005*
- The hypersonic Pre-X vehicle :current status, *Y. GERARD, J.MOULIN, S.GUEDRON, 4th International Symposium on Atmospheric Re-entry Vehicles & Systems, Arcachon, 21-23 March 2005*
- IAC-06-D2.P.2.2 - The PreX atmospheric re-entry experimental reentry lifting body , program status and system synthesis, *P. BAIOCCO, S GUERON, J.MOULIN, P. PLOTARD IAC, Valancia 2006*

This document is the property of Astrium. It shall not be communicated to third parties without prior written agreement. Its content shall not be disclosed.