**A.Y. 2021-2022**
**Launch Systems**

# 06 – Part 1
# Missile Aerodynamics
# Lift and drag

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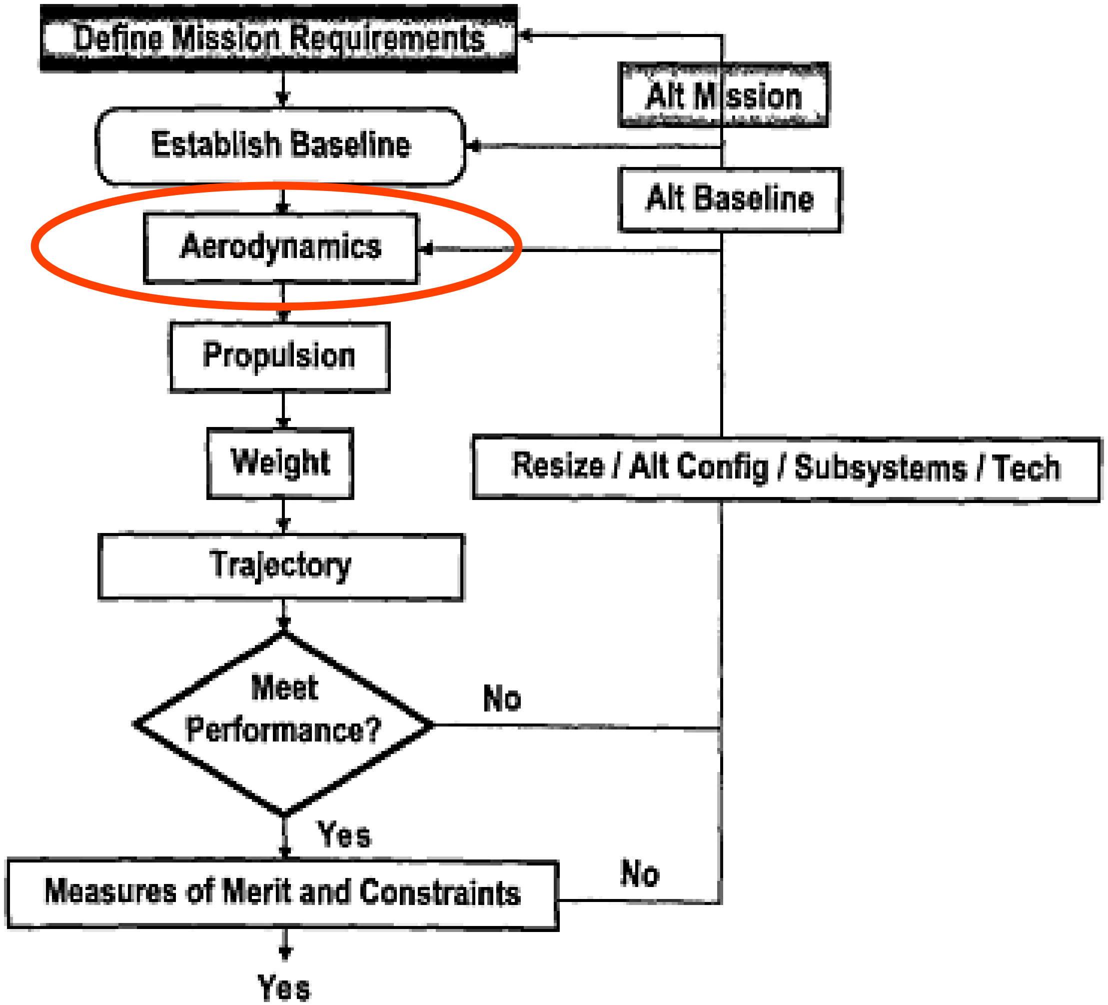
# Plan and Objectives

- Computation of main aerodynamic properties with simplified methodologies
- Show and analyze different design solutions
- Flight control and maneuvers

# Where are we?



Define Mission Requirements
Alt Mission
Establish Baseline
Alt Baseline
Aerodynamics
Propulsion
Weight
Resize / Alt Config / Subsystems / Tech
Trajectory
Meet Performance?
No
Yes
Measures of Merit and Constraints
No
Yes

# Aerodynamics in missiles

# Aerodynamics in missiles

## Modeling approaches

### Concentrated loads

Global forces/moments

Useful for:
- trajectory analysis
- stability

How to:
- Empirical models
- Component build-up

### Distributed loads

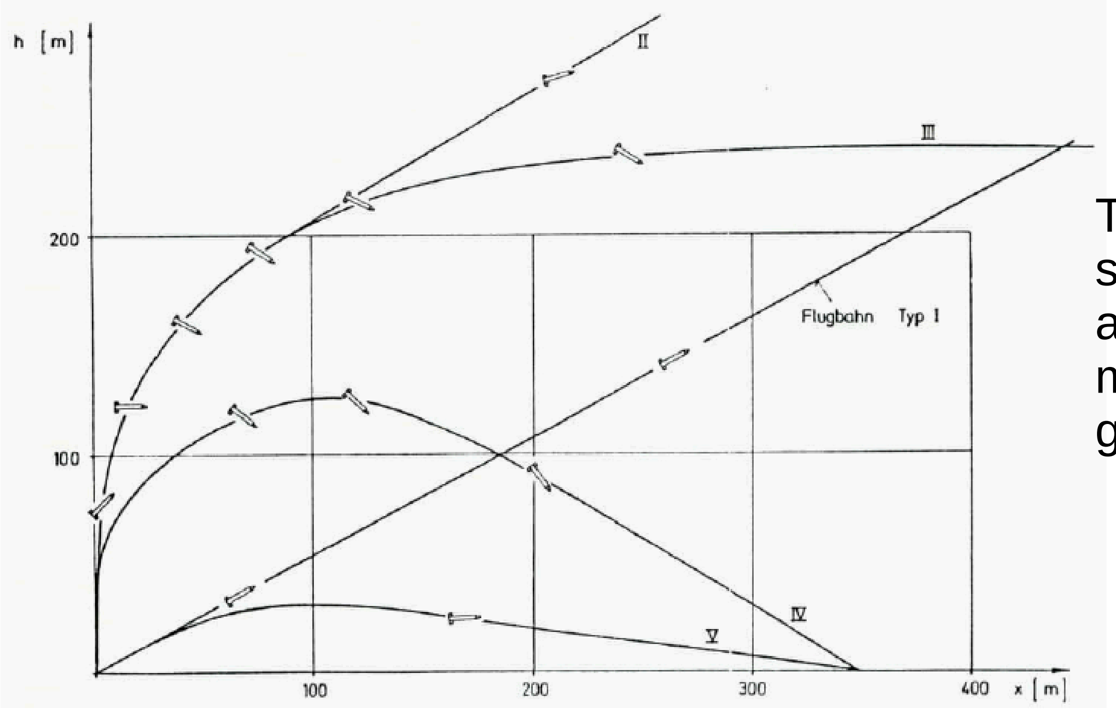
Local pressure distribution

Useful for:
- Structural analysis
- Shape optimization

How to:
- Methods based on local shape
- e.g. Paneling method
- e.g. CFD

# Where is aerodynamics important?

- **Tactical missiles**
  - Aerodynamic efficiency $C_L/C_d$ **does not represent a primary concern**, especially for short range missions
  - Range is short. Penalty on propellant mass is small




Tactical missiles with symmetrical body can operate at high angles of attack for maneuvers due to lift generation

# Where is aerodynamics important?

- **Long-range cruise missiles** (subsonic or supersonic)
  - Often they are winged bodies, they are designed to generate lift
  - Aerodynamic efficiency $C_L/C_d$ is **important** for range increment.
  - For **air-breathing** units (ramjets or turbojets), **integration with the intake** becomes critical, coupled with radar visibility
  - Aerodynamics for **maneuvers** and trajectory control is important (e.g. bank-to-tunr maneuvers)

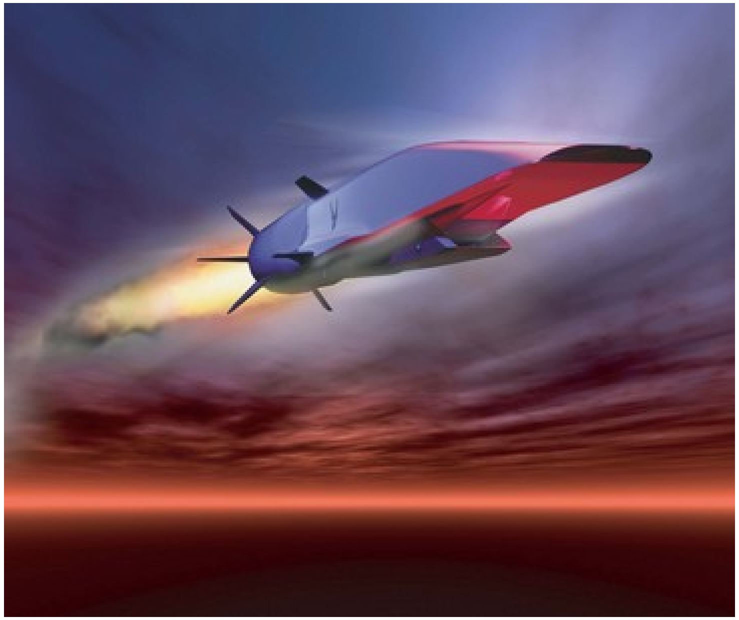
# Where is aerodynamics important?

- **Hypersonic space planes**

  Waveriders have very **peculiar aerodynamics** to improve efficiency through “compression lift.”

  Issues with **integration of the inlet and aerodynamic heating**

Flight regime: hypersonic range (about higher than Mach 5-6)



X-51 waverider

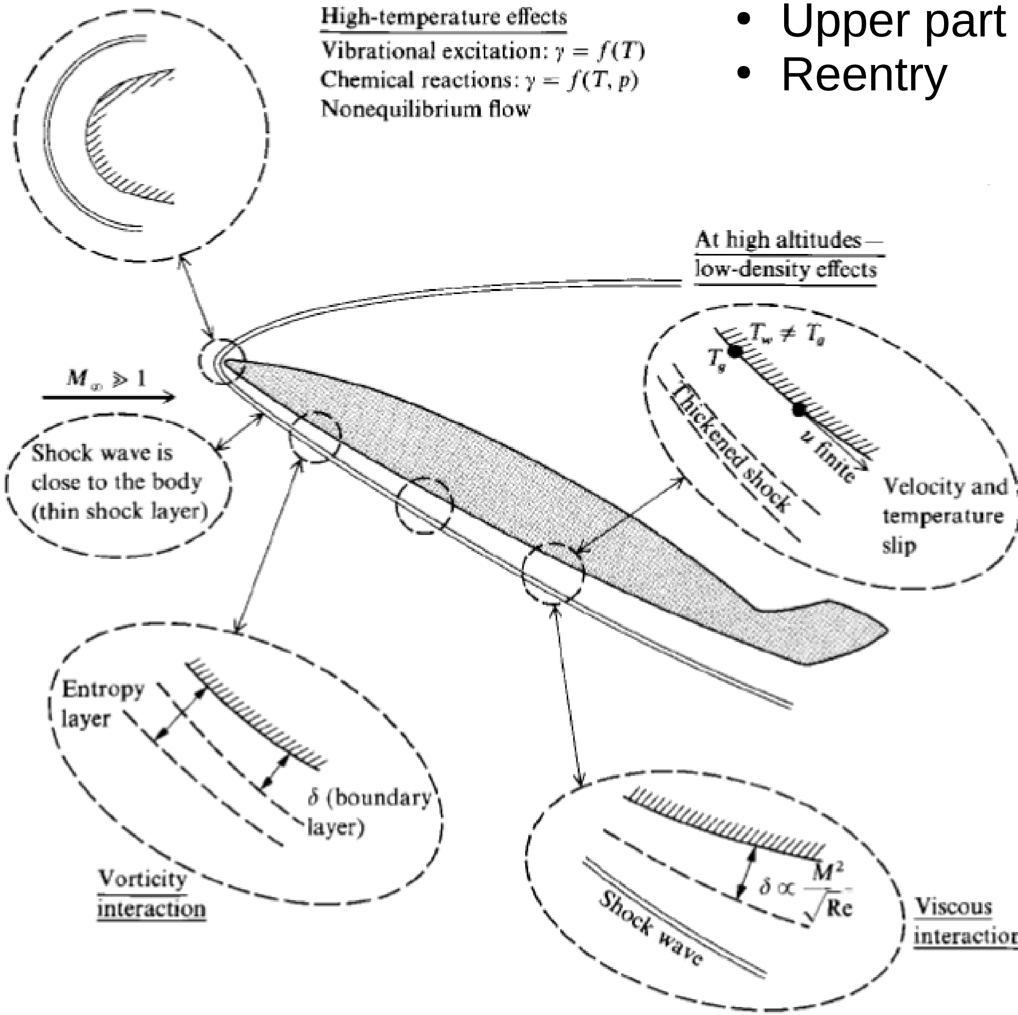
# Where is aerodynamics important?

## Space launchers and ballistic missiles

- Aerodynamic drag for **Delta V losses** (e.g. drag penalty in Tsiolkovsky equation)
- **Stability** issues
- **Structure** due to long L/D ratio of the missile
- Aerodynamic **heating**

Launch vehicles do not perform sharp maneuvers. In general, they do not exceed few degrees of angle of attach (say, max 2-5°)

# Aerodynamic phenomena at high Mach



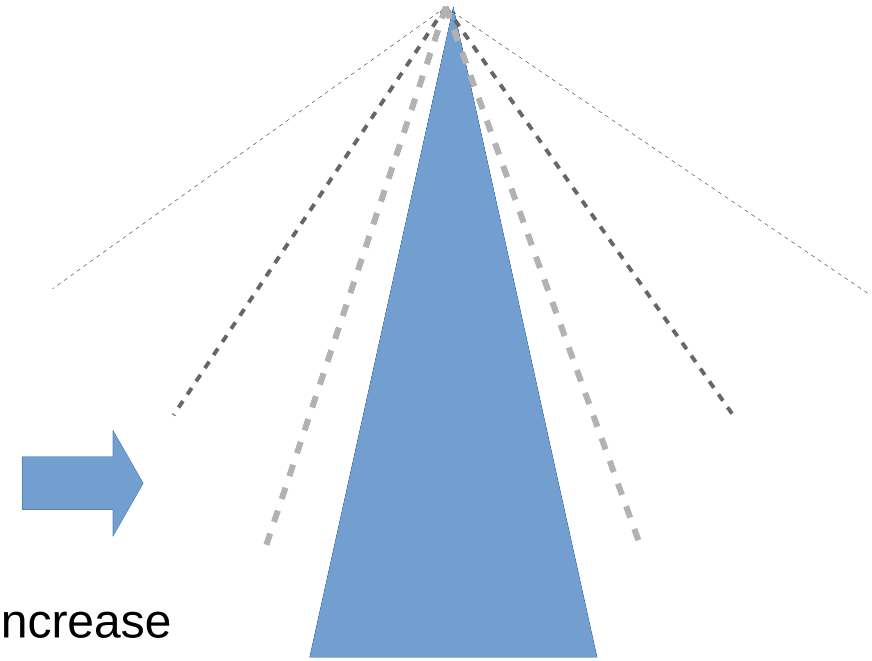

- Upper part of the atmosphere
- Reentry

# Aerodynamic phenomena at high Mach

- Thin shock layer

- The higher the Mach number the thinner the shock layer
- For M → ∞ the layer adheres to the body surface

For example on 15° half angle wedge:
Mach 36 → 18° half angle shock

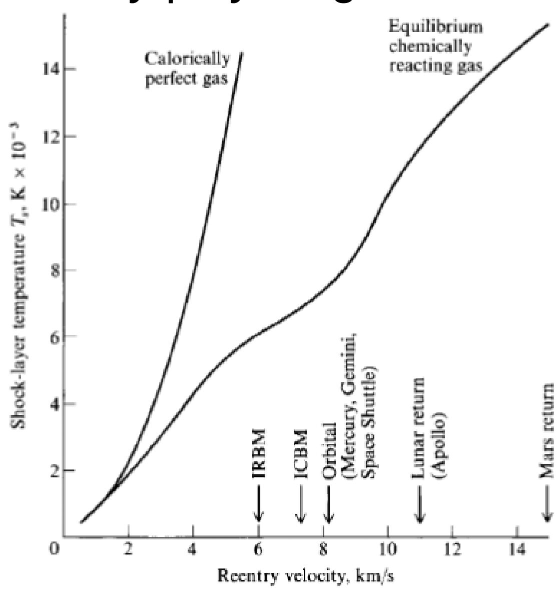


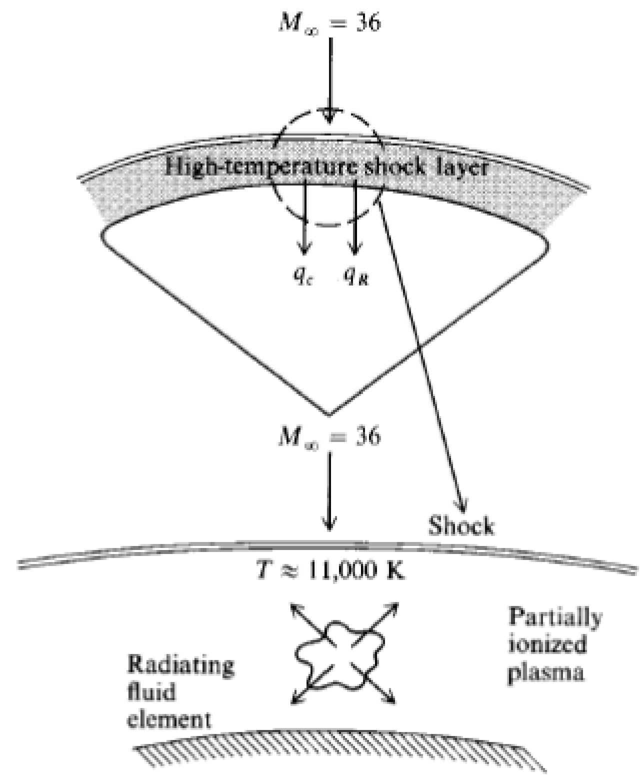
Mach increase

# Aerodynamic phenomena at high Mach

- Front bow shock and high temperature effects

- The strength of the shock increases with the flight Mach number.
- Static temperature and pressure grow substantially
- In hypersonic regime (after about Mach 5-6 … no sharp border) air chemistry plays a great role

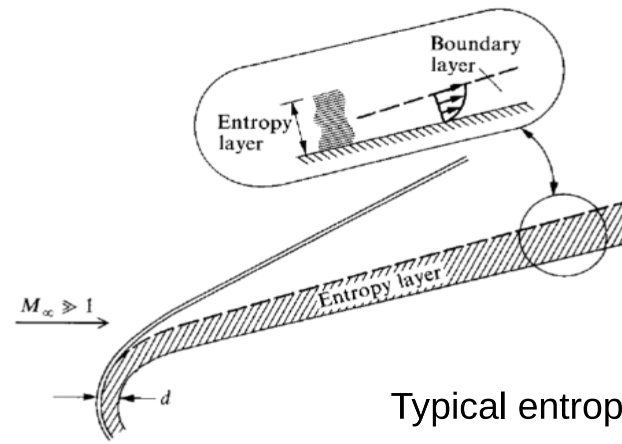


# Aerodynamic phenomena at high Mach

- Entropy layer

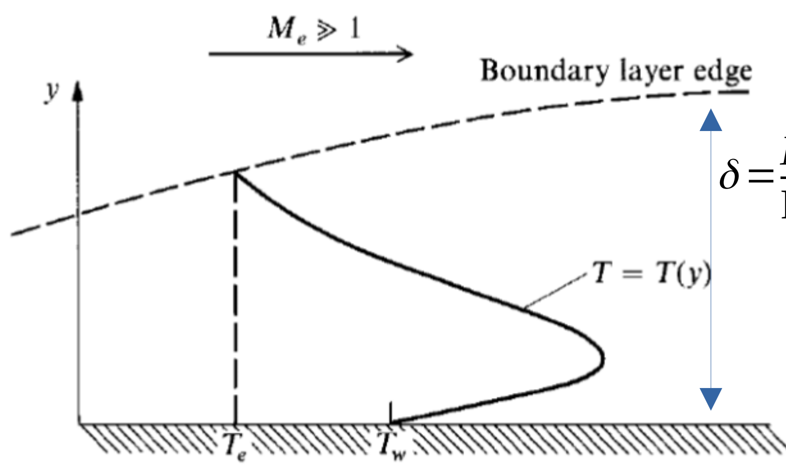
  - Entropy is generated by the fornt shock.
  - The thickness of the **entropy** layer grows. It is a region with high vorticity.
  - Analytical problems in managing the computations of the boundary layer.




Typical entropy layer

- Viscous layer interactions

  - Static temperature grows in the boundary layer due to slow-down (**viscous dissipation**)
  - The increment of temperature leads to higher viscosity
  - Higher viscosity produces a thicker boundary layer and an interaction with the external "inviscid" flow (**viscous interaction**)



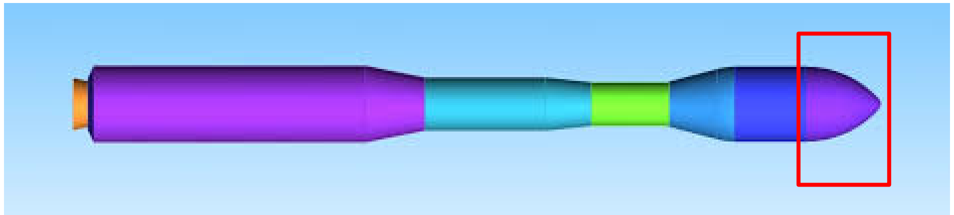

$$\delta = \frac{M^2}{\mathrm{Re}}$$

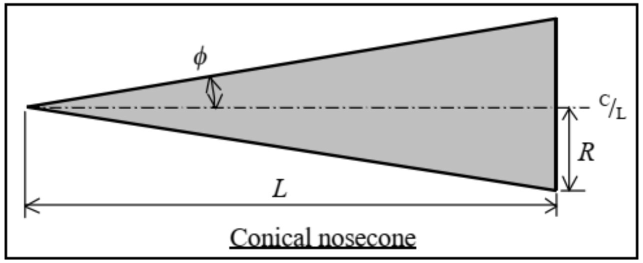
Typical static temperature profile

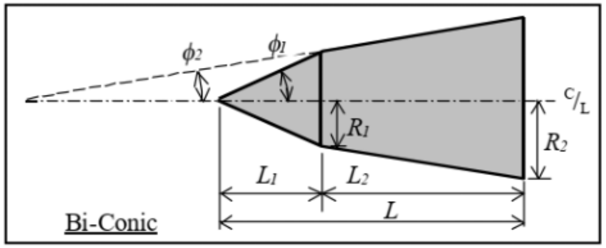
# Typical shapes in launchers

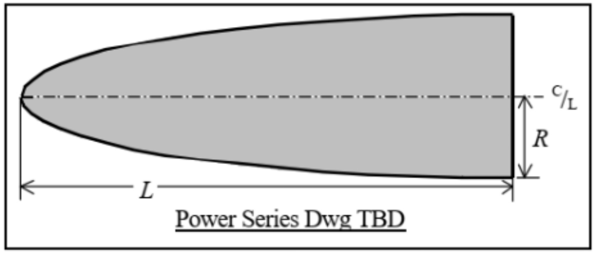
# Typical shapes in launchers

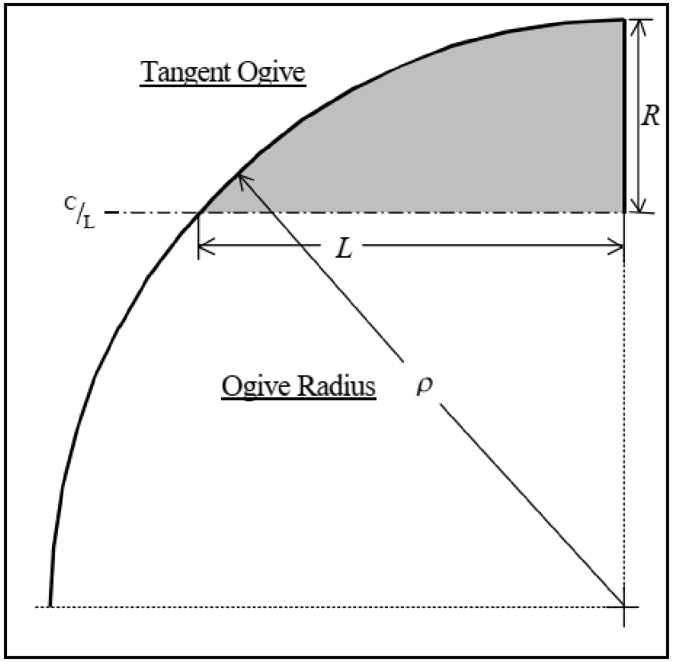
**Nose**





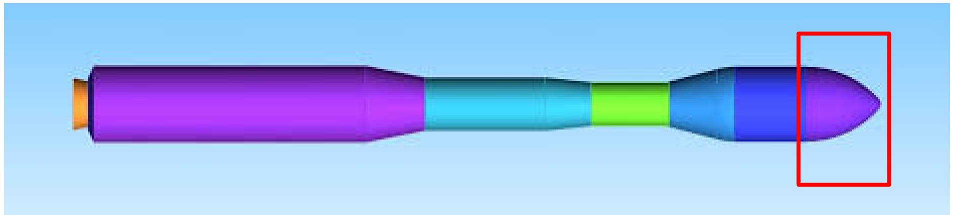



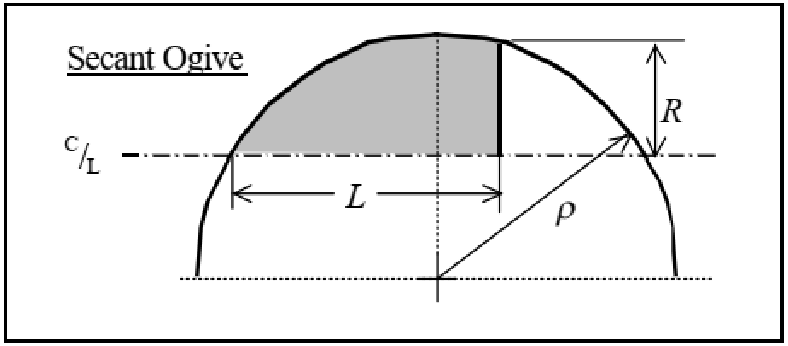



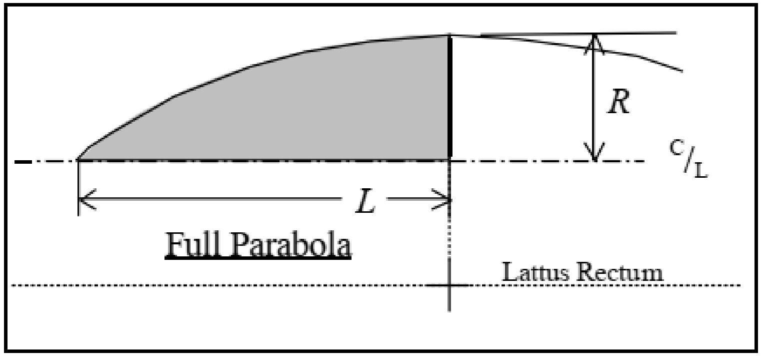



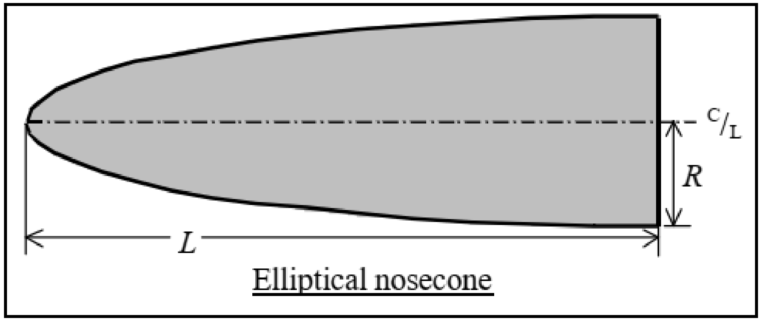
# Typical shapes in launchers

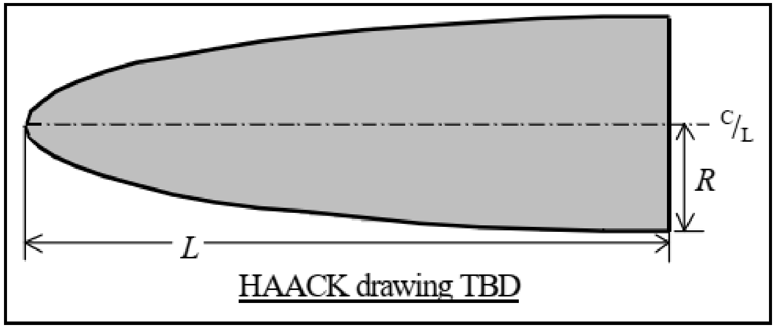
**Nose**



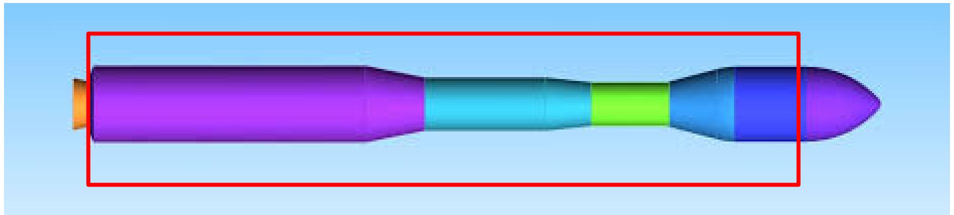


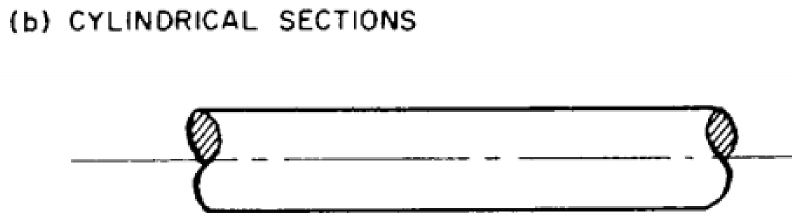



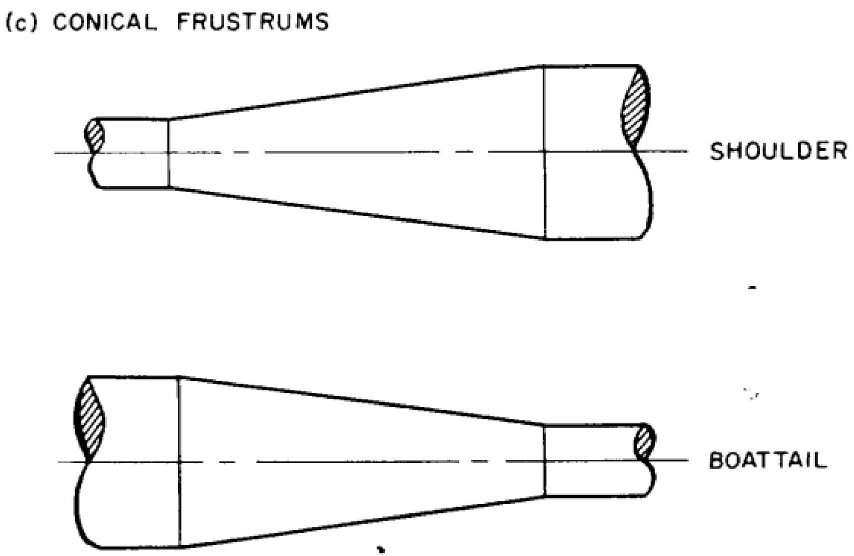



**Body**

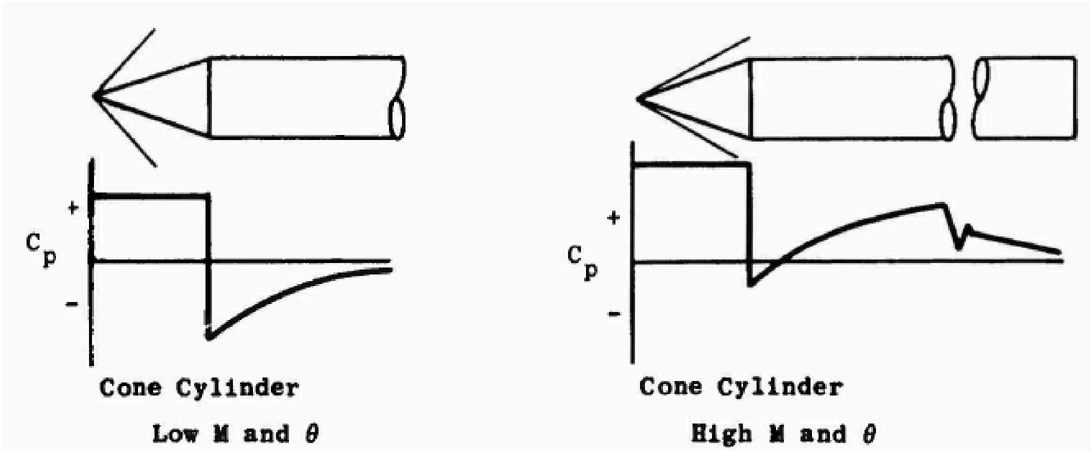


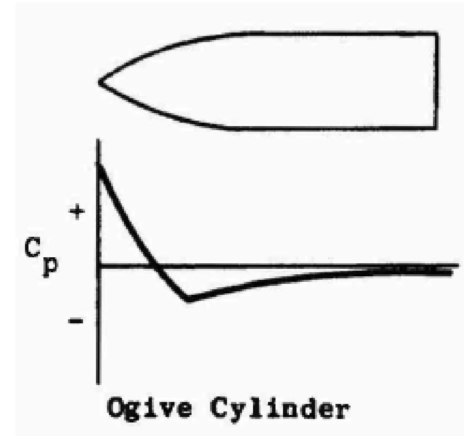

(b) CYLINDRICAL SECTIONS


(c) CONICAL FRUSTRUMS
SHOULDER
BOATTAIL

# Pressure on body surface

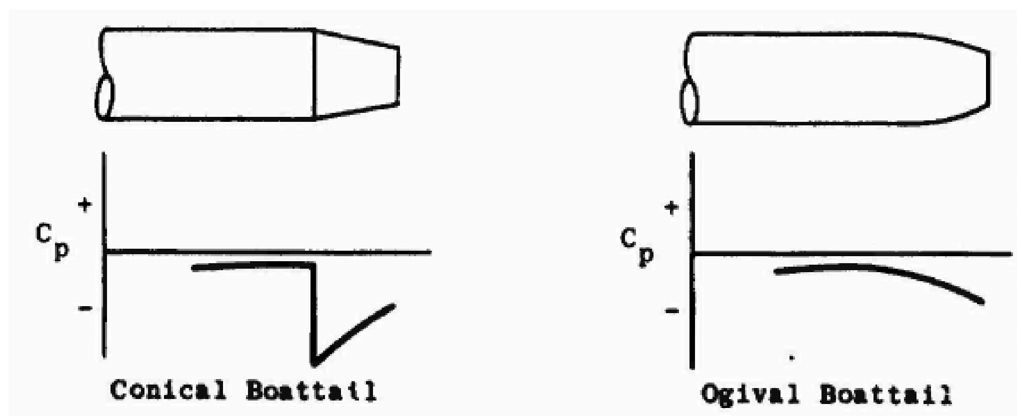
## NOSE



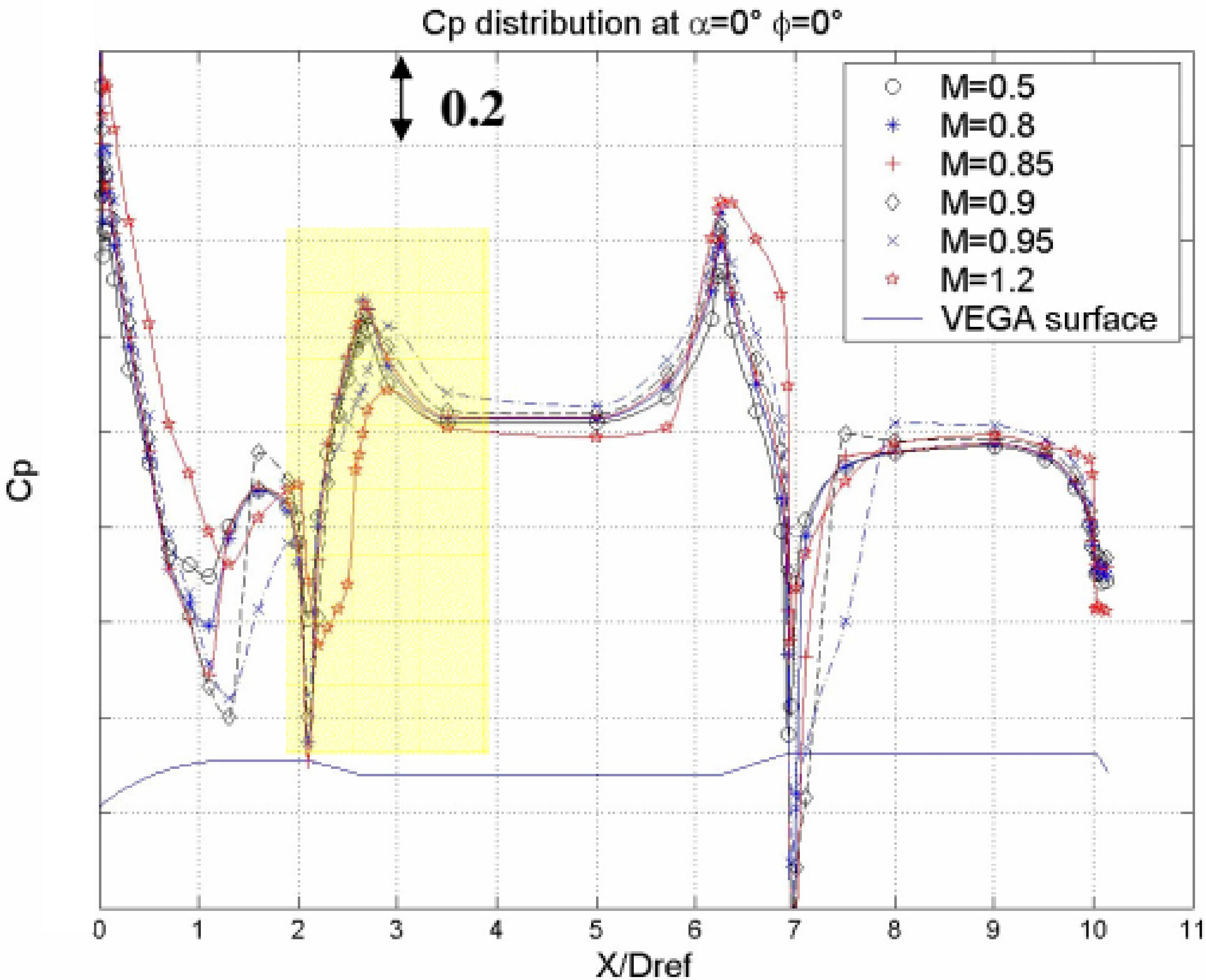




## Boattail

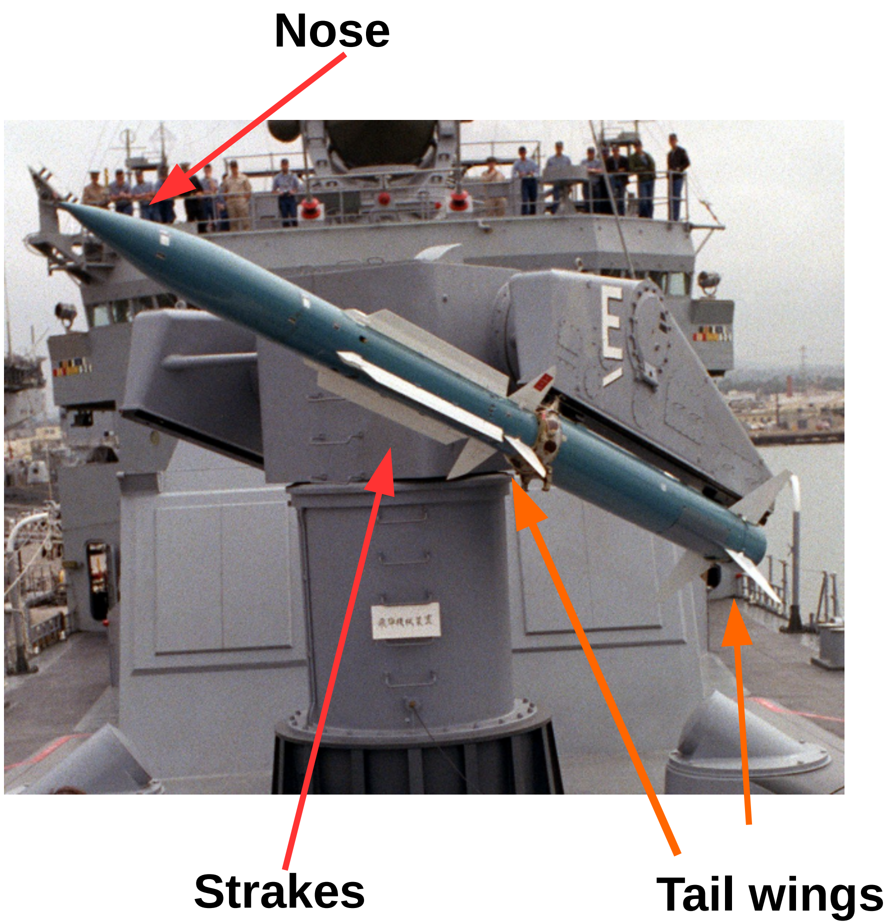
$$C_p = \frac{p - p_\infty}{q}$$

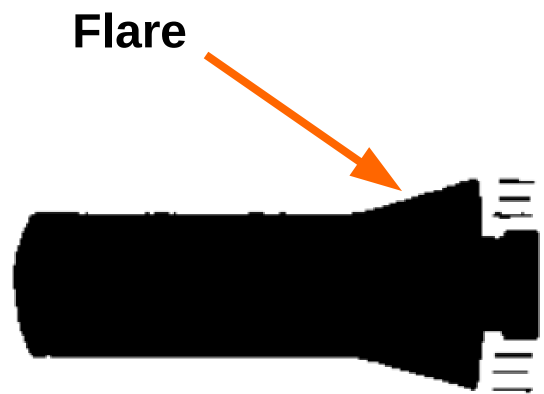


# Example of pressure coefficient: VEGA



# Typical shapes in launchers

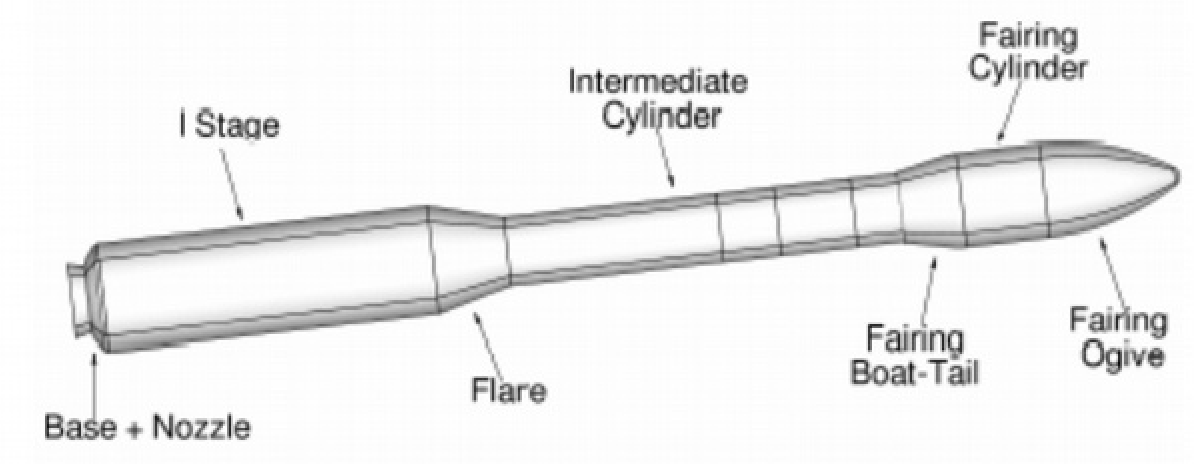


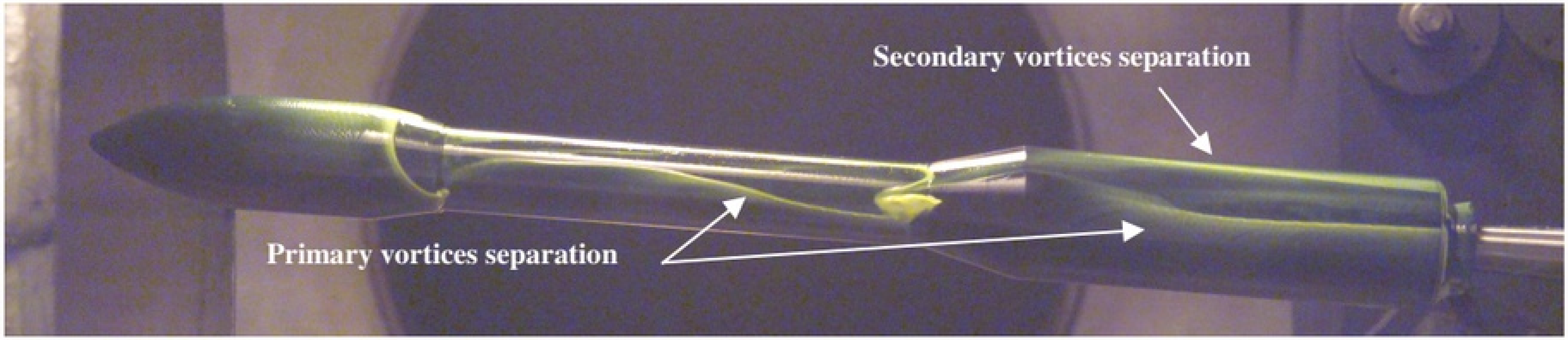

These components are introduced for stability

# Typical flow phenomena in launchers

# Typical flow phenomena in launchers

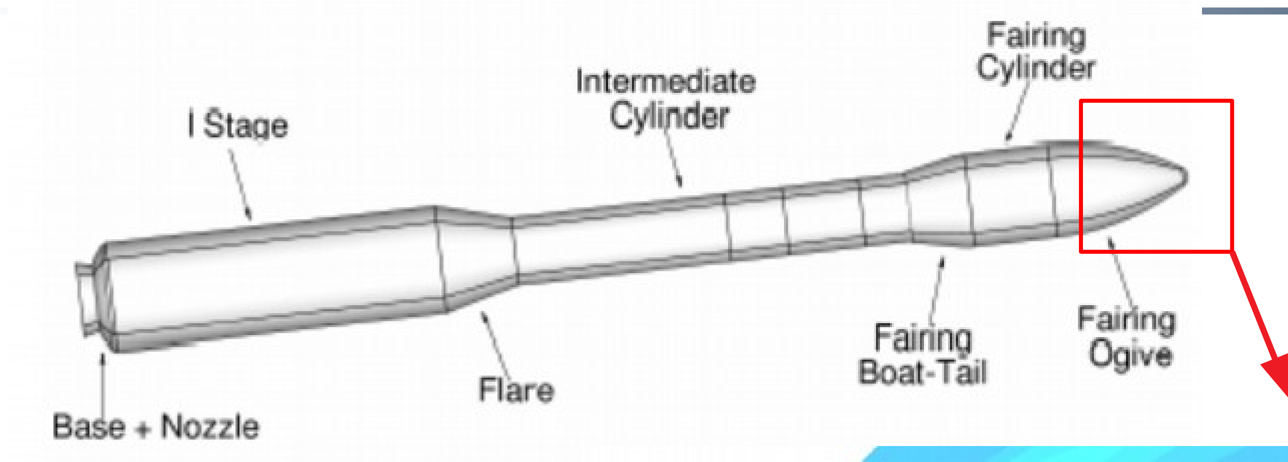


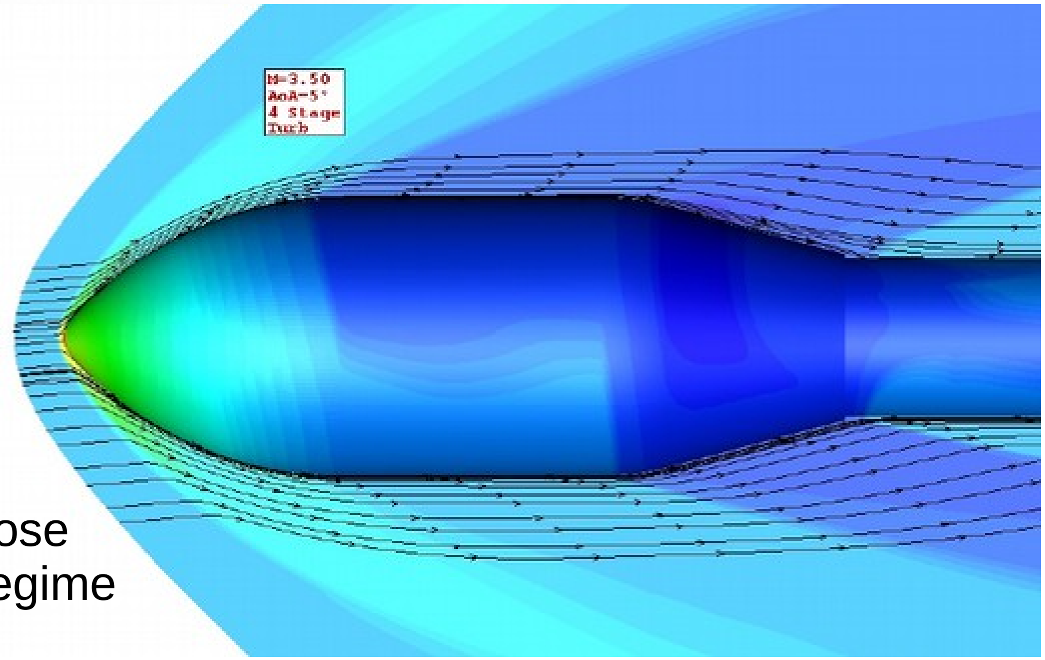

Oil flow visualizations: Mach 6, angle of attack 6°




What is an oil flow visualization test? Click here to see (internet needed)

# Typical flow phenomena in launchers

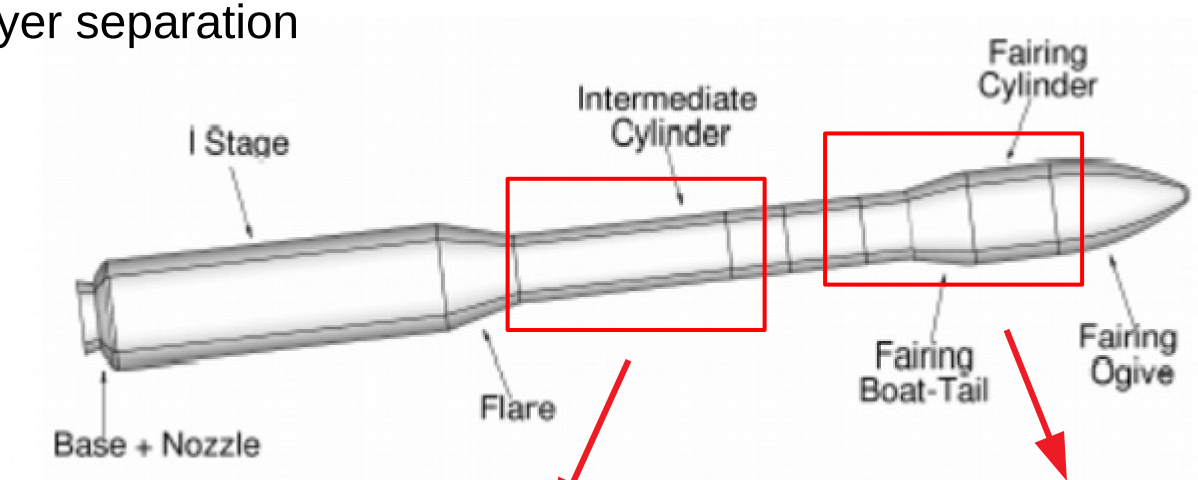


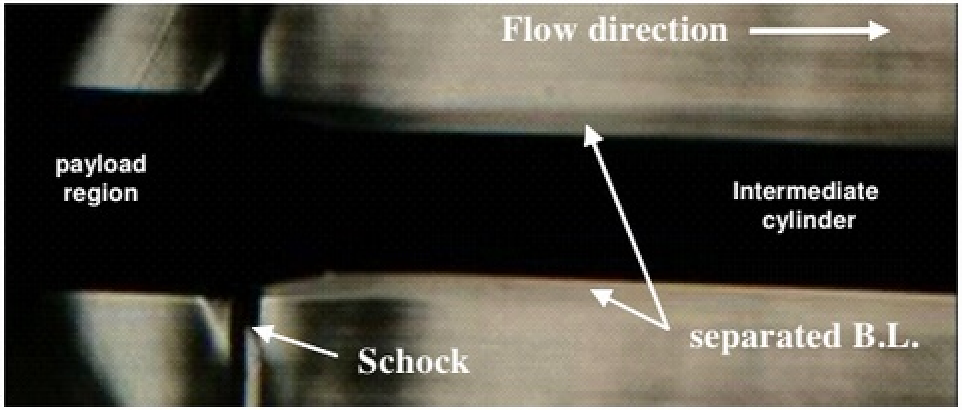

Bow shock in front of the nose
at supersonic/hypersonic regime

# Typical flow phenomena in launchers

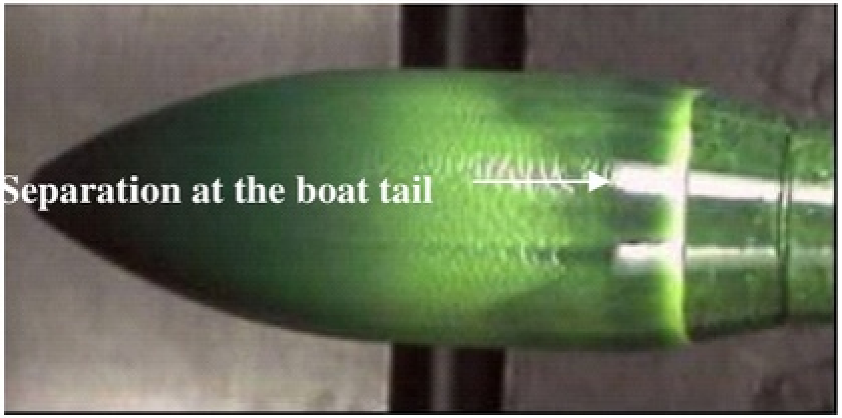
Boundary layer separation




Mach 0.95, angle of attack 1°

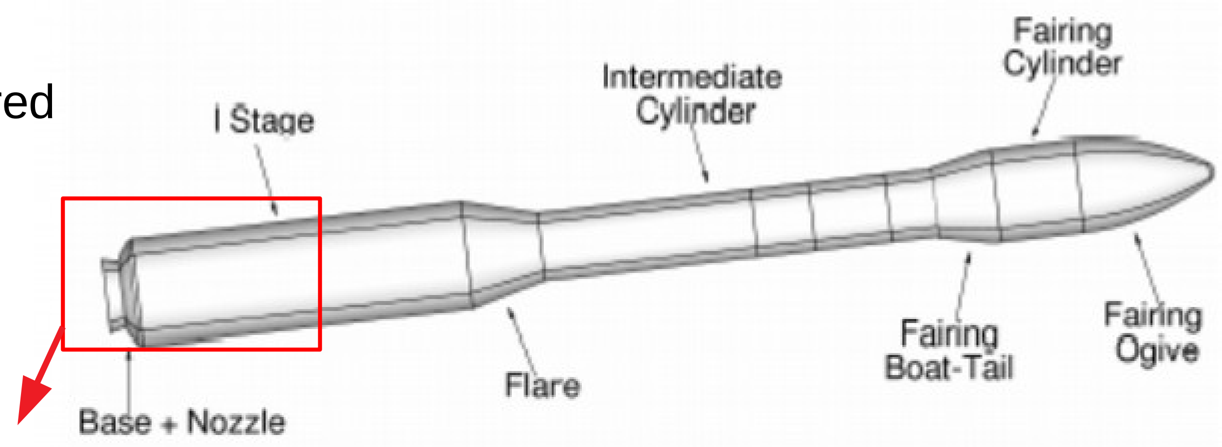


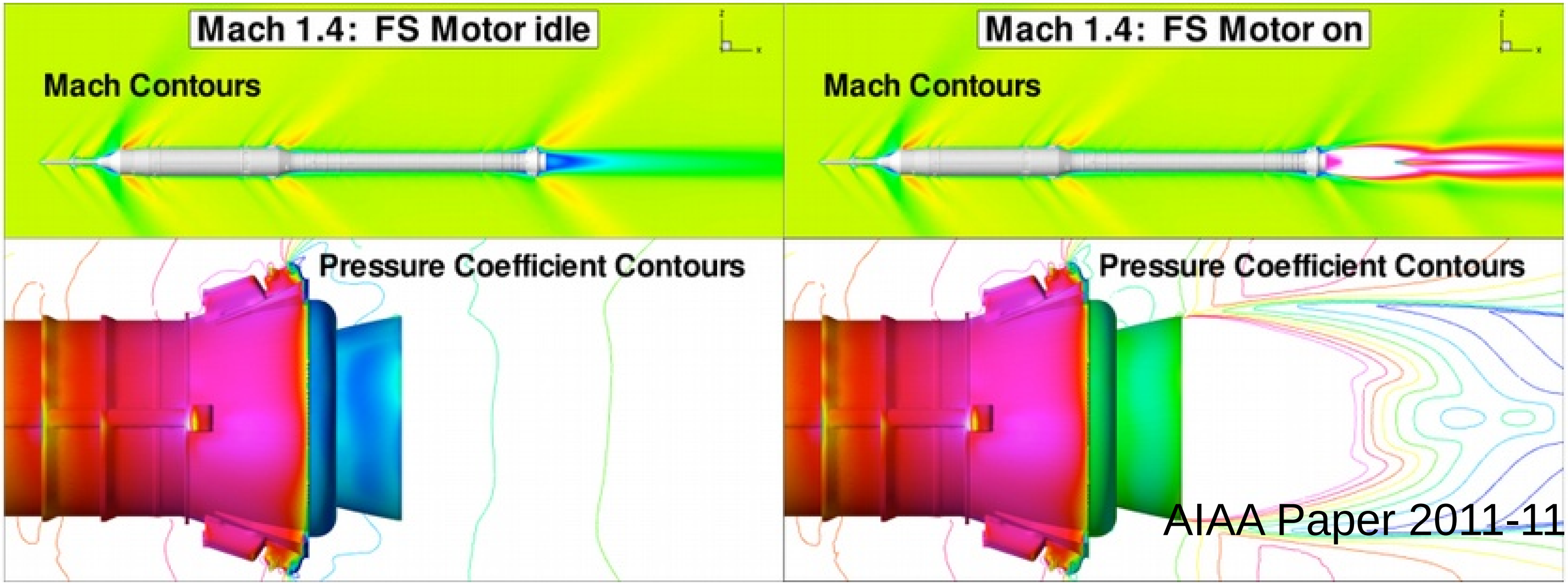

Mach 6, angle of attack 1°



# Typical flow phenomena in launchers

Base drag:
Powered and unpowered

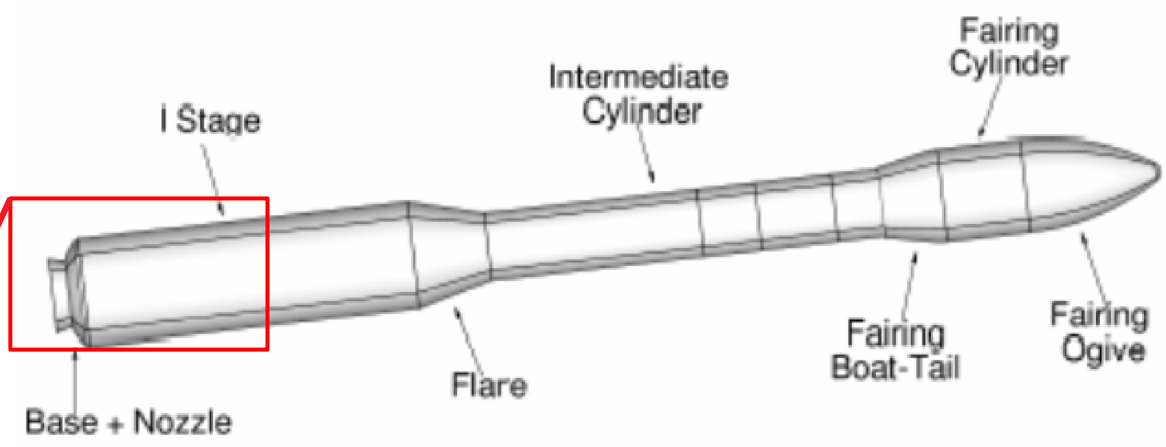


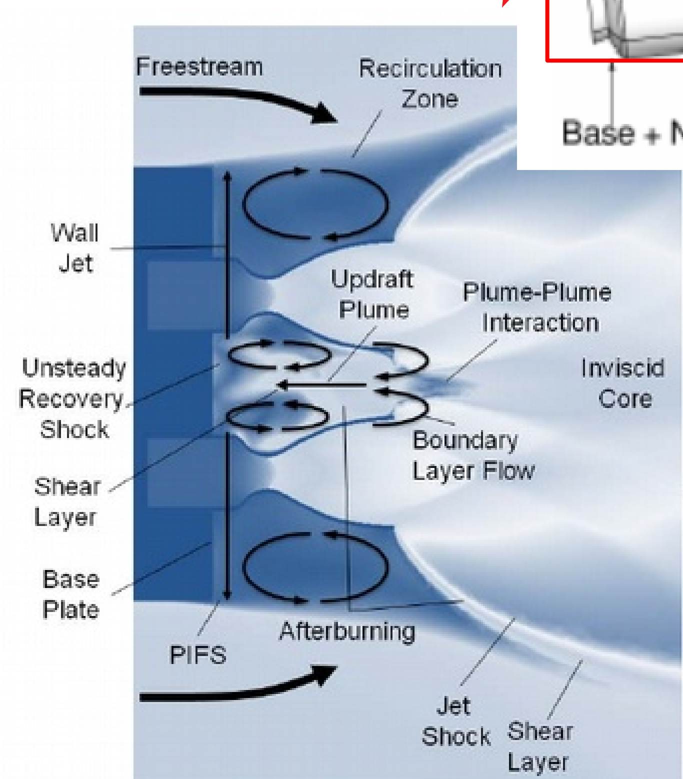



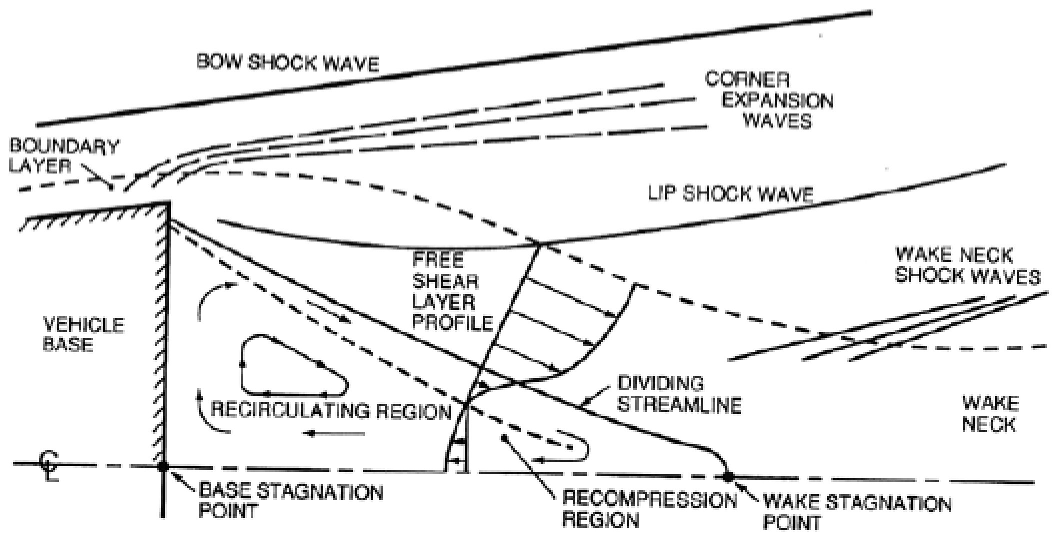

AIAA Paper 2011-11

# Typical flow phenomena in launchers

Plume interaction with shear flow and after-burning

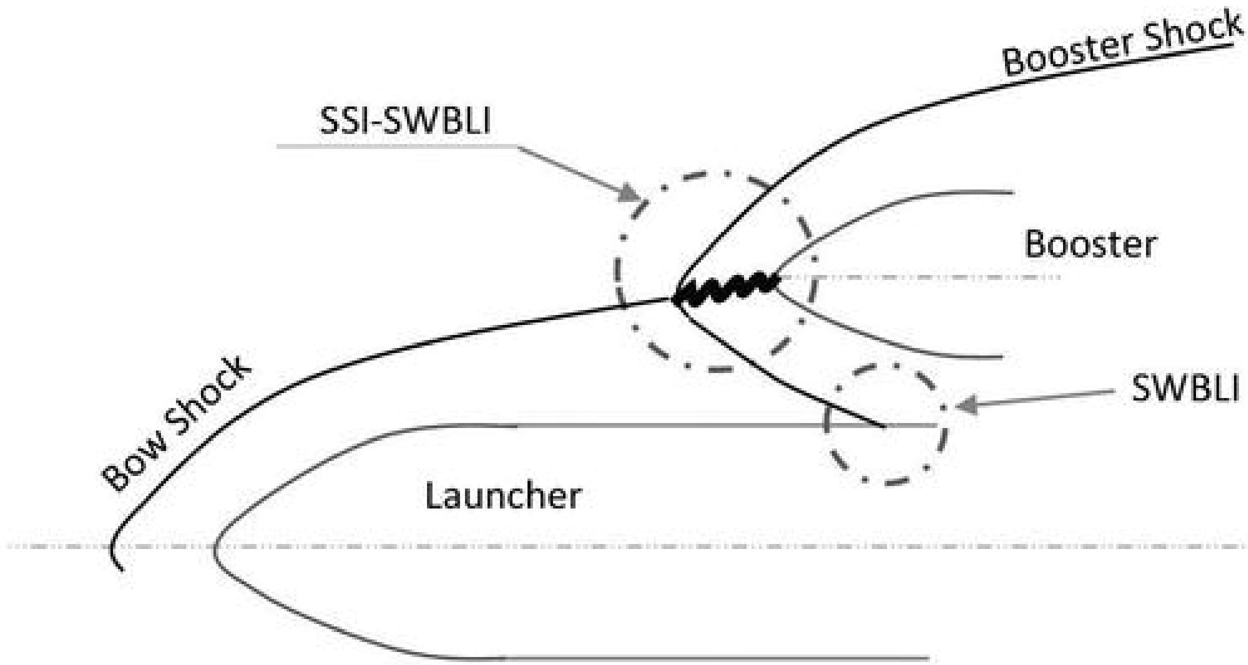


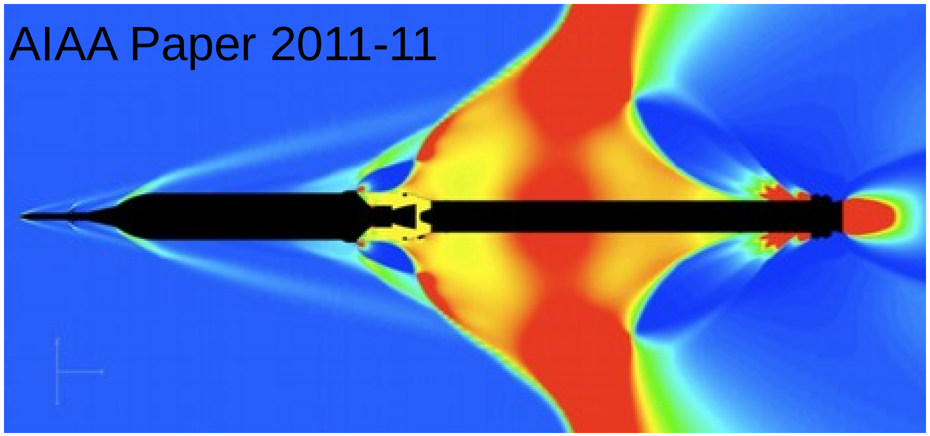
# Typical flow phenomena in launchers

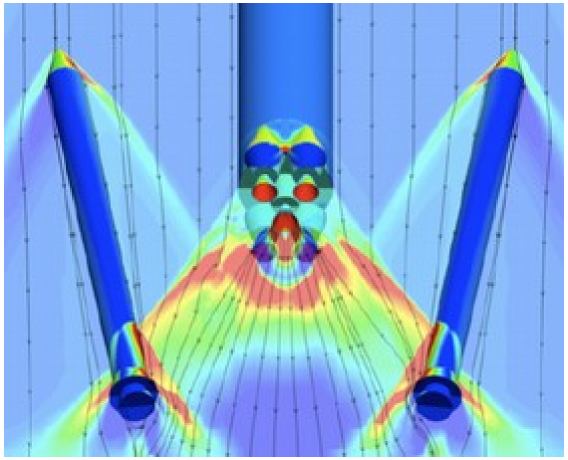
Shock-surface interaction for parallel configurations

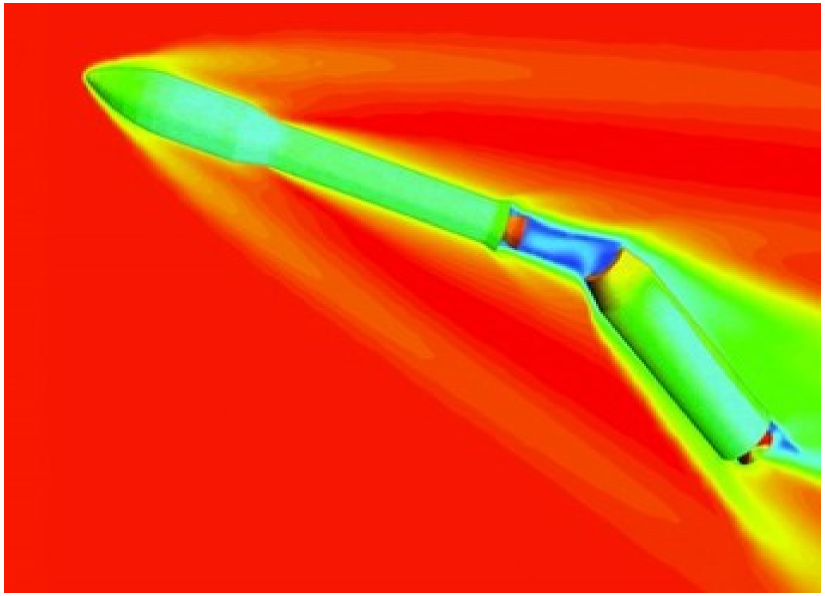


# Typical flow phenomena in launchers

During separation retro-rocket plume interacts with the main flow





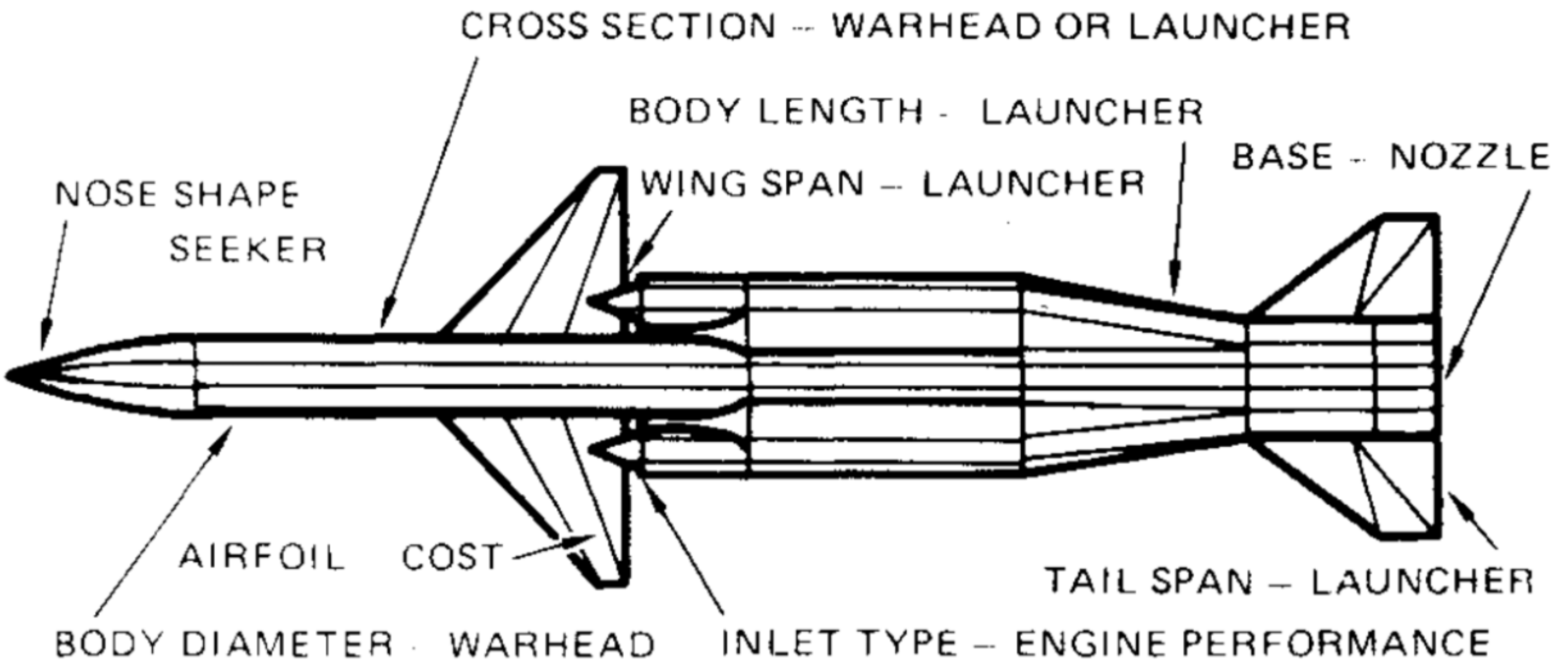
From: Star-CCM+ image gallery
Interstage separation

# Preliminary aerodynamic analysis

# Target of aerodynamic analysis

- **Normal force coefficient and derivative**
- **Drag coefficient  and derivative**
- **Moment coefficient and derivative**
- **Center of pressure**
- Roll forcing moment coefficient derivative
- Roll damping moment coefficient derivative
- Pitch damping moment coefficient derivative

# Sizing parameters for aerodynamics




From S.R. Vukelich and J.E. Jenkins. Evaluation of Component Buildup Methods for Missile Aerodynamic Predictions. In: J. Spacecraft and Rockets, 19(6):481-488, 1982

# Aerodynamic design and analysis

Steps for the aerodynamic iteration (example: symmetric body)

1 – Define/derive the DIAMETER of the body

2 – Select a model and evaluate aerodynamic forces

- normal force coefficient derivative
- zero-lift drag
- moment coefficient derivative

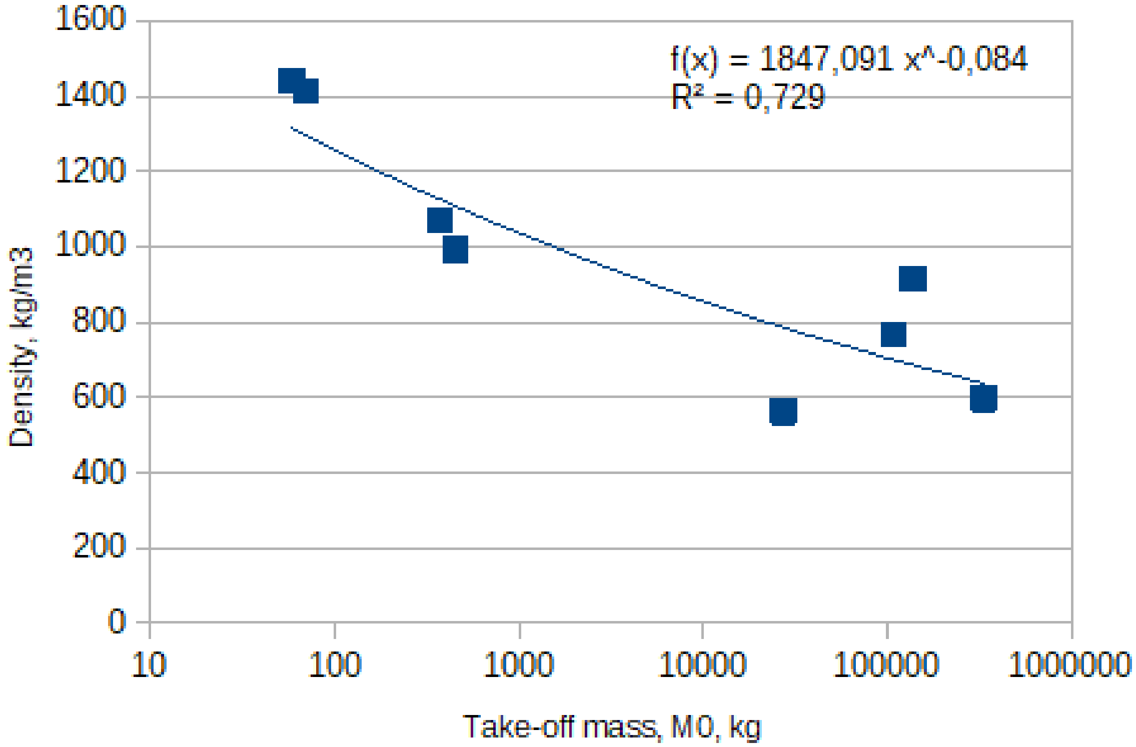
3 – Find the center of pressure

# Aerodynamics step 1. Diameter

- What defines the diameter?
  - Constraints of size
    - Payload diameter (accommodation)
    - For longer range, propulsion diameter (mass budget and reduction of length for CoG reasons)
    - For shorter range, guidance apparatus (seeker, radar, …)
  - Constraints of volume
    - Global mass of the missile (propellant + structure + payload)
    - “Density” of the missile

# Diameter from missile density

- Missile "density". It depends on the mission and configuration. Fitting laws can be derived from historical data.




Total volume of a missile

$$V_0 = \frac{M_0}{\rho_{\text{missile}}}$$

$$V_0 = \pi L \frac{d^2}{4} = \frac{\pi}{4} \left( \frac{L}{d} \right) d^3$$

# Diameter from missile density

- Small data collection of missile “densities”.
  NOTE: the volume is not precisely computed.

| ID | Type | Density ($M_0$/Vol), kg/m3 | Liftoff mass, $M_0$, kg |
|---|---|---|---|
| AIM-9M | Missile | 2268 (not fitted) | 85,2 |
| AIM-4 | Missile | 1442 | 58 |
| AIM-4F | Missile | 1414 | 69 |
| AIM-47 | Missile | 1069 | 371 |
| AIM-54C | Missile | 992 | 450 |
| VEGA | Space launcher | 917 | 137000 |
| Kosmos 3M | Space launcher | 765 | 109000 |
| Falcon 9 | Space launcher | 596 | 333000 |
| Falcon 1 | Space launcher | 562 | 27200 |

# Diameter from propellant density

Liftoff mass can be computed on the basis of structural coefficients and $M_p$

$$M_0=(1+k_s)M_p=(1+k_s)\rho_p V_p=(1+k_s)\rho_p\frac{\pi}{4}d^3\left(\frac{L}{d}\right)f_p$$

where $k_s=\frac{M_s}{M_p}$

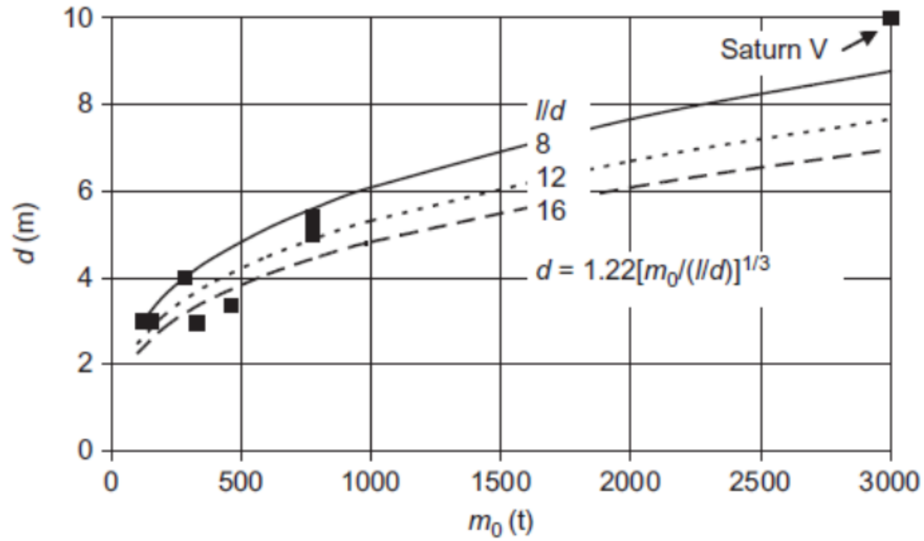
And the propellant volume fraction is

$$f_p=\frac{V_p}{V_{tot}}$$

Volume of propellant

Total volume

**Statistical fitting**




**<u>If there are not other constraints, L/d is a choice</u>:**
Smaller L/d → better structural integrity
Larger L/d → less drag penalties

# Diameter from propellant density

- Typical propellant densities

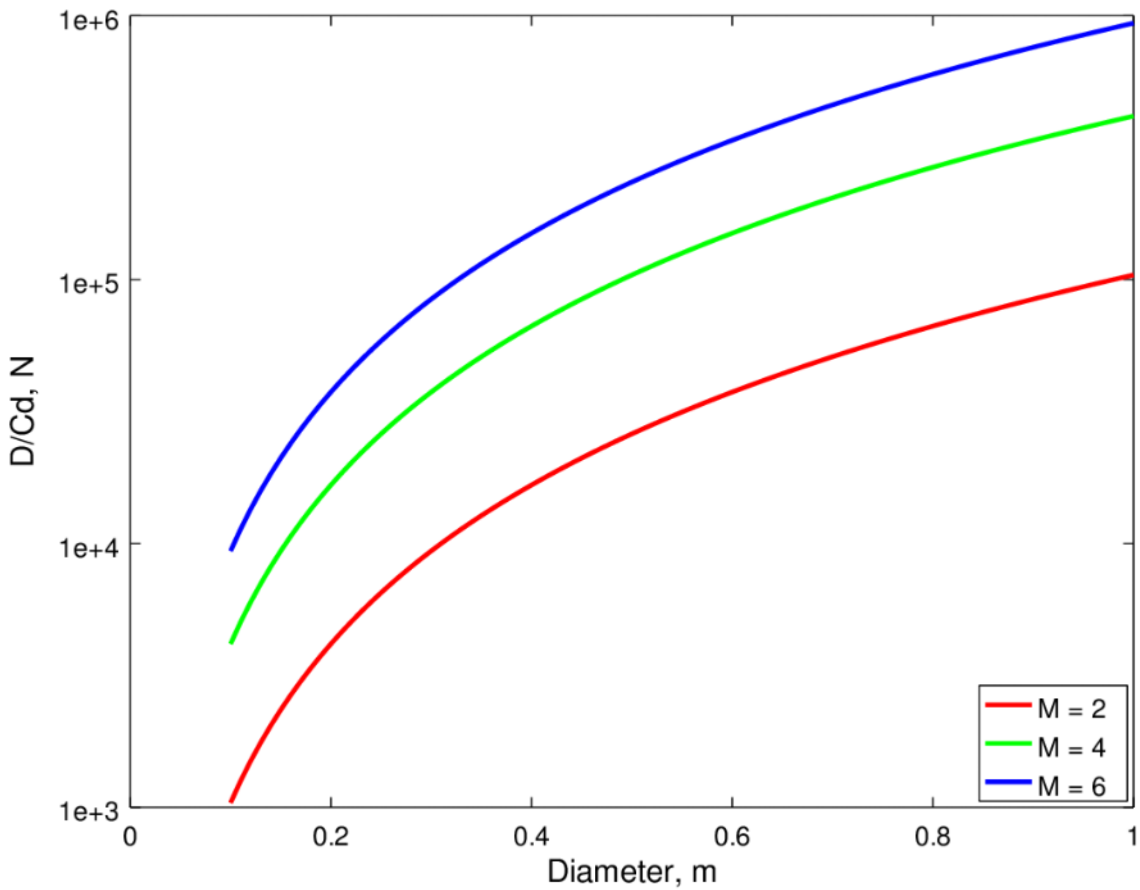
| propellant type | density, g/cm$^3$ |
|---|---|
| metallized solid | $1.7 - 1.8$ |
| unmetallized solid | $1.5 - 1.6$ |
| $F_2$ cryogenic liquid oxidizer at 66 K | 1.636 |
| $H_2O_2$ storable liquid monopropellant | 1.463 |
| $N_2O_4$ storable liquid oxidizer | 1.449 |
| $N_2O$ cryogenic liquid oxidizer at 185 K | 1.226 |
| $O_2$ cryogenic liquid oxidizer a 90 K | 1.149 |
| $N_2H_4$ storable liquid monopropellant | 1.005 |
| $RP1$ storable liquid fuel | 0.807 |
| $CH_4$ cryogenic liquid fuel at 112 K | 0.424 |
| $H_2$ cryogenic liquid fuel at 20 K | 0.071 |
| $H_2/O_2$ cryogenic liquid bipropellant | 0.270 |
| air under standard conditions at sea level | 0.001 |

# Diameter: influence on drag

$$\frac{D}{C_d} = q\frac{\pi}{4}d^2$$

**Drag:**
Squared influence on diameter

Constant q



# Length-to-diameter (L/D) ratio

- The diameter can be constrained by several reasons:
  - Payload minimum diameter (satellite, warhead, sensors)
  - For air-breathing: combustion chamber, air intakes
- Without constraints the fineness ratio is found to be:
  - Higher than 5-8  imposed by stabilization concerns (fin-stabilized)
  - Lower than 20-25 imposed by structural reasons
- Trade-off may be imposed by:
  - Imposed diameters or lengths of the whole system (integration issues)
  - Storage constraints
  - Imposed fineness ratio
  - Diameter limitations due to the payload
  - Accuracy requirements (long ad slender configurations make **higher ballistic coefficient** and give more sensitivity to weather/environmental conditions)
  - Acceleration requirements: acceleration is inversely correlated to L/d due to rocket internal ballistics for solid propellants, or structural issues due to instability

$$BC = \frac{M}{C_d A_{ref}} = \frac{\rho L_{ref}}{C_d}$$

# L/D trade-off example

Tactical ballistic missiles with high acceleration

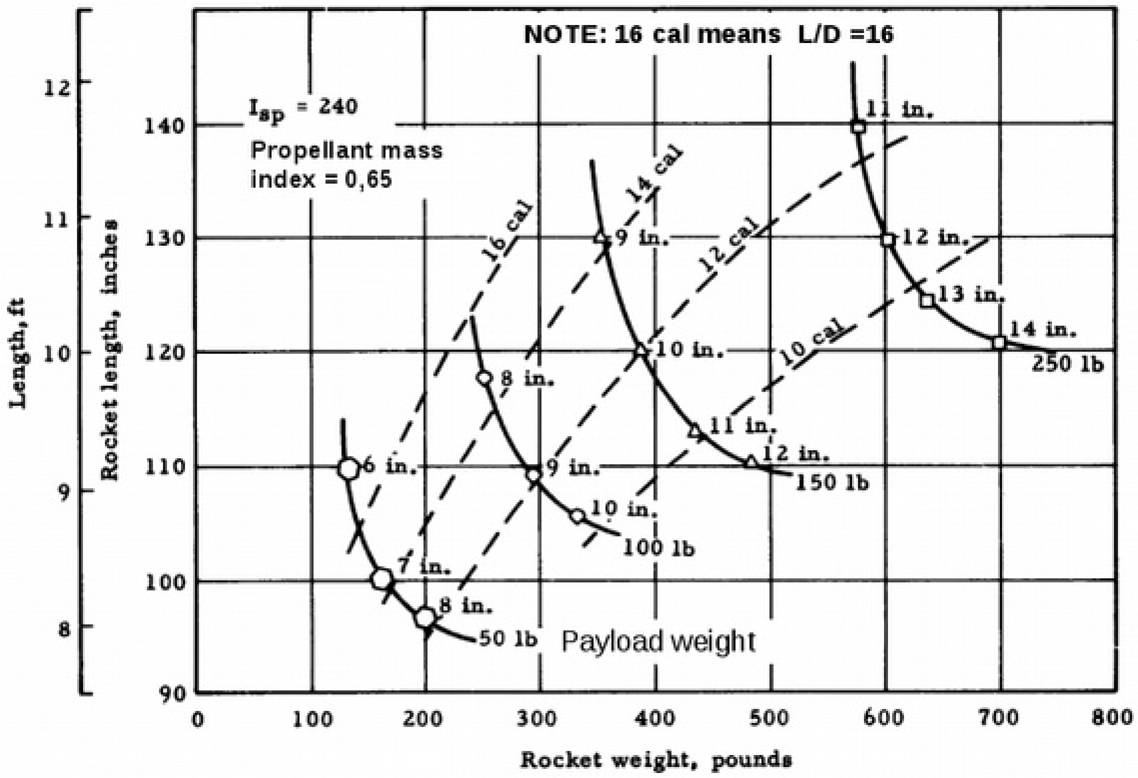



Figure 20. WEIGHT AND LENGTH TRADEOFFS FOR RANGE = 30 KM.

From: Parametric Design Curves for Short rage Acceleration ballistic Rockets
US Army Missile Command, Redstone Arsenal, USA, 1963, Sec. 9.

solid line: constant payload

dashed line: const. L/d ratio

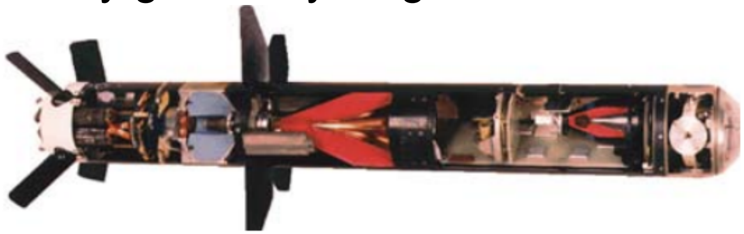
For the same payload, the diameter is reduced.

The length mush grow for constant payload and same propellant mass index.

The weight has asymptotic behavior incrementing fineness ratio

# L/d trade-off example

- **Javelin (Raytheon/Lockheed Martin)**
  - Shoulder-fired multipurpose missile automatically guided by long-wave IR seeker
  - Range 2.5 km
  - Low fineness ratio: 42,6 in / 5 in = 8,52

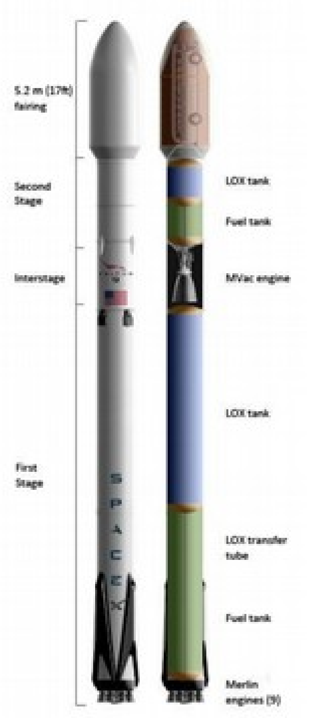



- **AIM 120 AMRAAM (Raytheon)**
  - radar-guided, air-to-air missile, single stage SRM
  - Beyond visual range capability, 50-75 km (depending on versions)
  - High fineness ratio: 144 in / 7 in = 20,5

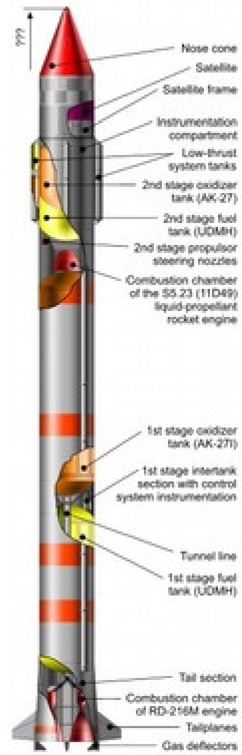
- **BrahMos (BrahMos aerospace)**
  - Two stage (SRM boost + ramjet sustain) supersonic cruise missile (ship or land launch, air-launch in progress)
  - Range 290 km, altitude 15 km, Mach 2.8-3.0
  - Medium fineness ratio: 8,2 m / 0,67 m = 12,2

# L/D trade-off example

- **Falcon 9 FT**
  - Two-stage launch vehicle (LOX/RP1).
  - Payload: 22.8 tons in LEO
  - High fineness ratio: 70 m / 3,66 m = 19,1
  - New design




- **Kosmos 3M 11K65M**
  - Two-stage launch vehicle (UDMH/HNO3+N2O4).
  - Payload: 1,5 tons in LEO
  - High fineness ratio: 26,3 m / 2,4 m = 10,9
  - Derived from ICBM



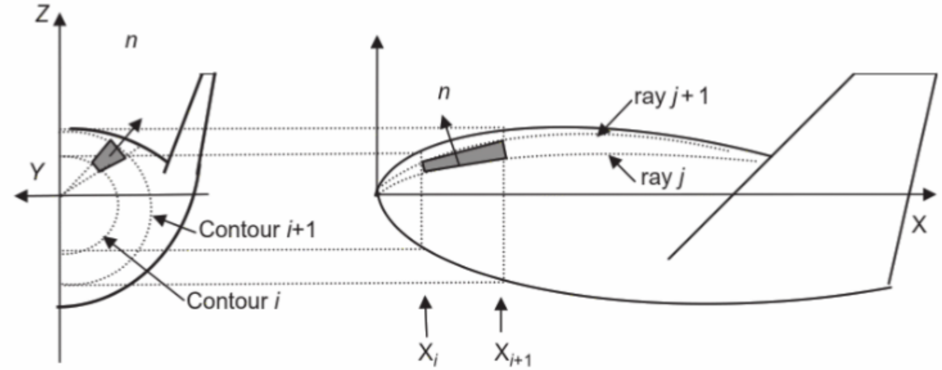
# Step 2: aerodynamic forces

# Step 2: aerodynamic forces

There are three main approaches

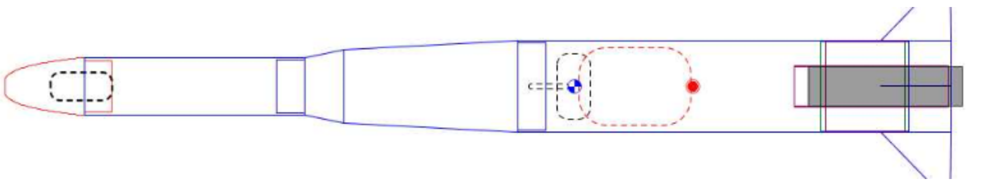
**Paneling methods**

Divide the surface on a number of panels and compute the local effect




**Component buildup methods**

Split the rocket in components and sum the contributions



Check openRocket software for examples

**DATCOM**

Software based on wide semi-empirical database (not treated here)

# Aerodynamics: local inclination methods

We need:

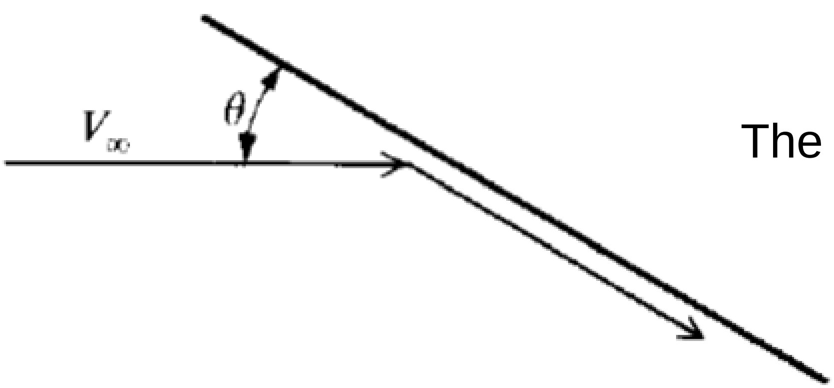
- A paneling code for the interested surface
- A model for local pressure coefficient estimation
- Wide range of models and choices

Local surface inclination methods can be used

- Here we use modified Newtonian approach for supersonic/hypersonic flow
- The Barrowman model can be used for subsonic flow

# Aerodynamics: local inclination methods

- Newtonian flow: dated back in 1687
- The idea is that the flow impacts on the surface and deviates parallel to the surface (close to real hypersonic behavior)




The Newtonian theory states that:

$$C_p = 2(\sin\theta)^2$$

The modified Newtonian theory states that:

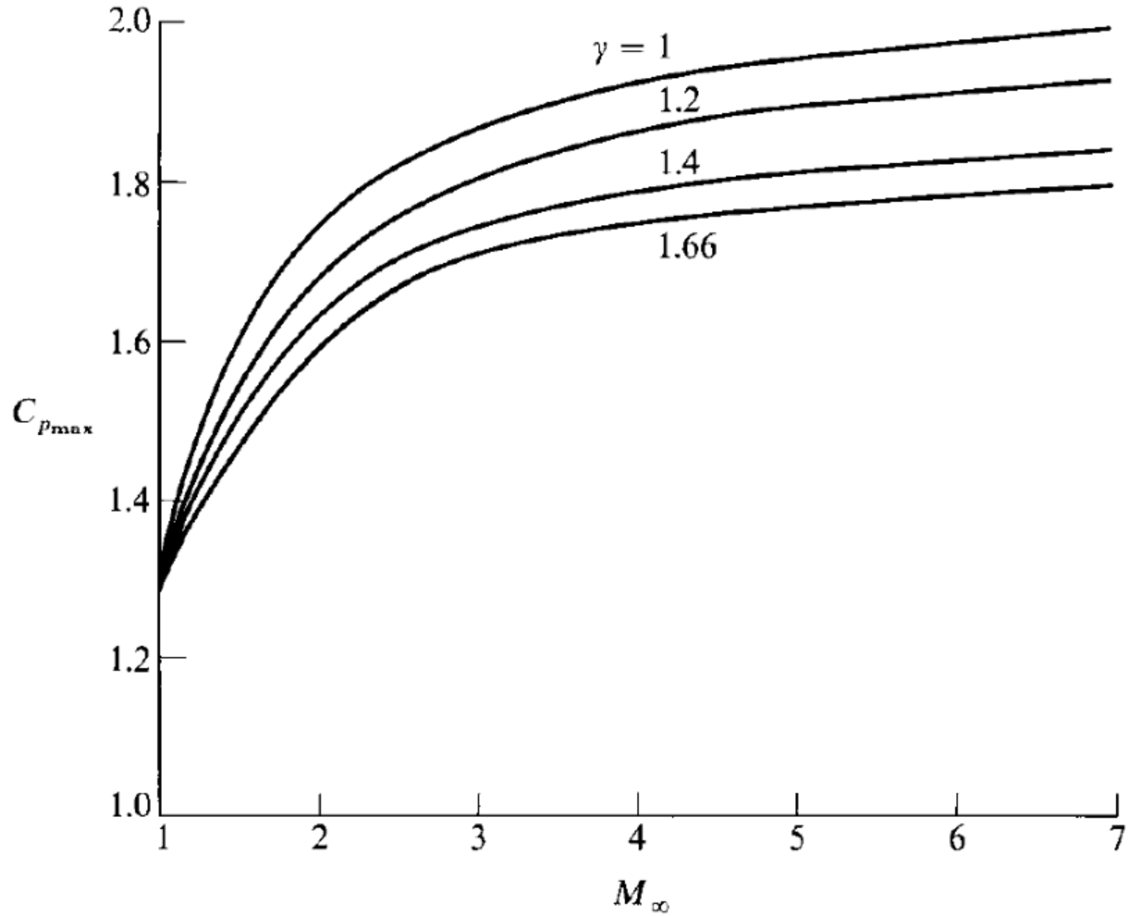
$$C_p = C_{p-max}(\sin\theta)^2$$

$$\text{where } C_{p-max} = \frac{p_{O2} - p_\infty}{1/2\,\rho_\infty V_\infty^2}$$

$P_{o2}$: total pressure behind normal shock at free stream Mach

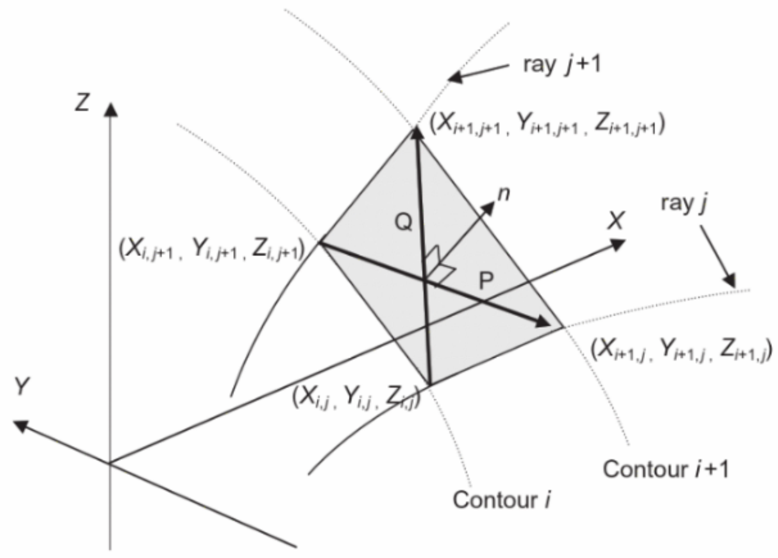
# Aerodynamics: local inclination methods

$$C_{p-max} = \frac{p_{O2} - p_{\infty}}{1/2\, \rho_{\infty} V_{\infty}^2}$$



# Aerodynamics: local inclination methods

- Implementation (supersonic)
  - The surface is divided into panels where the sides are known
  - Thanks to the side coordinates, the normal and the free stream inclination can be identified




From Sforza book.

$$\bar{N}=\bar{P}\times\bar{Q}$$

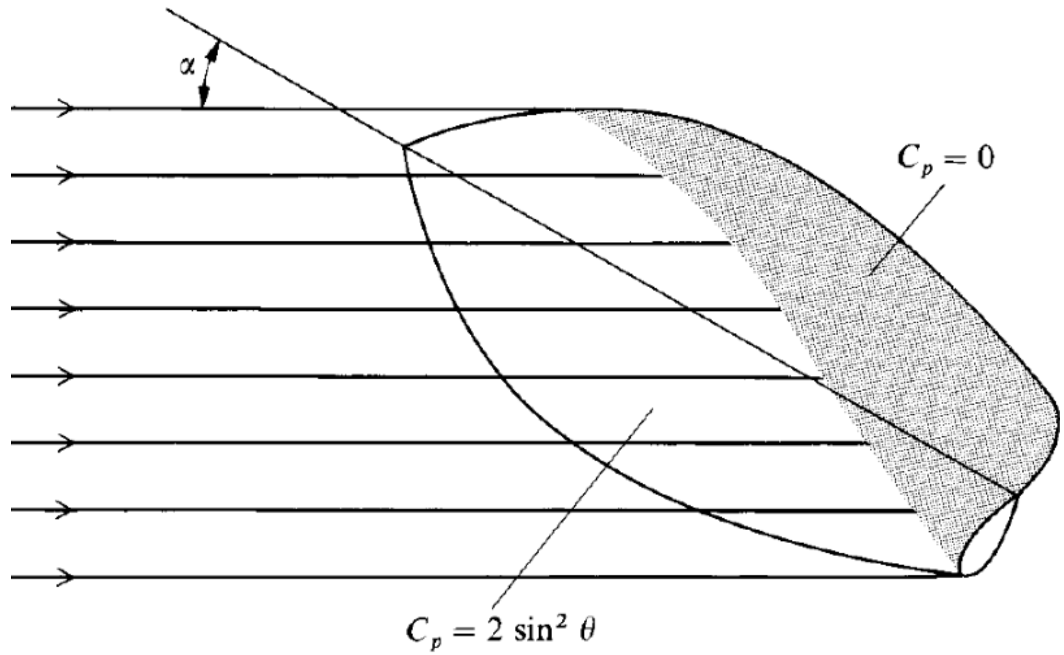
$$\bar{n}=\frac{\bar{N}}{\sqrt{\bar{N}\cdot\bar{N}}}$$ Normal versor

$$A=\frac{1}{2}|\bar{P}\times\bar{Q}|=\frac{1}{2}|\bar{N}|$$ Element area

$$d\bar{F}=-C_p q A \bar{n}$$ Element force

# Aerodynamics: local inclination methods

Shadow region

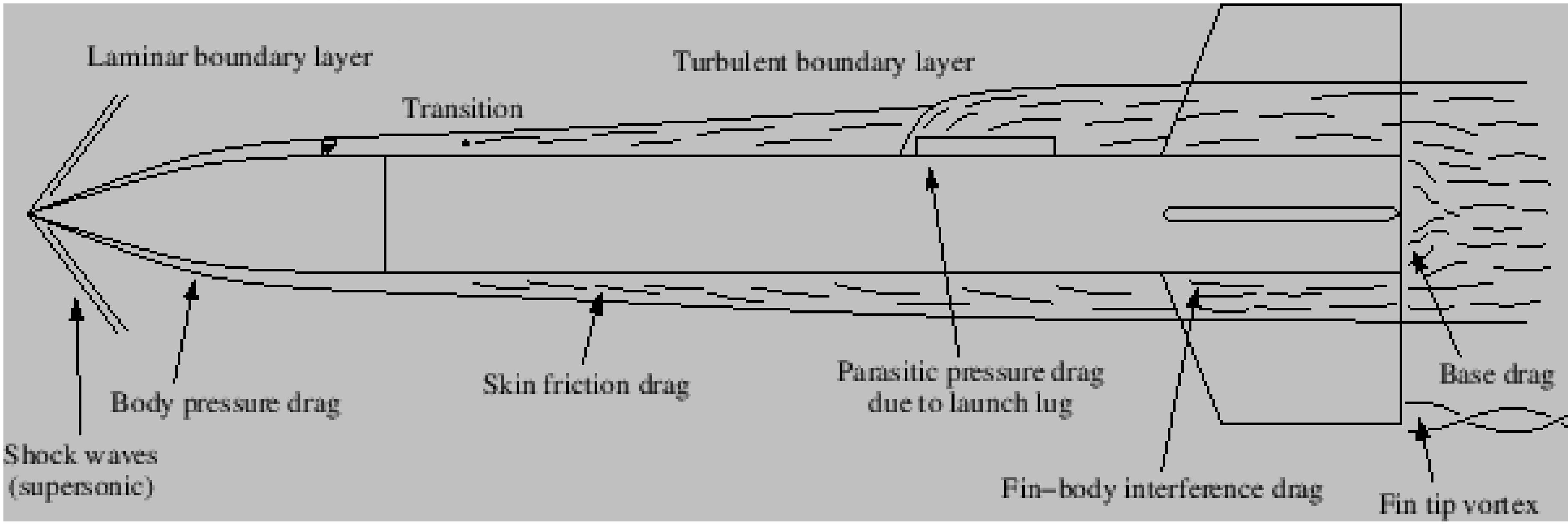



Notes on the Newtonian method:

- the accuracy of the method lowers when Mach becomes smaller than 4
- The accuracy also is lower when surface inclination is smaller than 45°

# Aerodynamics: component buildup

**Zero-lift flight condition** of a symmetric body
(simplest case: slender body, nose, tail)




Main direct drag sources
- **Pressure drag**
- **Skin friction drag**

Main contributions to body drag
- Friction/pressure/form drag
- Base drag
- Wave drag (if supersonic)

$$\left(C_{D0}\right)_{\text{body}} = \left(C_{D0}\right)_{\text{body, friction}} + \left(C_{D0}\right)_{\text{base}} + \left(C_{D0}\right)_{\text{body, wave}}$$

# Aerodynamics: component buildup

$$\left(C_{D0}\right)_{\text{body}} = \left(C_{D0}\right)_{\text{body, friction}} + \left(C_{D0}\right)_{\text{base}} + \left(C_{D0}\right)_{\text{body, wave}}$$

Interference coefficients weight the interaction of components

$$\left(C_{D0}\right)_{\text{body}} = K_i\left(\left(C_{D0}\right)_{\text{body, friction}} + \left(C_{D0}\right)_{\text{base}} + \left(C_{D0}\right)_{\text{body, wave}}\right)$$

Good approximation: 1,25

For details: Tactical Missile Design by Redmond

# Aerodynamics: component buildup

- Empirical or semiempirical relations exist for components and their interference. Limits apply.
- Check the paper by Vukelich (on BEEP Extradoc folder) for extensive knowledge.

Example of applicability limits for friction models

(from Vukelich paper)

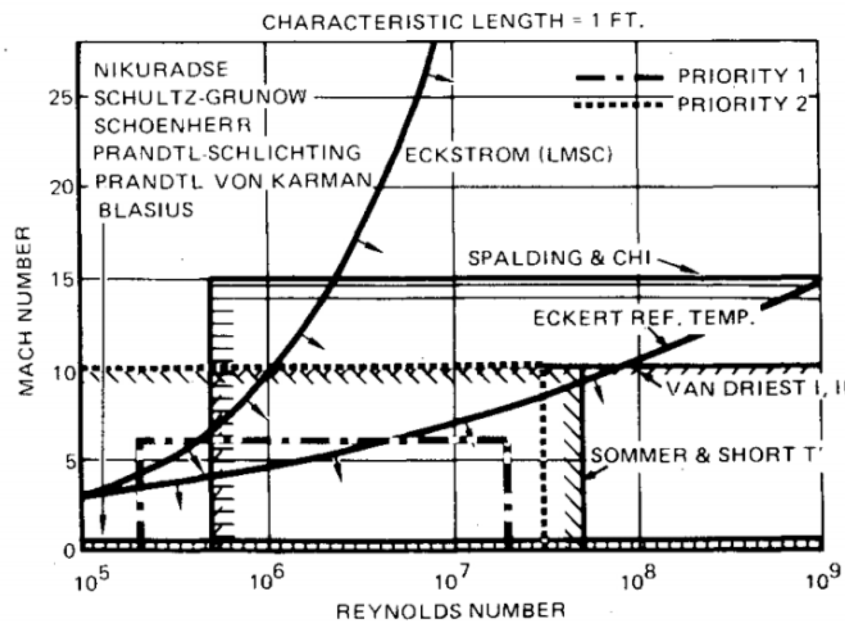



**Fig. 2** **Applicability of friction methods.**

# Aerodynamics: general considerations

General considerations for slender bodies (fineness ratio 8 to 12)

- Pressure drag is 1/10 to ¼ of the total drag
- Skin friction and base drag: 1/3 to 2/3 each of the pressure, depending on flight speed, configuration, Reynolds number

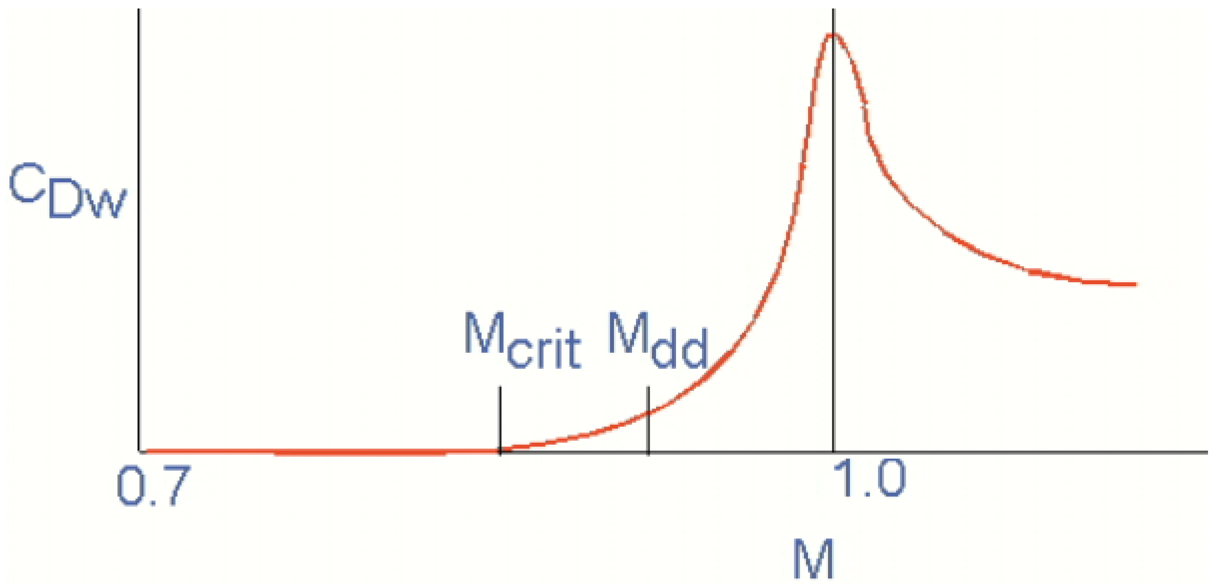
- As the Mach number increases both skin friction and pressure drag increase. The base drag reduces the weight and becomes almost negligible after Mach 5

- Simplest approach to pressure drag: compute the integral of pressure along the direction of motion

- Data and relations can be found in the book: Handbook of Supersonic Aerodynamics, Section 8, Chapter 6, Navweps report 1488, 1961 or in Hoerner book.

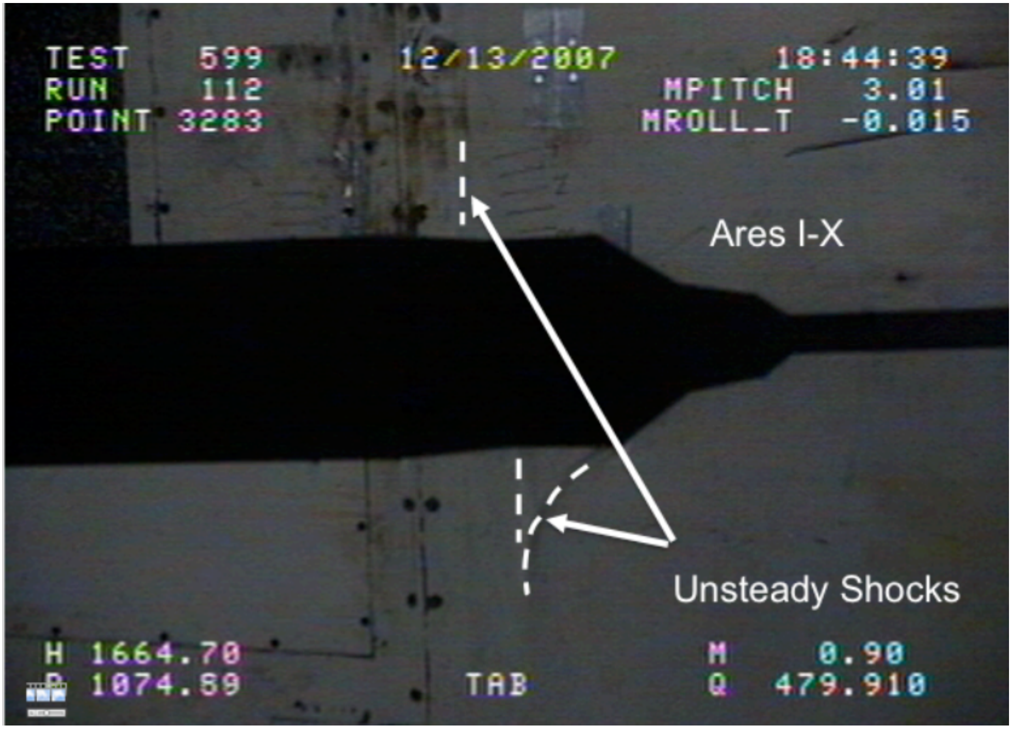
# Aerodynamics: wave drag

- Part of pressure drag, present in transonic region due to shock wave generation
- It increases sharply after the $M_{CR}$ (critical Mach number)
- Difficult to predict in the transonic regions: often fittings are used

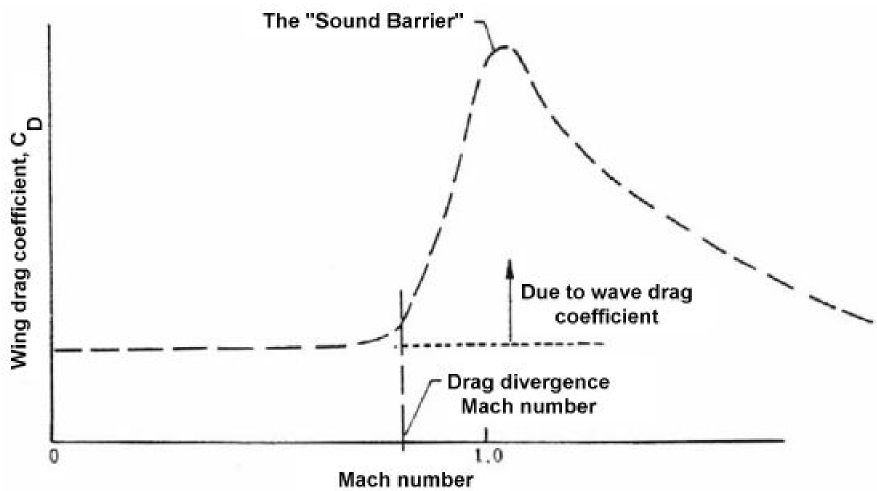


# Aerodynamics: wave drag example

- Example of ARES I-X tested in transonic regime: non-symmetric unsteady shock are generated at the base of the cone.



# Aerodynamics: wave drag simple model




- Drag correlated to the set of events caused by the generation of shock waves
- Main source: pressure distribution on the body
- Peak of drag coefficient is obtained in the transonic region. Local shocks can be generated even in subsonic regime

- Strong influence on nose Length-to-diameter ratio and bluntness
- Simplified approach for sharp noses by Bonney (for M > 1)

$$\left(C_{D0}\right)_{\text{body,wave}} = \left(1{,}586 + \frac{1{,}834}{M^2}\right)\left[\arctan\left(\frac{0{,}5}{\left(L_N/d\right)}\right)\right]^{1{,}69}$$

$L_N$: nose length

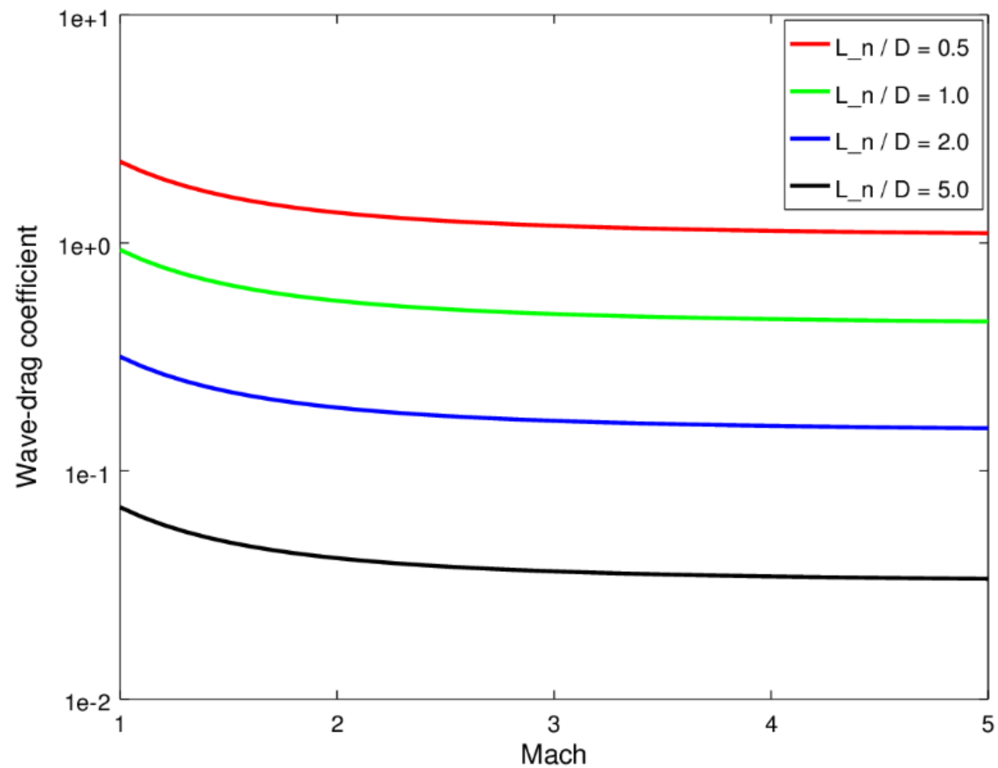
d: body diameter

# Aerodynamics: Wave-drag of nose

Example: $l_N / d = 0.5$ ( hemisphere )


Examples: $l_N / d = 2$ tangent ogive


Example: $l_N / d = 5$ tangent ogive


For more refined approaches:

- J.D. Anderson. Hypersonic and High Temperature Gas Dynamics, AIAA
- Handbook of supersonic aerodynamics, NavWeps Report 1488

# Aerodynamics: blunted noses wave drag

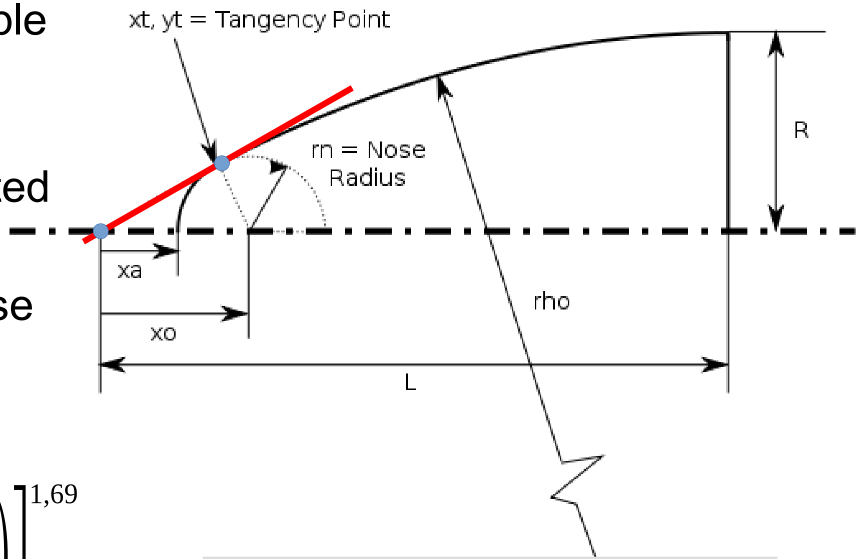
- Small amount of nose tip bluntness is desirable to alleviate local stress concentration and tip heating
- A procedure can be performed to relate blunted nose to cone and hemispherical formulas
- From the nose geometry a tangent sharp nose should be derived, as shown here
- Compute the wave drag for sharp nose according to body geometry

$$\left(C_{D0}\right)_{\text{body,wave}}=\left(1{,}586+\frac{1{,}834}{M^2}\right)\left[\arctan\left(\frac{0{,}5}{\left(L_N/d\right)}\right)\right]^{1{,}69}$$

- Compute the hemispherical wave drag ($L_N$ / D = 0,5)

$$\left(C_{D0}\right)_{\text{wave, hemi}}=0{,}665\left(1{,}586+\frac{1{,}834}{M^2}\right)$$

- Scale the contributions by their respective areas




$A_{nose}$: cross section of the circle describing the bluntness

$A_{ref}$: cross section of the body

$$\left(C_{D0}\right)_{\text{body,blunt}}=\left(C_{D0}\right)_{\text{body,sharp}}\left(A_{ref}-A_{nose}\right)/A_{ref}+\left(C_{D0}\right)_{\text{wave,hemi}}A_{nose}/A_{ref}$$

# Aerodynamics: other noses wave drag

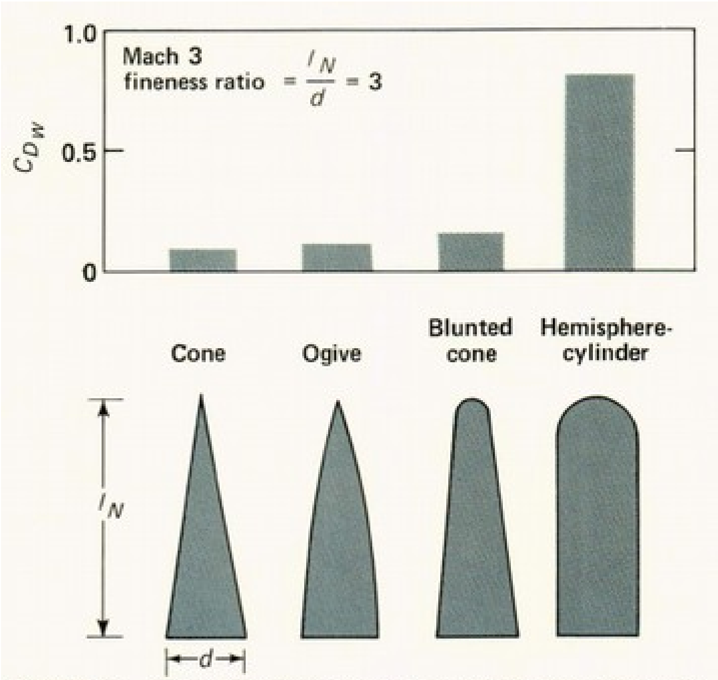
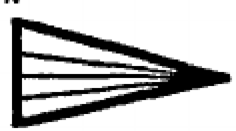


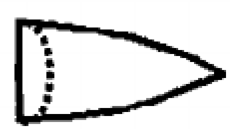

Figure 2 — The effect of sensor dome bluntness on the wave drag coefficient, $C_{D_W}$ .

$l_N$/ d = 2 faceted



$l_N$/ d = 2 window


$l_N$/ d = 2 multi-lens



Small bluntness may introduce a limited increment of drag, compared to a pure hemispherical nose.

Other nose geometries (non-symmetrical, faceted, multilens, etc. ) can be used. None of them are optimized from the aerodynamic viewpoint but respod to other needs such as electromagnetic wave distortion for sensors, seekers, radards. These geometries can be handled with simplified gas dynamic approaches (see mentioned refs.)

# Aerodynamics: body drag skin friction

- Major component of subsonic drag for slender bodies
- Primarily driven by the body fineness ratio.
- Mild dependence from Mach, q, and body length
- Hypotheses:
  - Zero-lift, turbulent flow without boattail
  - In case of noncircular bodies, wetted area is approximated with the one of an equivalent cylinder
  - Speed of sound and viscosity do not change too much from the free stream with altitude
  - Independence from Re (simplified model)

$$\left(C_{D0}\right)_{\text{body,friction}} = 0{,}053 \left(\frac{L}{d}\right)\left(\frac{\mathrm{M}}{q\,L}\right)^{0{,}2}$$

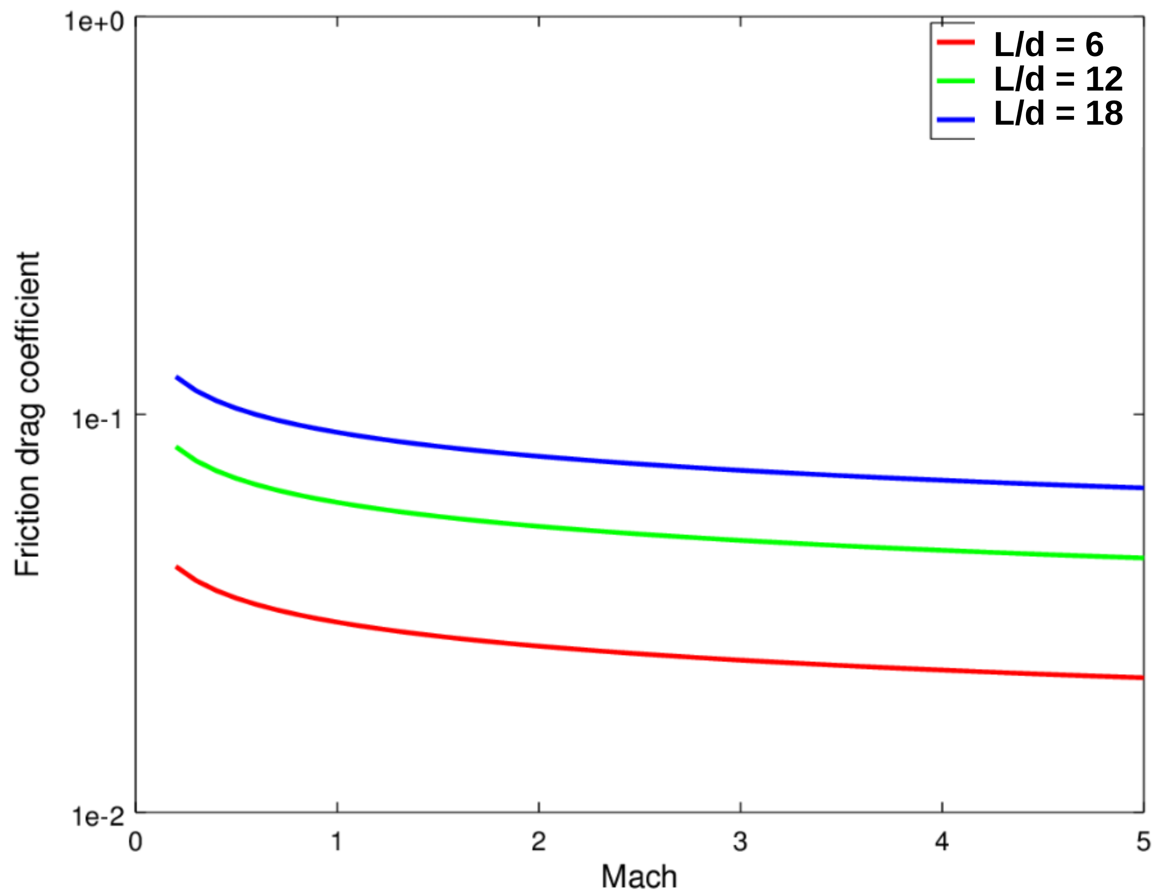
M: free stream Mach number

Fineness ratio

# Aerodynamics: skin friction example

**Computation conditions**

- L = 4 m
- Z = 6000 m




Improved relations and simulations can be found in referred literature

# Aerodynamics: body drag skin friction 2

- Another model: use of **flat plate assumption**

Incompressible skin friction coefficient:
Reynolds based on body length l

$$C_{fi}=\frac{0,455}{\left(\log_{10}\left(\mathrm{Re}_l\right)\right)^{2.58}}$$

Subsonic compressible correction:

$$C_f=\frac{C_{fi}}{1+0,08\,M^2}$$

Supersonic compressible correction:

$$C_f=\frac{C_{fi}}{\left(1+0,144\,M^2\right)^{0.65}}$$

Computation of drag coefficient:
(this one can now be summed up with the other drag coefficients)

Wetted surface by flow

$$C_D=C_f\frac{S_{wet}}{S_{ref}}$$

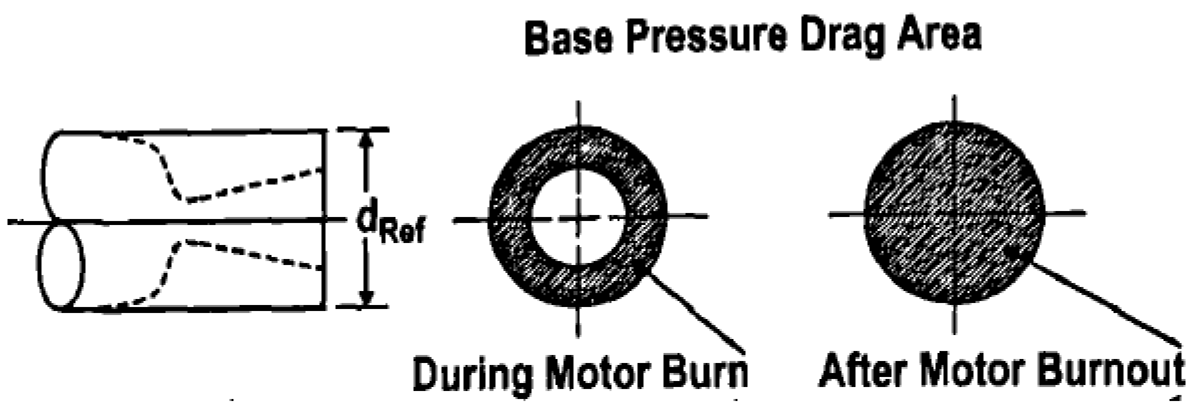
Reference surface of body

# Aerodynamics: base drag

The base drag is a pressure-based contribution and depends on the interaction between the flow and the nozzle section of the launcher.

The drag is changes if the regime is subsonic or supersonic

The base drag is lower during powered flight while it is higher during coast/unpowered flight




$A_e$: nozzle exit area

$A_{ref}$: base reference area

# Aerodynamics: base drag

- Coast/unpowered phase: base drag refers to the entire base area

**Supersonic**

$$\left(C_{D0}\right)_{\text{base,coast}}=\frac{0{,}25}{\text{M}}$$

**Subsonic**

$$\left(C_{D0}\right)_{\text{base,coast}}=0{,}12+0{,}13\,\text{M}^2$$

- Powered phase: base area decremented by nozzle exit area

**Supersonic**

$$\left(C_{D0}\right)_{\text{base,powered}}=\left(1-\frac{A_e}{A_{ref}}\right)\frac{0{,}25}{\text{M}}$$

**Subsonic**

$$\left(C_{D0}\right)_{\text{base,powered}}=\left(1-\frac{A_e}{A_{ref}}\right)\left(0{,}12+0{,}13\,\text{M}^2\right)$$

# Base drag reduction: boat-tailing

The base drag can be a major contribution during coast phase (unpowered) since the pressure value is low at the base of the nozzle.

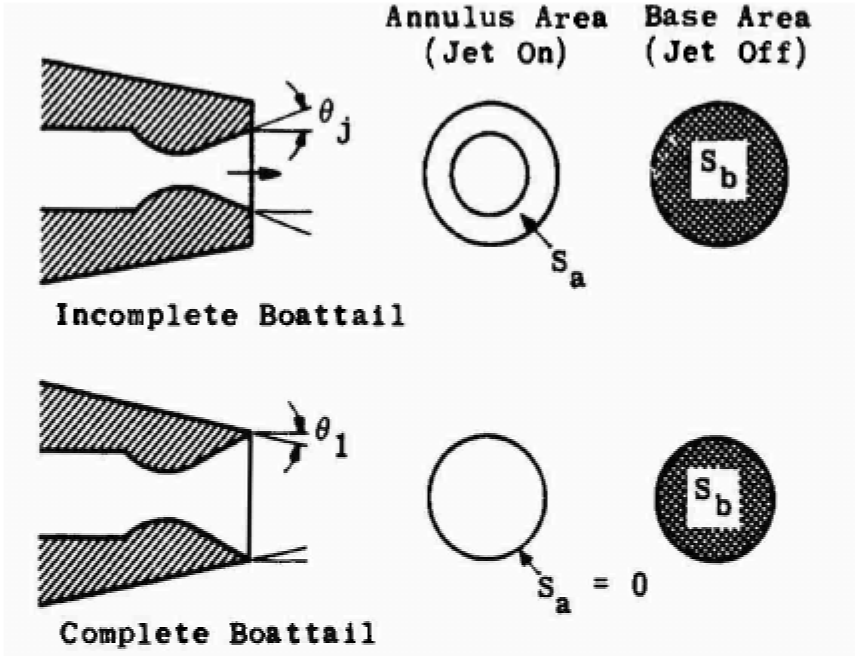
The boattail reduces the loss, because reduces the area where the pressure effect is acting

Boattail angle should be less than 7-10° to avoid separation

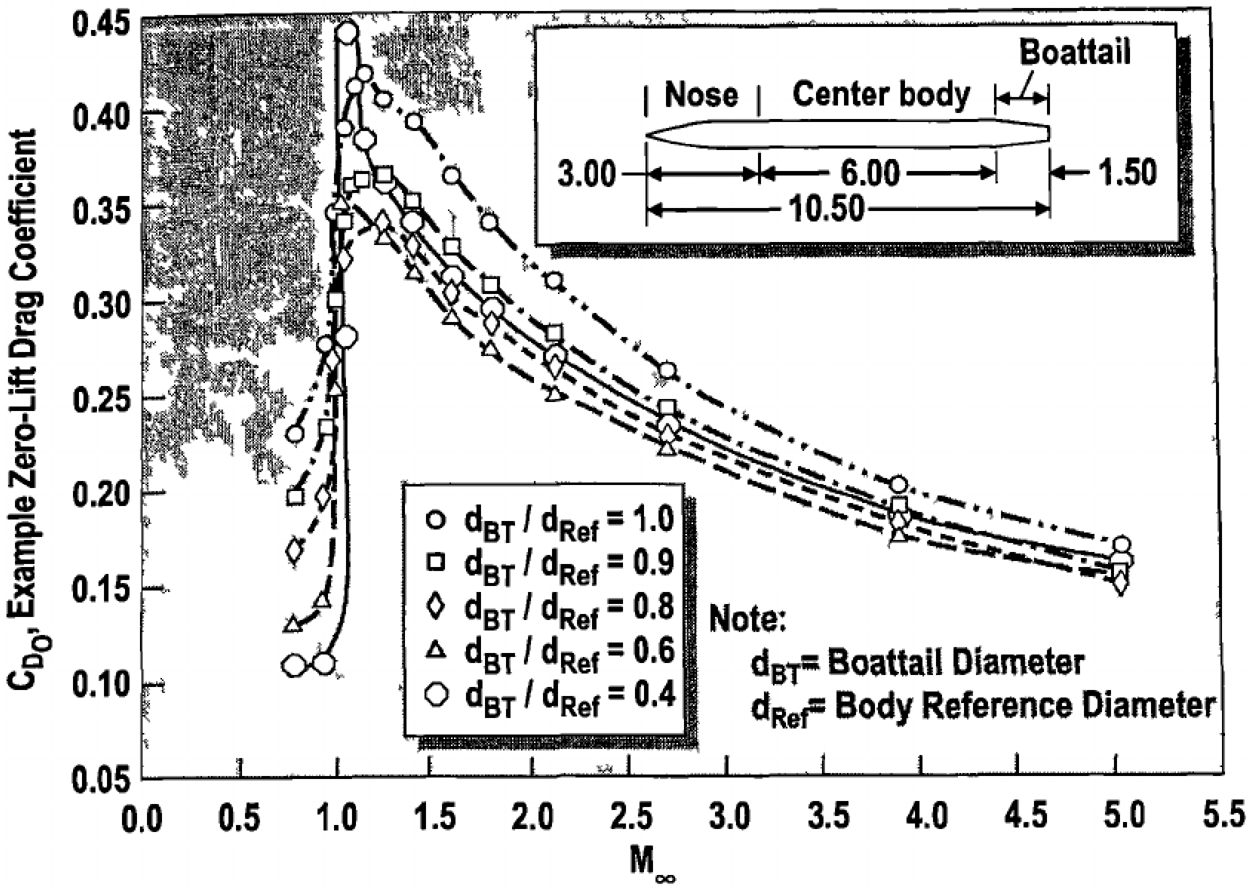
Best boattail advantage is obtained in subsonic launch systems.

In supersonic flight the flow separates from the bottom and boattail does not present great advantages **UNLESS** complete boattail is adopted. In this case separation does not occur.

Issue: lodging of actuators



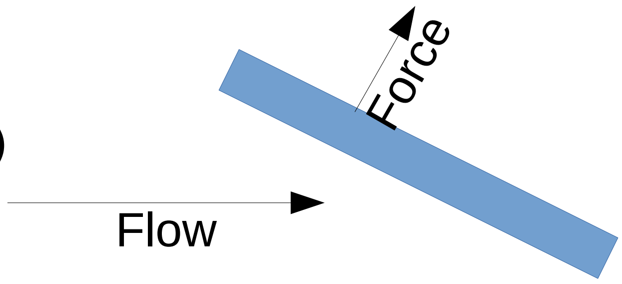
# Effect of boattail on zero-lift drag




Note: Boatail half angle should be less than 10 deg, to avoid flow separattion.
Source: Mason, L.A., Devan, L. and Moore, F.G., "Aerodynamic Design Manual for Tactical Weapons," NSWC TR 81-156, July 1981

# Body normal force

- In this part the force along the direction normal to the body main axis is considered (lift and normal force can be exchanged for angle of attack < 25°)




- Two types of bodies can be considered
  - Lifting bodies (nonsymmetrical)
  - Axisymmetrical bodies

The normal force coefficient $C_N$ is defined as any other aerodynamic coefficient

In a slender body the $C_N$ is a function of the angle of attack and body geometry, independent from Mach and Reynolds.

The prediction depends on two different theories

- Slender body theory for low angle of attack
- Body  cross-flow theory on for high angles of attack
- For angles tending to 90° the theory relies on drag coefficient computation for cylinders in cross flow. No more Mach independent. Remember the increment of Cd close to the transonic region

# Missile lift and normal force

- The lift of a missile is perpendicular to the incoming flow velocity and is the sum of different components (e.g. nose, wing, and tail):

$$L = L_N + (K_{B(W)} + K_{W(B)})L_W + (K_{B(T)} + K_{T(B)})L_T$$

Interference coefficient
body on wing

Interference coefficient
Wing on body

Interference coefficient
Body on tail

Interference
Tail on body

Similar equations can be written for the normal force

For details: Missile Design Toolbox by Ekker

# Missile lift and normal force

- The relation can be transferred to coefficients

$$C_L \bar{q} S_{ref} = C_{LN} \bar{q} S_{ref} + \underbrace{(K_{B(W)} + K_{W(B)})}_{\text{Typically 1.5-2.0}} C_{LW} \bar{q} S_W + \underbrace{(K_{B(T)} + K_{T(B)})}_{\text{Typically 1.5-2.0}} C_{LT} \bar{q}_T S_T$$

$$\begin{cases} C_L = C_{LN} + (K_{B(W)} + K_{W(B)}) C_{LW} \dfrac{S_W}{S_{ref}} + (K_{B(T)} + K_{T(B)}) C_{LT} \left( \dfrac{M_T}{M} \right)^2 \dfrac{S_T}{S_{ref}} \\ \bar{q}_T = \dfrac{1}{2} \rho M_T^2 a^2 = \dfrac{M_T^2}{M^2} \bar{q} \end{cases}$$

For details: Tactical Missile Design by Redmond

# Local inclination: Barrowman (subsonic)

- Barrowman method for subsonic axial symmetric bodies (based on downwash)

The normal force can be derived by the equation $N(x) = \rho V \frac{\partial}{\partial x}(A_c(x) w(x))$

Where
$A_c$ is the cross section area
$w = V \sin \alpha$
$\alpha$: angle of attack

$$C_n(x) = \frac{N(x)}{q} A_{ref} = 2 \frac{\alpha}{A_{ref}} \frac{dA}{dx}$$

Local shape is used

Check for details: OpenRocket documentation

# Allen - Perkins model

- The normal force is the superposition of the potential flow and a correction arising from the cross-flow experienced by the body.
- Several models have been derived from this assumption

$$C_n(x)=\frac{N(x)}{q}A_{ref}=\frac{A_{base}}{A_{ref}}\sin(2\alpha)\cos\left(\frac{\alpha}{2}\right)+\eta\, C_{D-N}\frac{A_{planform}}{A_{ref}}(\sin\alpha)^2$$

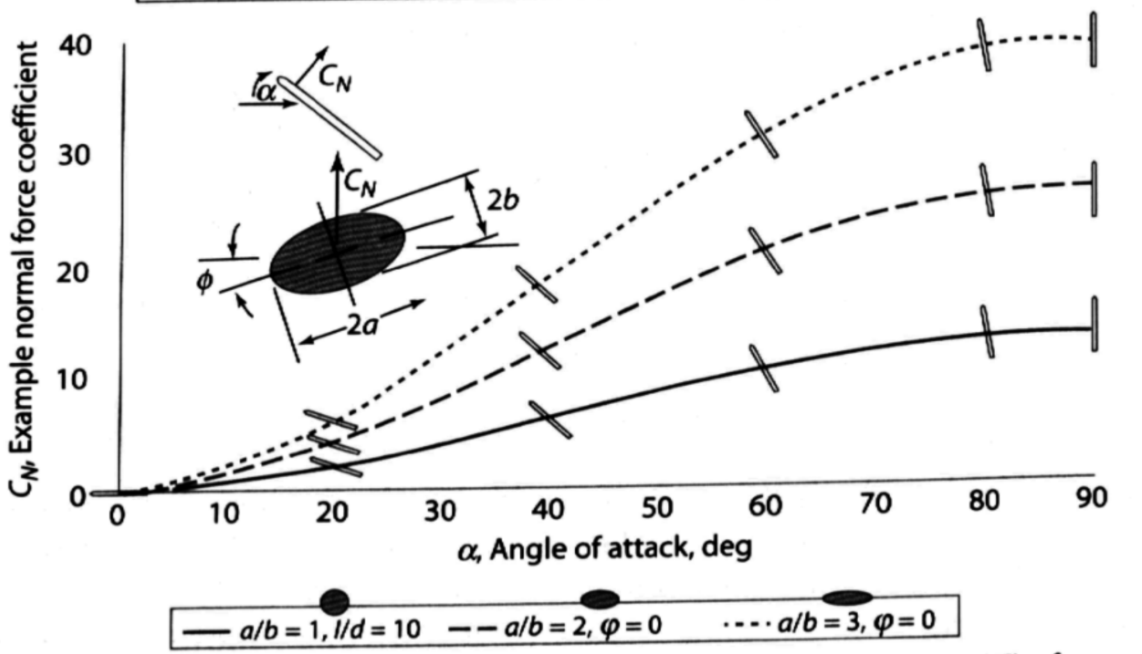
$$\eta=0{,}05\left(\frac{l}{d}\right)+0{,}52 \text{ for subsonic flight } \eta=1 \text{ for } M>1$$

Check for details:
NACA report 1048 by Allen and Perkins
Manned Spacecraft Design Principles, Chp. 7.6, by Sforza
Jorgensen NASA TN D-7228

# Allen - Perkins model

Other versions of the original model

$$|C_N| = \left[(a/b)\cos^2\phi + (b/a)\sin^2\phi\right]\left[\,|\sin(2\alpha)\cos(\alpha/2)| + 1.3(l/d)\sin^2\alpha\right]$$




Note: Based on slender body theory (Pitts et al. [8]) and cross flow theory (Jorgensen [9]) references,
Valid for $l/d > 5$, $d = 2\,(ab)^{1/2}$

**Lifting bodies**

**Axisymmetrical**

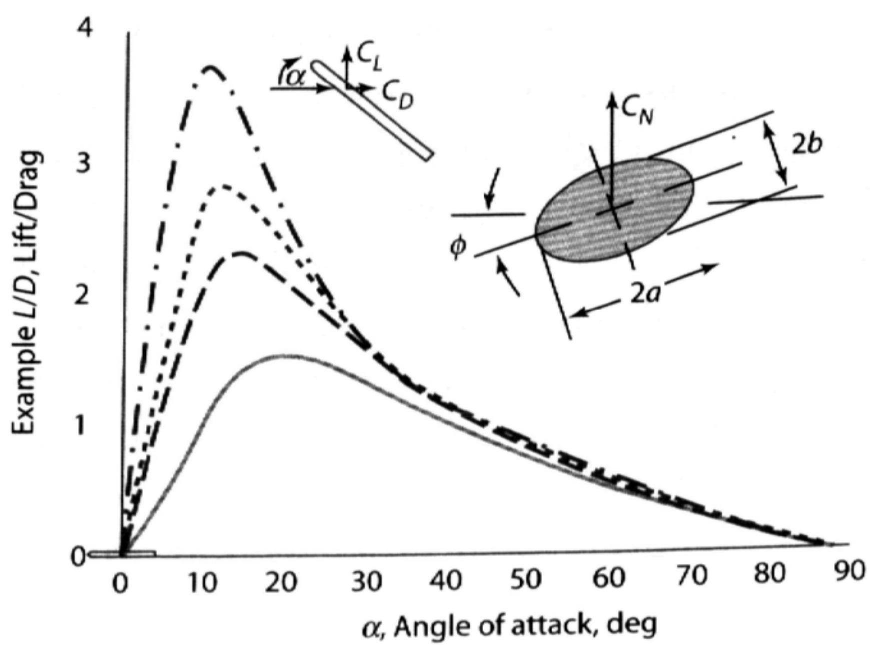
**Validity: L/d fineness ratio > 5**

For details:E. Fleeman. Missile design and system engineering. AIAA Educational Series, 2012

# Aerodynamic efficiency: Lift-to-drag ratio

$$L/D = C_L/C_D = (C_N \cos\alpha - C_{D_0}\sin\alpha)/(C_N \sin\alpha + C_{D_0}\cos\alpha)$$

For lifting body, $|C_N| = \left[(a/b)\cos^2(\phi) + (b/a)\sin^2(\phi)\right]\left[|\sin(2\alpha)\cos(\alpha/2)| + 1.3\,(l/d)\sin^2\alpha\right]$




- ——— High drag, low fineness body ($a/b = 1$, $l/d = 10$, $C_{D_0} = 0.5$)
- — — Low drag nose ($a/b = 1$, $l/d = 10$, $C_{D_0} = 0.2$)
- - - - High fineness, low drag ($a/b = 1$, $l/d = 20$, $C_{D_0} = 0.2$)
- — · — Lifting body, High fineness, low drag ($a/b = 2$ @ $\varphi = 0$ deg, $l/d = 20$, $C_{D_0} = 0.2$)

Note:
- $d = 2\,(ab)^{1/2}$
- Launch platform span and length constraints (e.g., VLS launcher, aircraft compatibility) may limit missile aero configuration enhancements

Note: Based on slender body theory (Pitts et al. [8]) and cross flow theory (Jorgensen [9]) references, valid for $l/d > 5$, $d = 2\,(ab)^{1/2}$

# Increment of Lift-to-drag ratio

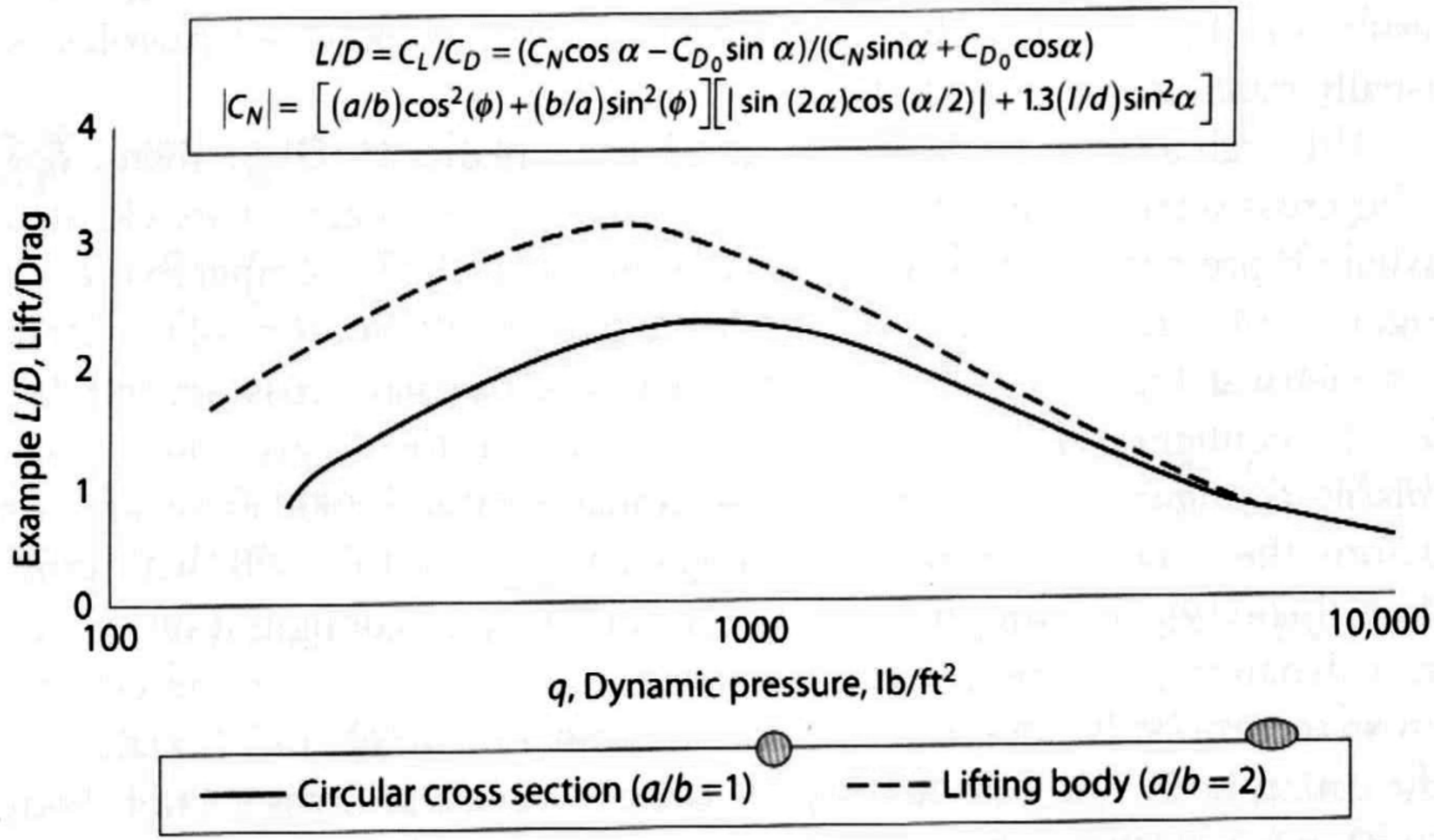
Increasing of aerodynamic efficiency is obtained:

- Increment the body fineness ratio
- Reducing the zero-lift drag coefficient
- Providing a lifting body shape (a/b > 1)

Other annotations:

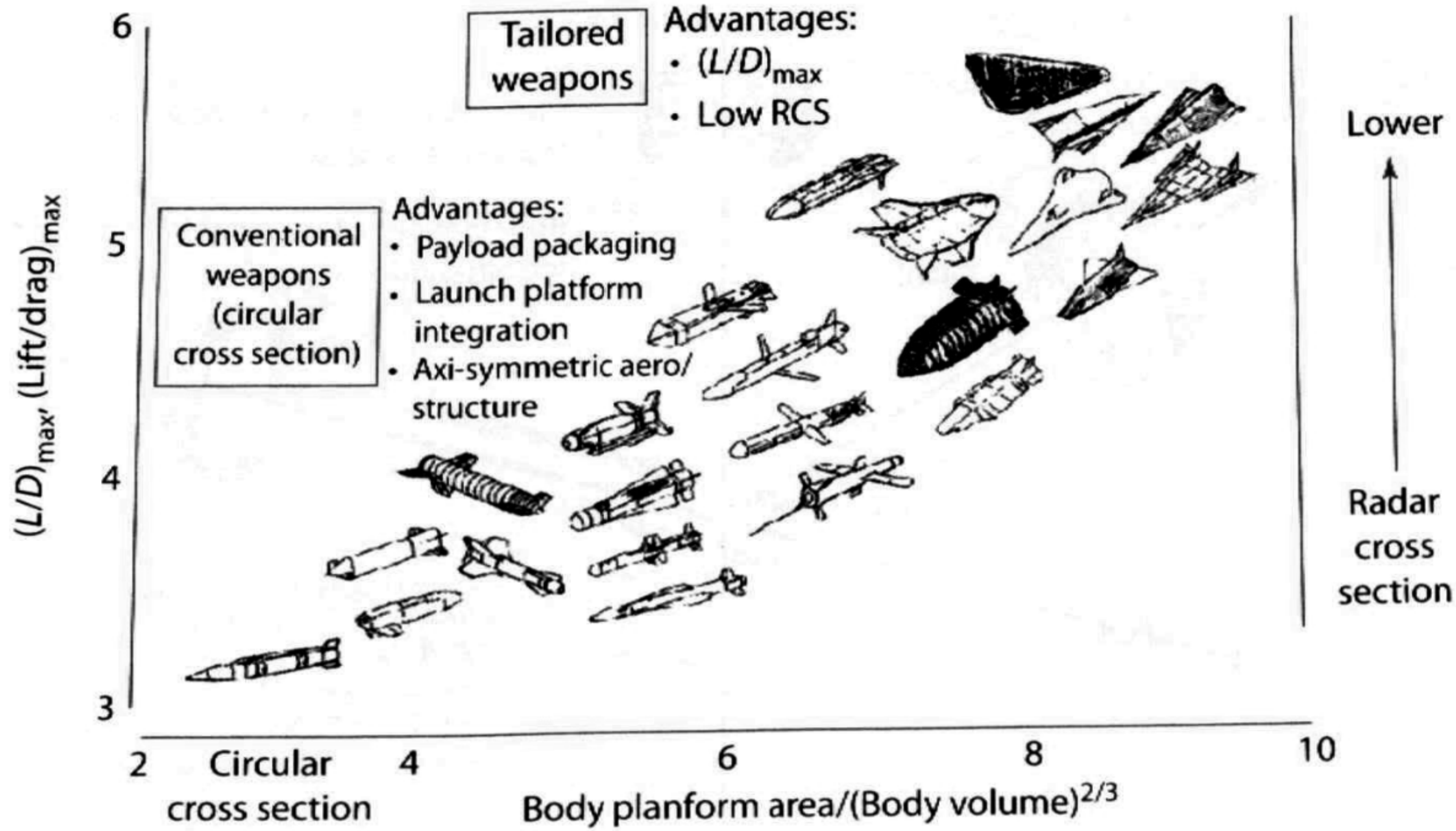
- As the L/D is incremented, the angle at which L/D is maximum decreases
- It should be noted that for cruise or low-angle of attack flights, the L/D is far from the optimal condition anyway. In such conditions the difference between a lifting and a axisymmetric body is not very high
- A lifting body requires flight at low dynamic pressure for high efficiency.

# L/D, dynamic pressure and body shape




Note: Example figure based on following assumptions:
Body lift only (no surfaces), lifting body + cross flow theory, cruise flight (lift = weight),
$W = L = 2000$ lb, $d = 2(ab)^{1/2}$, $S = 2$ ft$^2$, $l/d = 10$, $C_{D_0} = 0.2$, $\varphi = 0$ deg

# Observables vs efficiency



# On aerodynamics computation

- The models presented here are only a selection of the simplest techniques.

- Other models can be found in NASA TN D-6996 and TN D-7228 by Jorgensen.

- Another reference document can be obtained in Barrowman PhD dissertation integrated by Galejs corrections.

# So ...

- Drag of missiles are mostly due to:
  - Pressure drag (incremented by wave drag when transonic and base drag when engine is not working)
  - Friction drag
- The nose shape influences the wave drag
- An estimation of lift can be based on cross-flow and axial symmetric body aerodynamics
- Use of lifting bodies is convenient at low Mach number, where L/d ratio is much larger

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