# ENGINE – AIRFRAME INSTALLATION

**Lecture 5**

**Objectives Lecture 5:**
**To detail the issues arising from the installation of a propulsion system into a vehicle.**

**Topics:**

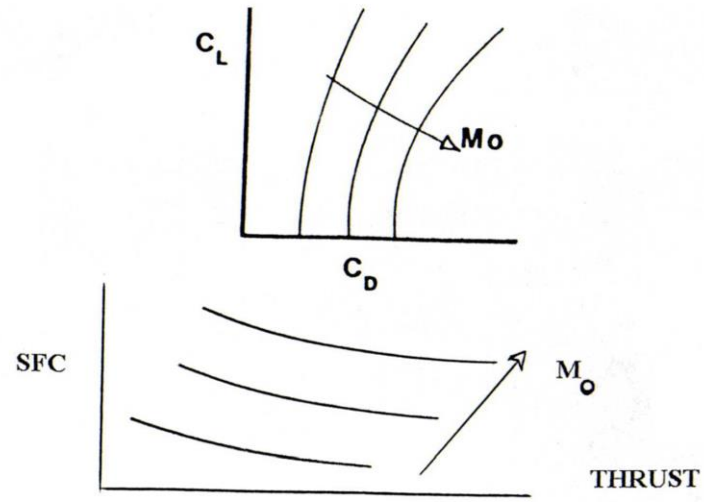
- ***Introduction*** √
- ***Thrust/Drag Accounting***
- ***Nacelle Geometry***
- ***Installed Drag***

# AIR VEHICLE PERFORMANCE

- **To calculate Air Vehicle Performance (in steady 1 'g' flight) the following are needed:**

➢ The drag & mass of the aircraft (usually in the form of drag polars & weight breakdowns)

➢ Engine thrust & fuel flow (characteristics usually in tabular form or as an "Engine Deck"




- Combining the drag polars with the engine performance gives the Air Vehicle performance

**BUT**

***The Aircraft effects the Engine & the Engine effects the Aircraft***

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# EFFECT OF ENGINE ON AIRFRAME

**Intake Flow:**

- Flow into Intake can effect fuselage and wing aerodynamics

**Exhaust Flow:**

- Scrubbing over fuselage can effect Drag & give rise to structural problems
- Exhaust Flow at certain values of incidence can cause instabilities & fatigue problems on Fin & tailplane
- Propeller slipstream can have a significant effect on both wing & tailplane aerodynamics and on the airframe structural design due to the levels of noise & vibration.

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# EFFECT OF AIRFRAME ON ENGINE

**Engine is the source of secondary power and bleed air:**

- Power to run systems
- Air for cabin conditioning & cooling etc.

**Nozzles**

- Special Nozzles can effect Engine Performance
- Vectoring Nozzles may be needed for combat manoeuvring and STOVL

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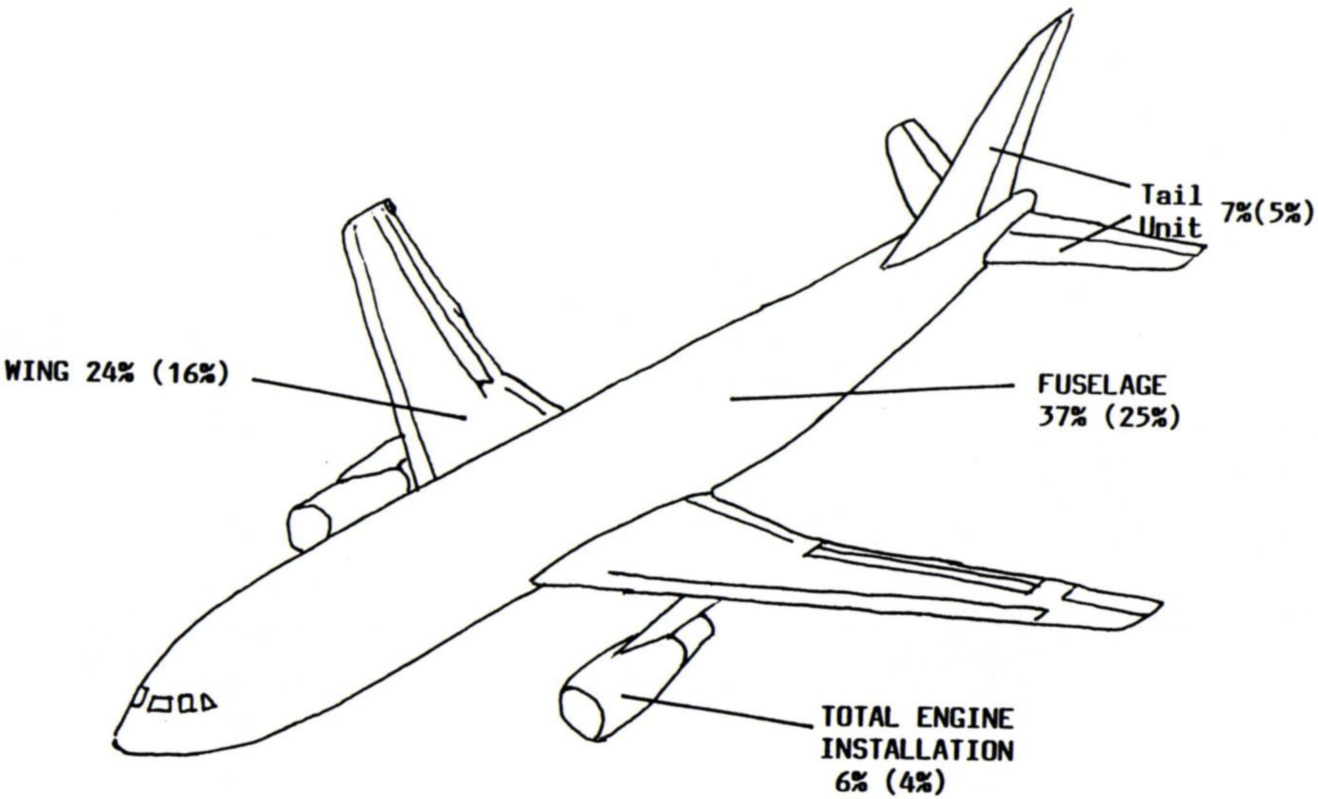
# Typical Drag Breakdown for Subsonic Airliner
## *Profile Drag as a percentage of Total Drag*




- **At Cruise Speed (at Minimum Drag Speed)**
- *Lift-Induced Drag* ~ *25% (50%)*
- *Profile Drag* ~ *75% (50%)*

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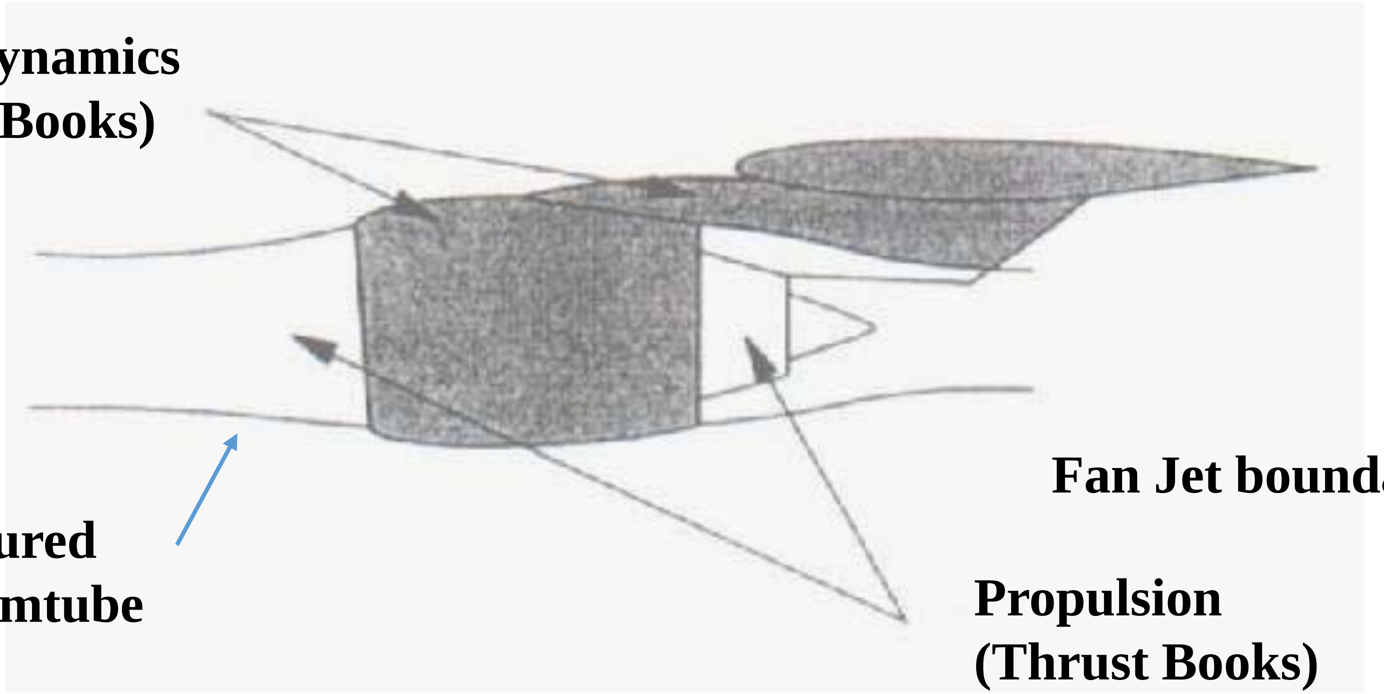
# Thrust/Drag Book-keeping Scheme

Aerodynamics
(Drag Books)



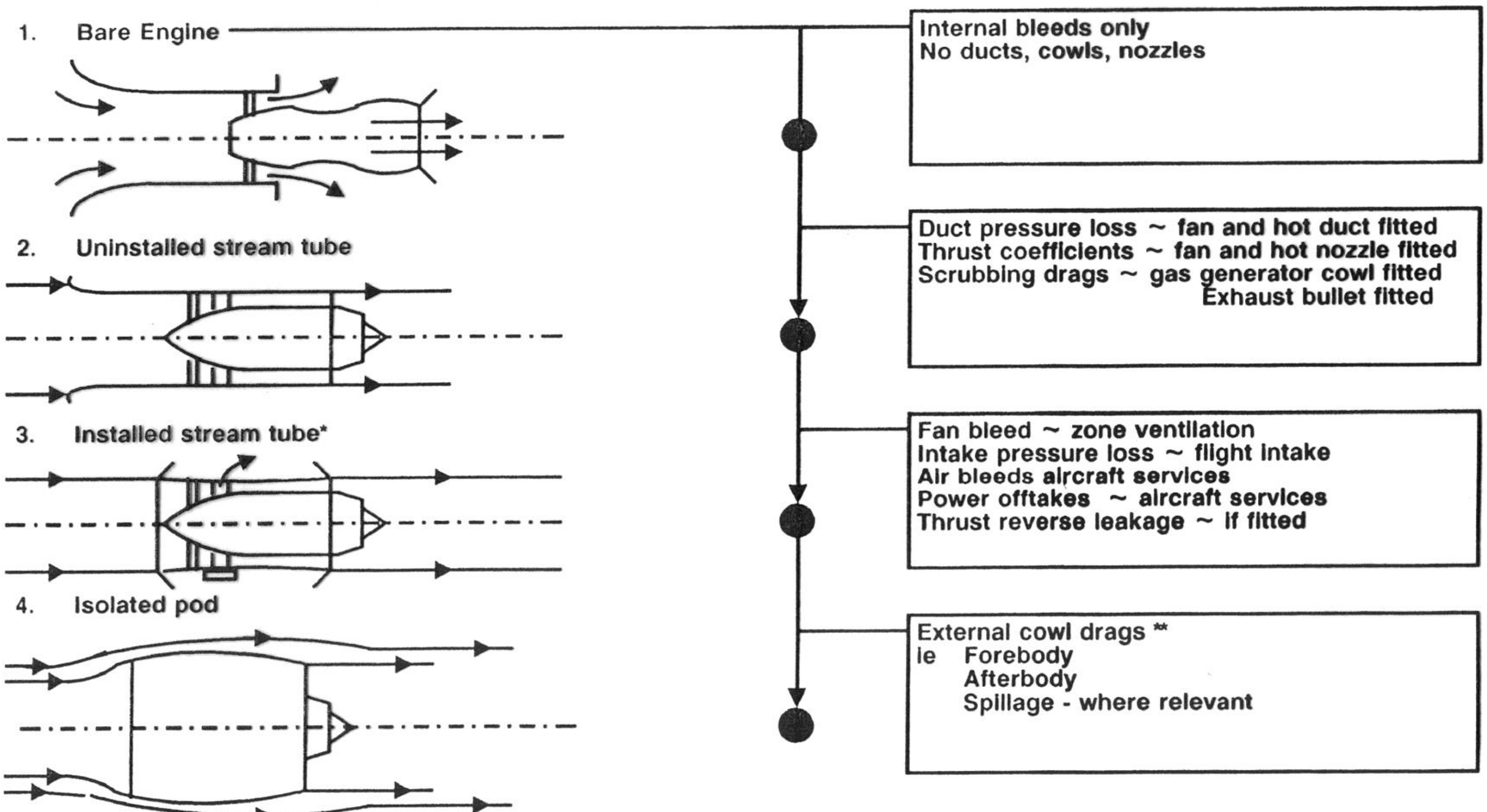
Fan Jet boundary

Captured
Streamtube

Propulsion
(Thrust Books)

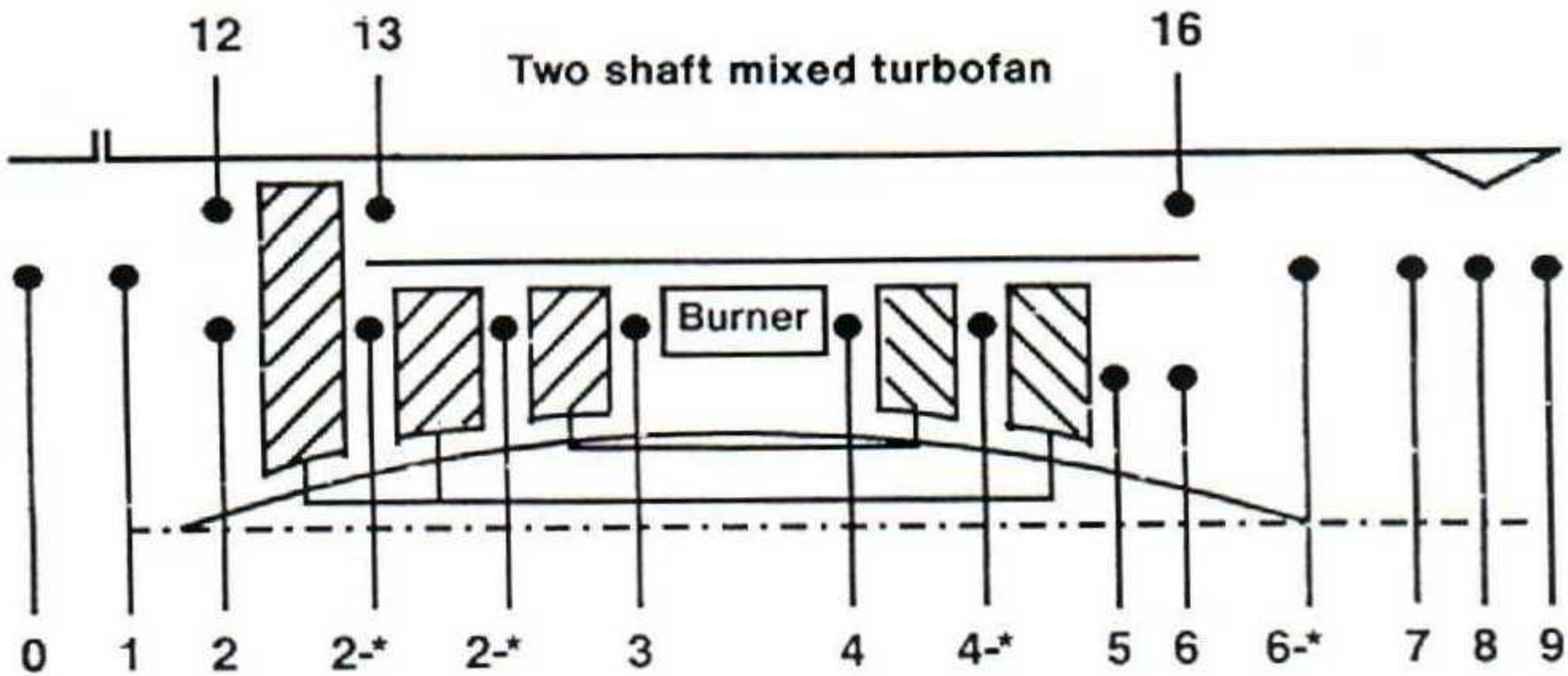
**Thrust** is the summation of the forces acting on the internal surfaces of the engine nacelle & pre-entry & post-exit stream-tubes from minus to plus infinity.
**Drag** is the summation of the forces acting on the external surfaces of the nacelle & pre-entry & post-exit stream-tubes from minus to plus infinity.

# Installed Performance Definition - 1




* Required for aircraft performance identical to a/c drag/number of engines for constant speed, straight and level flight
** Normally included in aircraft drag

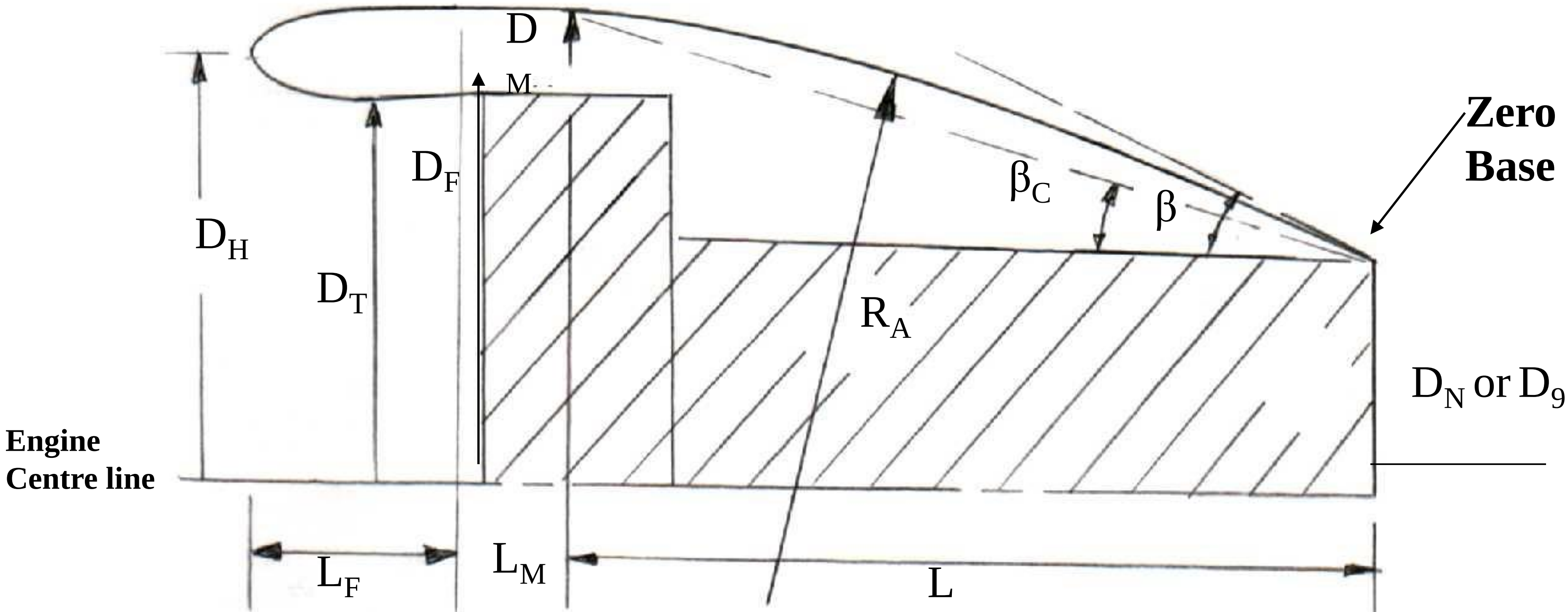
# STATION NUMBERING & NOMENCLATURE




The international standard is ARP755A.
However most companies use their own variations.

# Subsonic Nacelle Geometry

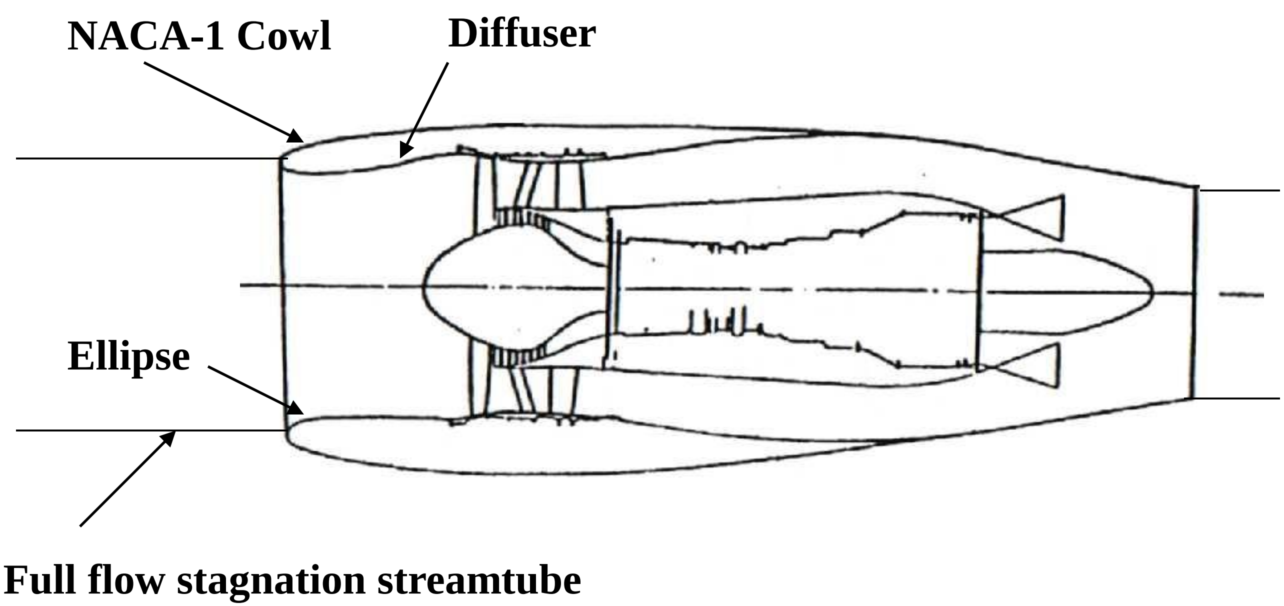
*Simplified axi-symmetric pod with circular arc afterbody*




- $L_F$ Forebody length
- $L_M$ Mid-section length
- $L_A$ Afterbody length
- $R_A$ Afterbody radius
- $\beta_C$ Afterbody chord angle
- $\beta$ Boat-tail half angle

- $D_M$ Maximum diameter
- $D_H$ Highlight diameter
- $D_T$ Throat diameter
- $D_F$ Fan diameter
- $D_N$, $D_9$ Nozzle diameter

# Major Characteristics of Forebody



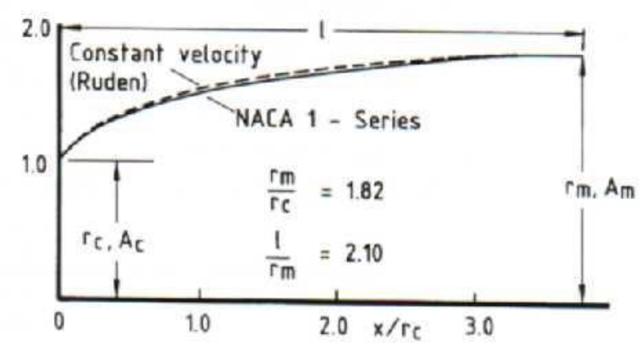

**NACA-1 Series Ordinates**

| x/ℓ | y/Y | x/ℓ | y/Y |
|---|---|---|---|
| 0 | 0 | 0.260 | 0.6035 |
| 0.004 | 0.0663 | 0.300 | 0.6489 |
| 0.008 | 0.0933 | 0.340 | 0.6908 |
| 0.015 | 0.1272 | 0.380 | 0.7294 |
| 0.025 | 0.1657 | 0.420 | 0.7648 |
| 0.035 | 0.1994 | 0.460 | 0.7974 |
| 0.050 | 0.2436 | 0.500 | 0.8269 |
| 0.080 | 0.3181 | 0.580 | 0.8795 |
| 0.110 | 0.3815 | 0.660 | 0.9220 |
| 0.140 | 0.4366 | 0.740 | 0.9548 |
| 0.170 | 0.4840 | 0.820 | 0.9787 |
| 0.200 | 0.5270 | 0.900 | 0.9940 |
| 0.230 | 0.5666 | 1.000 | 1.0000 |

***MAJOR CHARACTERISTICS***

Max Diam ~ 1.21 x Fan Diameter
Throat Mach 0.7 – 0.75
$A_h/A_{th}$ 1.2 – 1.35
Diffuser Ratio
Fan Face Area to Throat Area 1.25 – 1.35

√




Comparison of NACA-1 series and Ruden's constant-velocity profiles.

# Nacelle, Pylon & Interference Drag

$$\Delta\frac{D_o}{q} = CD \cdot S_{REF} = C_f \cdot S_A \cdot F\,Fi$$

$$q = \frac{1}{2}\rho \cdot V^2$$

- $\mathbf{S_{REF}}$ = Reference Area for vehicle (usually wing area)

- $\boldsymbol{C_f}$ = Skin Friction Coefficient:

$$C_f = 0.455\,x\,(\log_{10} Re)^{-2.58}$$ *(Prandtl-Schlichting)*

  - Reynolds Number Re based upon pod length or pylon chord

- $\mathbf{S_A}$ = Surface area of pod (pylons)

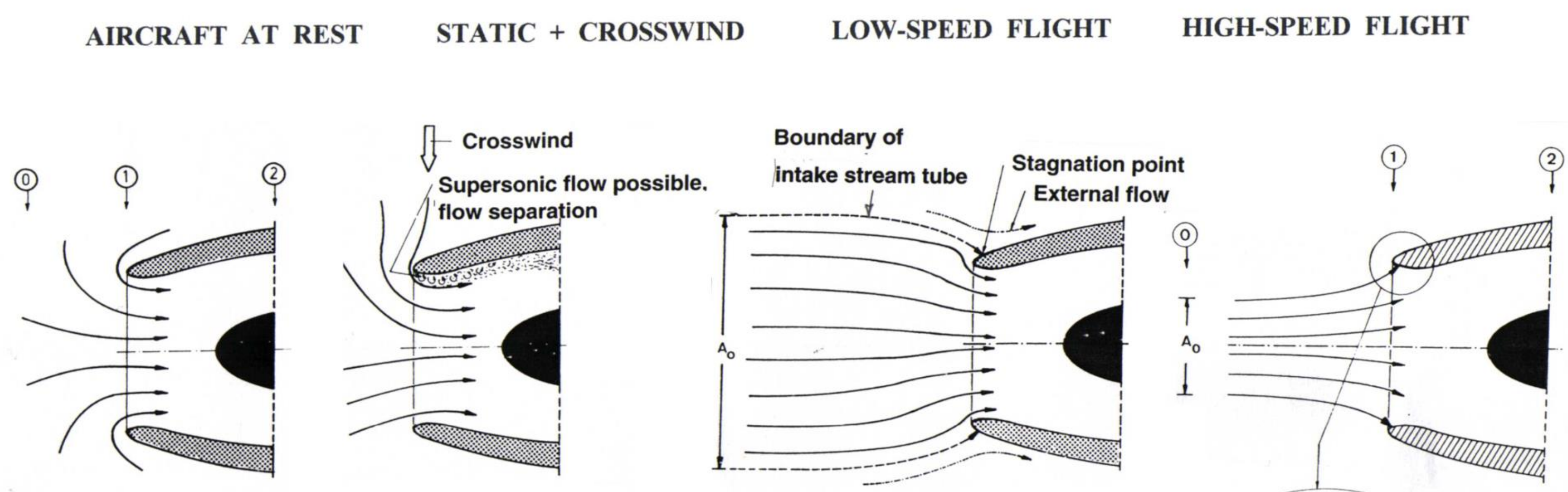
# Nacelle, Pylon & Interference Drag

$$\Delta\frac{D_o}{q} = CD \cdot S_{REF} = C_f \cdot S_A \cdot F\ Fi$$

$$q = \frac{1}{2}\rho \cdot V^2$$

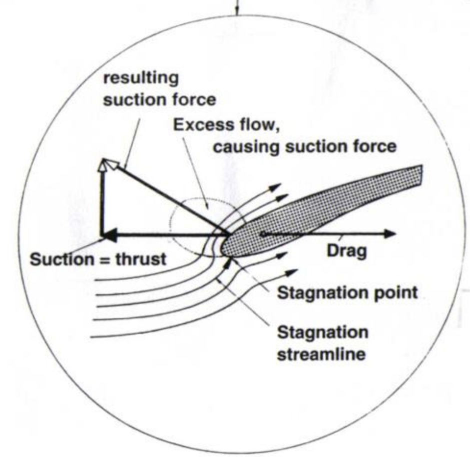
- **F** = Form Factor i.e. (integrated pressure distribution)
- **F$_i$** = Installation Interference factor.
- **F F$_i$** ~ 1.0
  - for well designed rear fuselage mounted engines & low slung underwing nacelles (close coupled underwing installations have F F$_i$ have in excess of 1 see later lecture).
  - Surface Area of pod from geometry.
- Assumes full flow entry streamtube, static pressure at nozzle exit plane is equal to free-stream static pressure & jet velocity similar to free-stream velocity.

# Intake Flow-fields




**MFCR >> 1**

**MFCR > 1**




**MFCR < 1**

Note: Mach Number at compressor face ~ 0.6

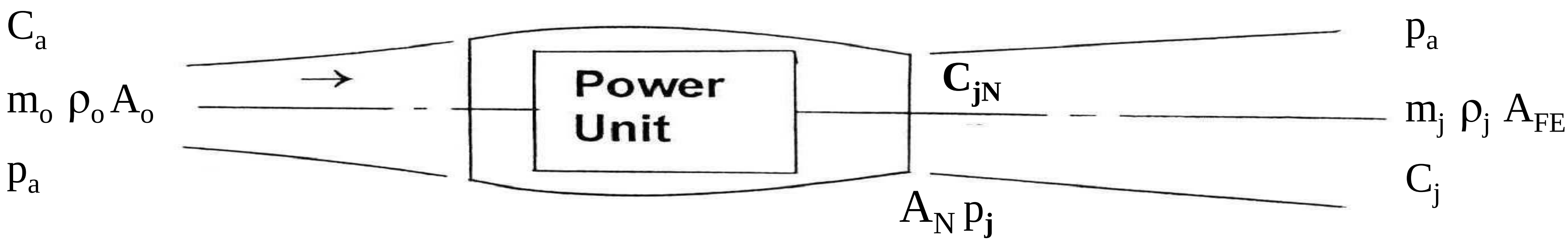
Mass Flow Capture Ratio:

$$\boldsymbol{MFCR} = A_o/A_i = \frac{\rho_i \cdot C_i}{\rho_0 \cdot C_o}$$

ρ = density; $A_o$ = Upstream Flow Area;

C = Velocity $A_i$ = Intake Highlight Area

# THRUST DEFINITIONS




**Fully-expanded Net Thrust:** Gross thrust at infinity downstream minus intake momentum drag

$$F_{N'} = F_{G_\infty} - F_{G_o} = (\dot{m}_j \cdot C_j - \dot{m}_o \cdot C_a) = \rho_j \cdot A_{FE} \cdot C_j^2 - \rho_o \cdot A_o \cdot C_a^2$$

**Standard Net Thrust** Gross thrust at Nozzle Plane minus intake momentum drag

$$F_N = FGN - FGo = \dot{m}_j \cdot C_{jN} + AN\,(P_j - P_a) - \dot{m}_o \cdot C_a$$

- ***Note: This definition relies upon engine parameters only & is independent of installation***

**$F_{Go}$** = Intake Momentum Drag = $\dot{m} \cdot C_a$

**$F_{G\infty}$** = Ideal Fully-expanded Gross Thrust

**$F_{GN}$** = Stream Gross Thrust

**$\dot{m}_o$** = Intake Mass flow = $\rho_o A_o C_a$

**$\dot{m}_j$** = Mass flow of jet = $\rho_j A_{FE} C_j$

**$C_a$** = Flight Velocity

**$C_{jN}$** = Velocity of jet at nozzle plane

**$\rho_o$** = Free stream density

**$A_o$** = Intake Capture Area

**$\rho_j$** = Density of jet

**$A_{FE}$** = Area of Fully Expanded Jet

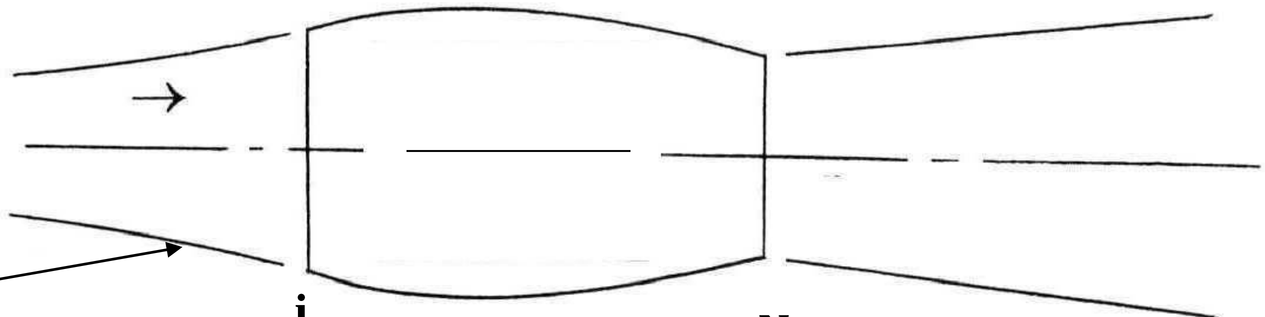
**$A_N$** = Area of Jet at Nozzle

**$C_j$** = Fully expanded jet velocity

# The Concept of the Aerodynamic Duct

**External flow** →

**Infinity Upstream $A_o$**



**Infinity Downstream ∞**

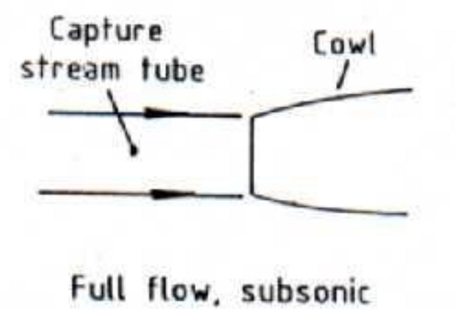
**Captured Streamtube**

**i** **N**

## Continuity ~ Mass Flow rate constant

$$\dot{m}_o = \rho_o \cdot A_o \cdot C_a$$

$$\dot{m}_i = \rho_i \cdot A_i \cdot C_i$$



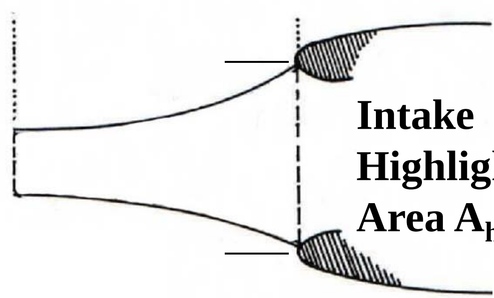

Mass Flow Capture Ratio $\boldsymbol{MFCR} = \frac{A_o}{A_i} = \frac{\rho_i \cdot C_i}{\rho_o \cdot C_o}$

**ρ = density**

**C = Velocity**

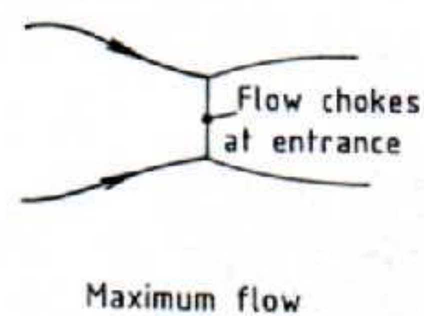
**$A_o$ = Upstream Flow Area**

**$A_i$ = Intake Highlight Area**



**Intake Highlight Area $A_h$**

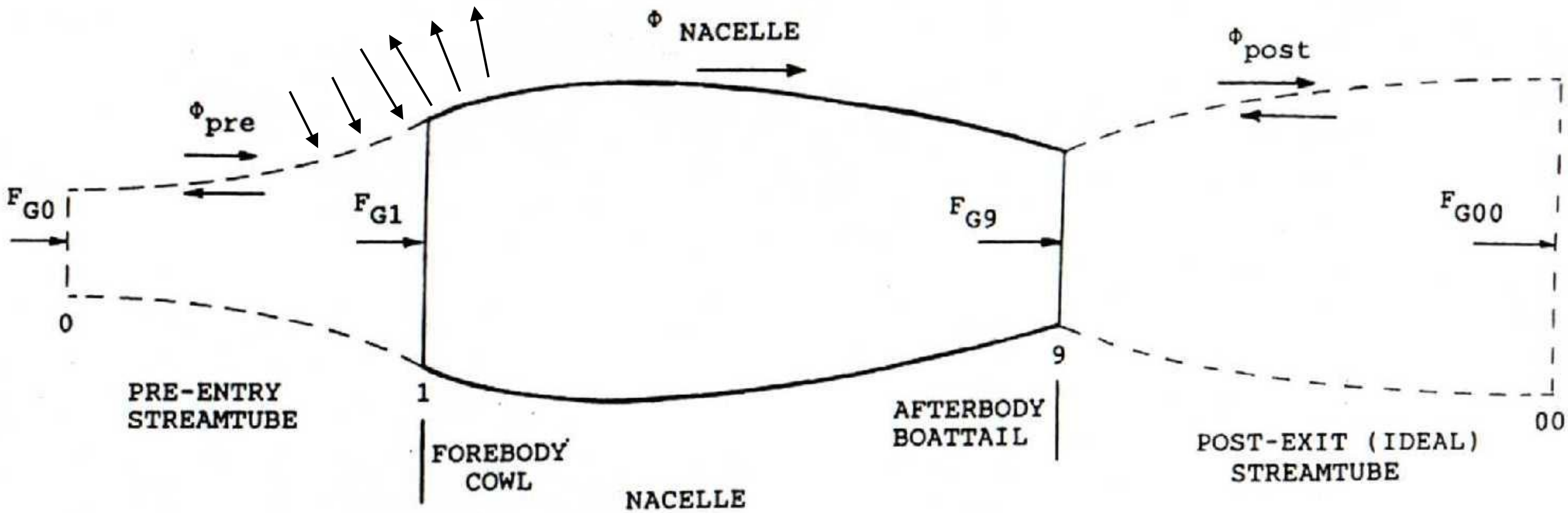
**o** **i**




<u>For incompressible flow</u>

√ MFCR $= \frac{C_i}{C_o}$

# Forces acting on a Single-stream Nacelle




**Thrust** is the summation of the forces acting on the internal surfaces of the engine nacelle & pre-entry & post-exit stream-tubes from minus to plus infinity.

**Drag** is the summation of the forces acting on the external surfaces of the nacelle & pre-entry & post-exit stream-tubes from minus to plus infinity.

$\mathbf{F_{Go}}$ = Intake Momentum Drag = $\dot{m} \cdot C_a$

$\mathbf{F_{G\infty}}$ = Ideal Fully-expanded Gross Thrust

$\mathbf{F_G}$ = Stream Gross Thrust

$\mathbf{\Phi}$ = Nacelle & Streamtube Forces

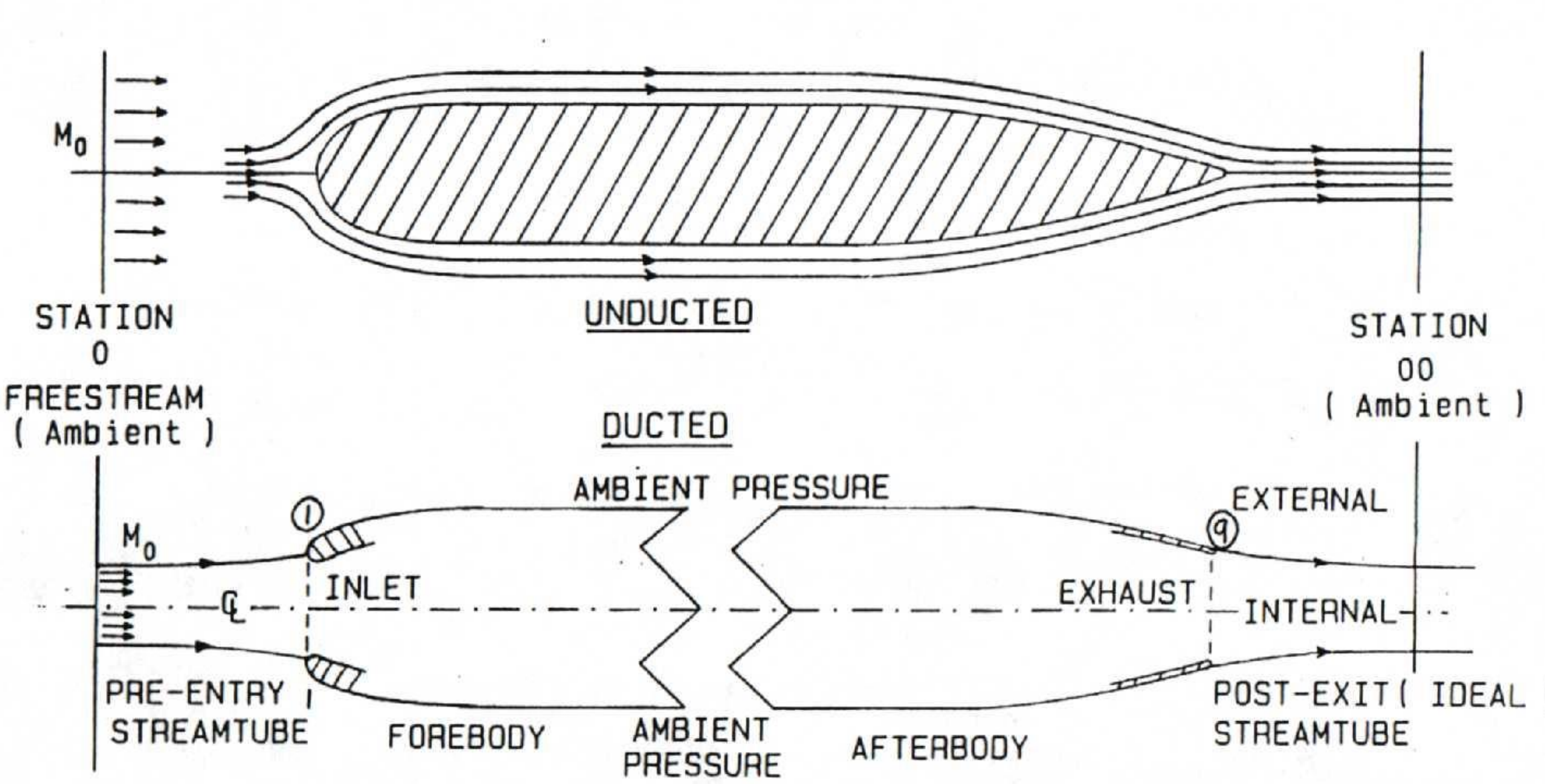
$\mathbf{\Phi_{pre}}$ = Force on pre-entry streamtube

$\mathbf{\Phi_{post}}$ = Force on post-exit streamtube

$\mathbf{\Phi_{pre}}$ = Force on nacelle

√

# SEMI-INFINITE BODIES




For the purpose of analysis the nacelle can be divided into two semi-infinite bodies:

- from infinity upstream to the nacelle max diameter
- from the nacelle maximum diameter to infinity downstream

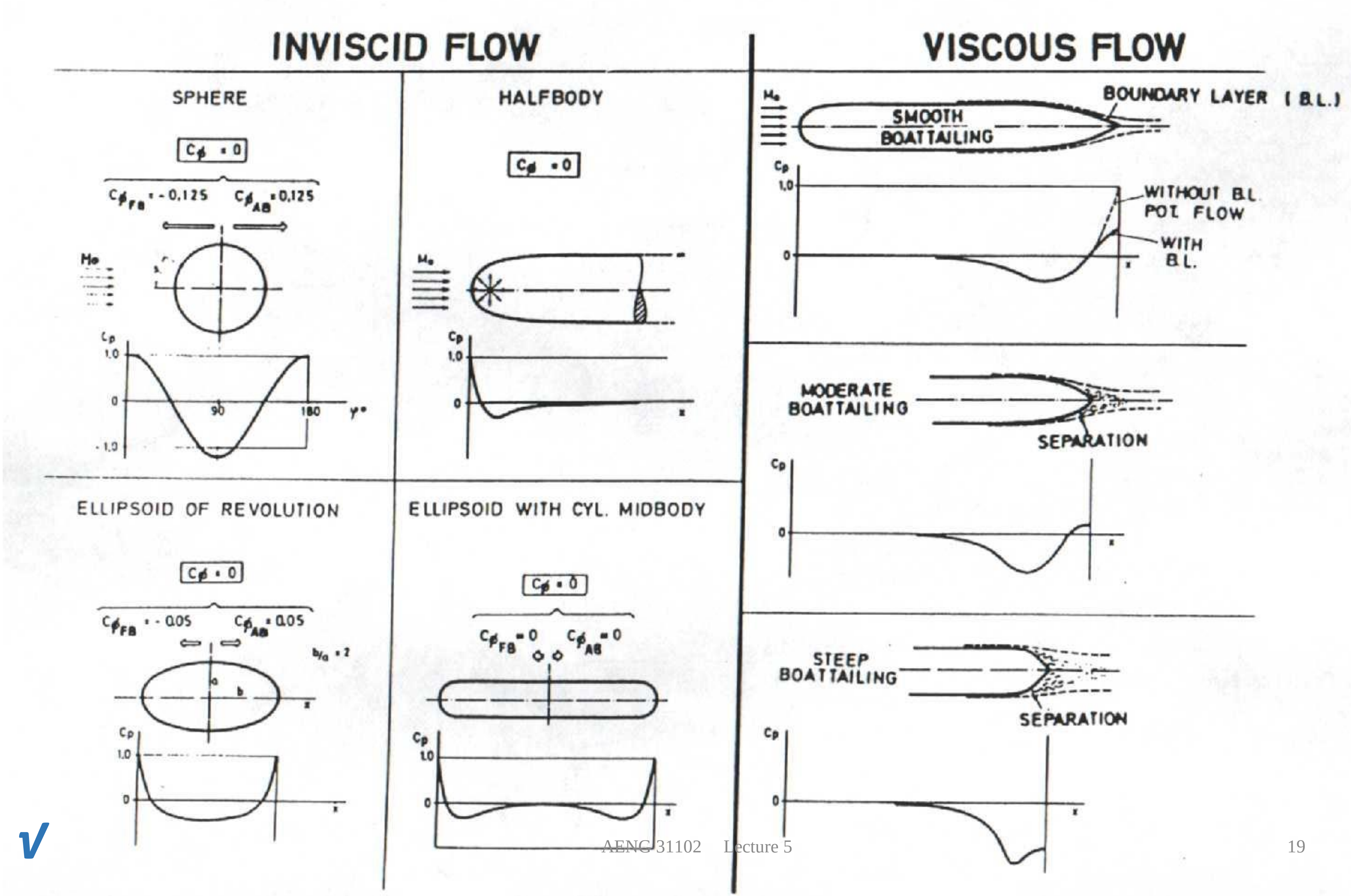
# Axial Forces in Inviscid & Real Flows

- **d'Alembert's Paradox:**
  - The net force on a closed non-lifting body in isolation in infinite subsonic, potential flow is zero.

- **Prandtl Extension to d'Alembert's paradox:**
  - The net force on an infinite or semi-infinite body in subsonic, potential flow is zero.

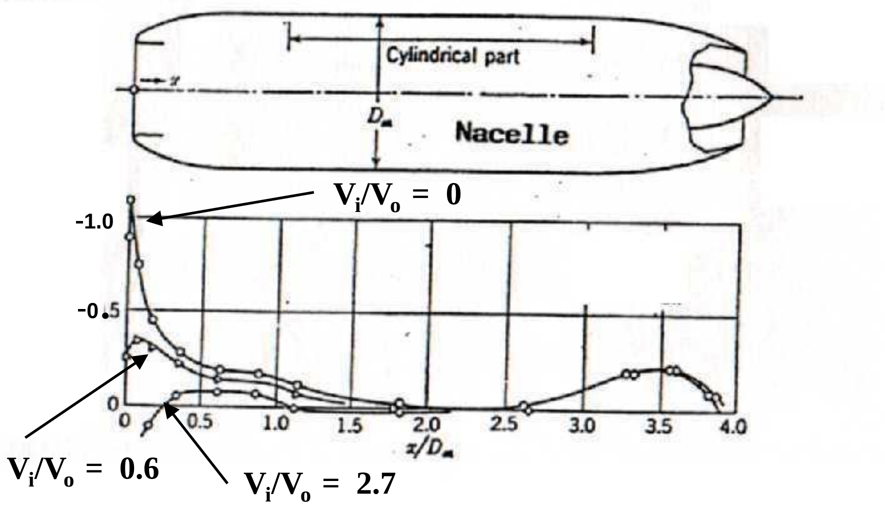
- ***NOTE:*** Though the total drag of a body is zero, non-zero forces act in different axial directions on parts of the body. Thus a clear distinction must be made between the force on part of the body and the drag of that part of the body.

# PRESSURE FORCES ON UNDUCTED BODIES

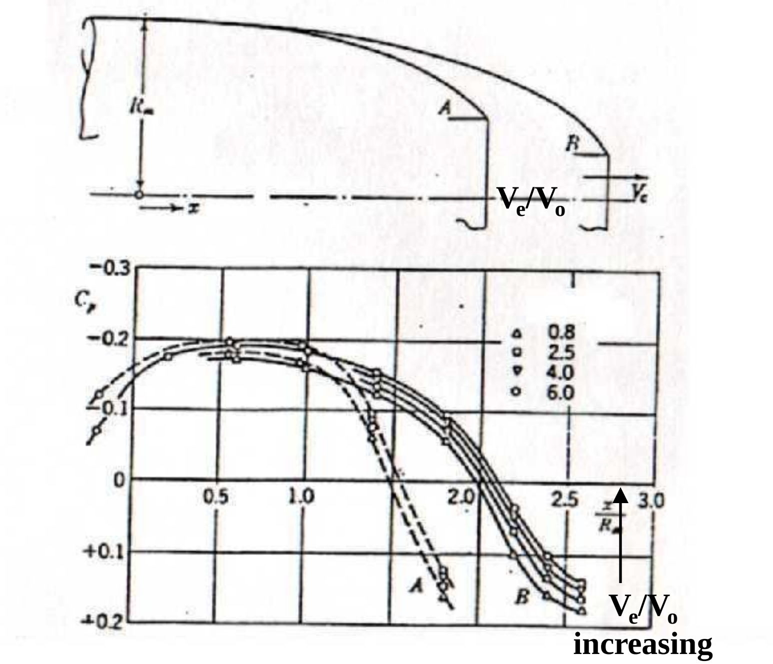


# Static Pressures on a Nacelle & Afterbody

*Experimental Results*




$V_i/V_o$ = Intake Velocity ratio
= Mass Flow ratio in incompressible flow




**Pressure distribution along a nacelle**

**Pressure distribution along an afterbody**

# Pre-entry Force

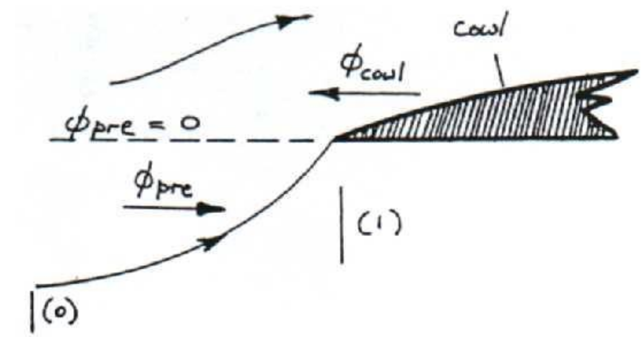
- Assuming a semi-infinite body, then from Prandtl/d'Alembert :

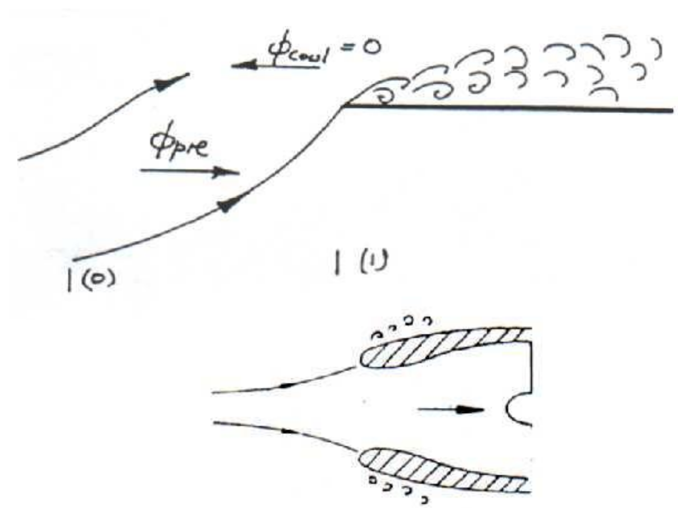
$$\Phi_{pre} + \Phi_{cowl,\,pot} = 0$$

$$D_c = \Phi_{cowl} - \Phi_{cowl,\,pot}$$

- Hence: $D_c = \Phi_{pre} + \Phi c_{owl}$

- Under normal operating conditions then the $\Phi_{pre}$ balances $\Phi_{cowl}$ and the cowl drag is simply that due to skin friction & form.




**At very low intake mass flows, separation will occur over lip**

# Typical Nacelle Forebody Drag Characteristics

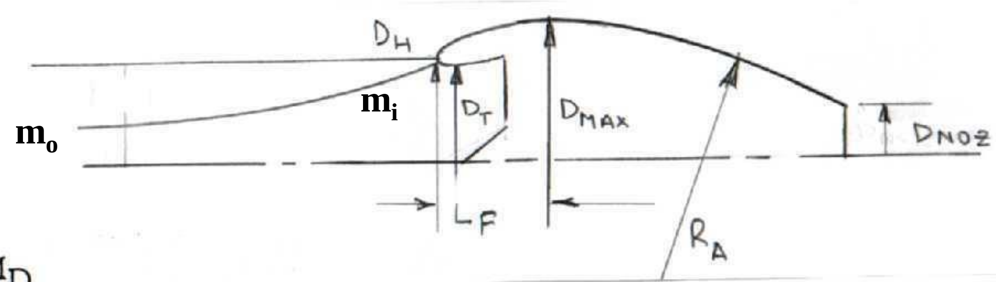
*Empirical relationships*

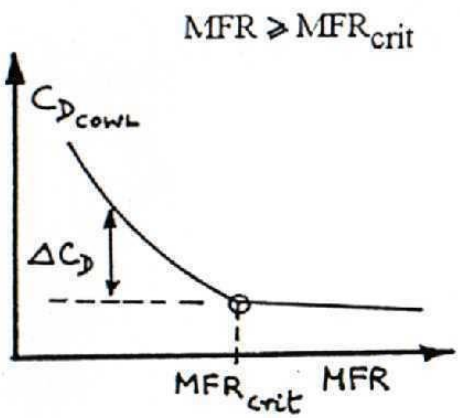
Mass Flow Capture Ratio:

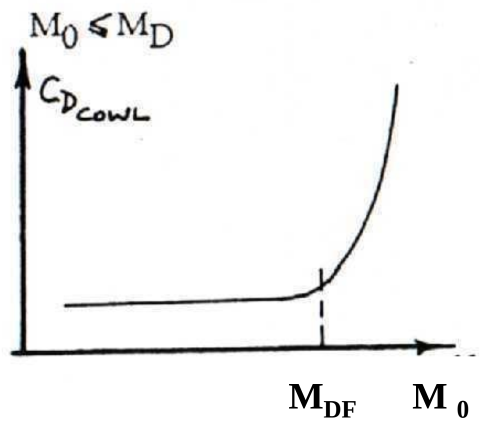
$$MFCR = A_o/A_i = \frac{\rho_i \cdot C_i}{\rho_o \cdot C_o}$$

$\rho$ = density; $A_o$ = Upstream Flow Area

C = Velocity; $A_i$ = Intake Highlight Area




**Forebody Drag Rise Mach Number**

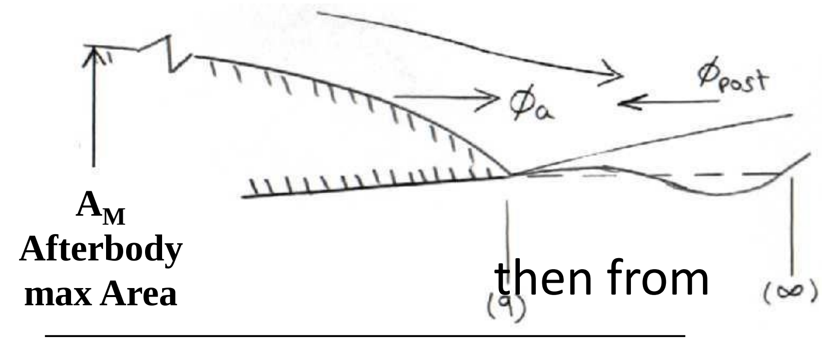
$$M_{DF} = M_{Cruise} + 0.1$$

$$M_{DF} = 1 - \frac{1}{8}\,\frac{\left[\sqrt{1-\left(D_H/D_M\right)}\right]^2}{L_F/L_M}$$

**Critical Mass Flow Ratio**

$$MFR_{crit} = \left[1 - \frac{4\left(1 - D_H/D_M\right)^2}{L_F/D_M}\right]^{5/2}$$

# Post-exit Force




- Assuming a semi-infinite body, Prandtl/d'Alembert :

$$\Phi_{post} + \Phi_{c\,pot} = 0$$
$$D_a = \Phi_a - \Phi_{a\,pot}$$

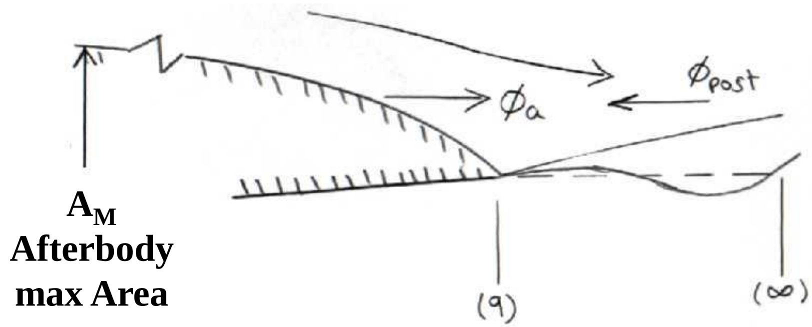
- In the ideal flow case:

$$\Phi_{post} = FG_9 - FG_\infty$$

- Where $F_{G\infty}$ is the idea, potential-flow or isentropic gross thrust that exists at fully expanded engine exhaust conditions

- As the post-exit force represents the difference between two gross thrusts, it is called **Post-Exit Thrust**.

# Post-exit Force




- In general the exhaust static pressure $P_{o9}$ is not equal to the ambient static pressure $P_a$.

- $(P_{o9}$ - $P_a)$ < 0; the exhaust flow is said to be OVEREXPANDED
- $(P_{o9}$ - $P_a)$ = 0; the exhaust flow is said to be FULLYEXPANDED
- $(P_{o9}$ - $P_a)$ > 0; the exhaust flow is said to be UNDEREXPANDED

Note the Nozzle Pressure ratio = Nozzle Total Pressure/ambient pressure = $P_{o9}/P_a$

- In the ideal case when the engine exhaust flow is fully expanded so that $P_{o9} = \mathrm{P_a}$ , then the gross thrust $F_{G9} = F_{G\infty}$ (the gross thrust at ∞ downstream)

- The post-exit stream tube area is constant between stations (9) & (∞) and $\Phi_{post}$ = 0

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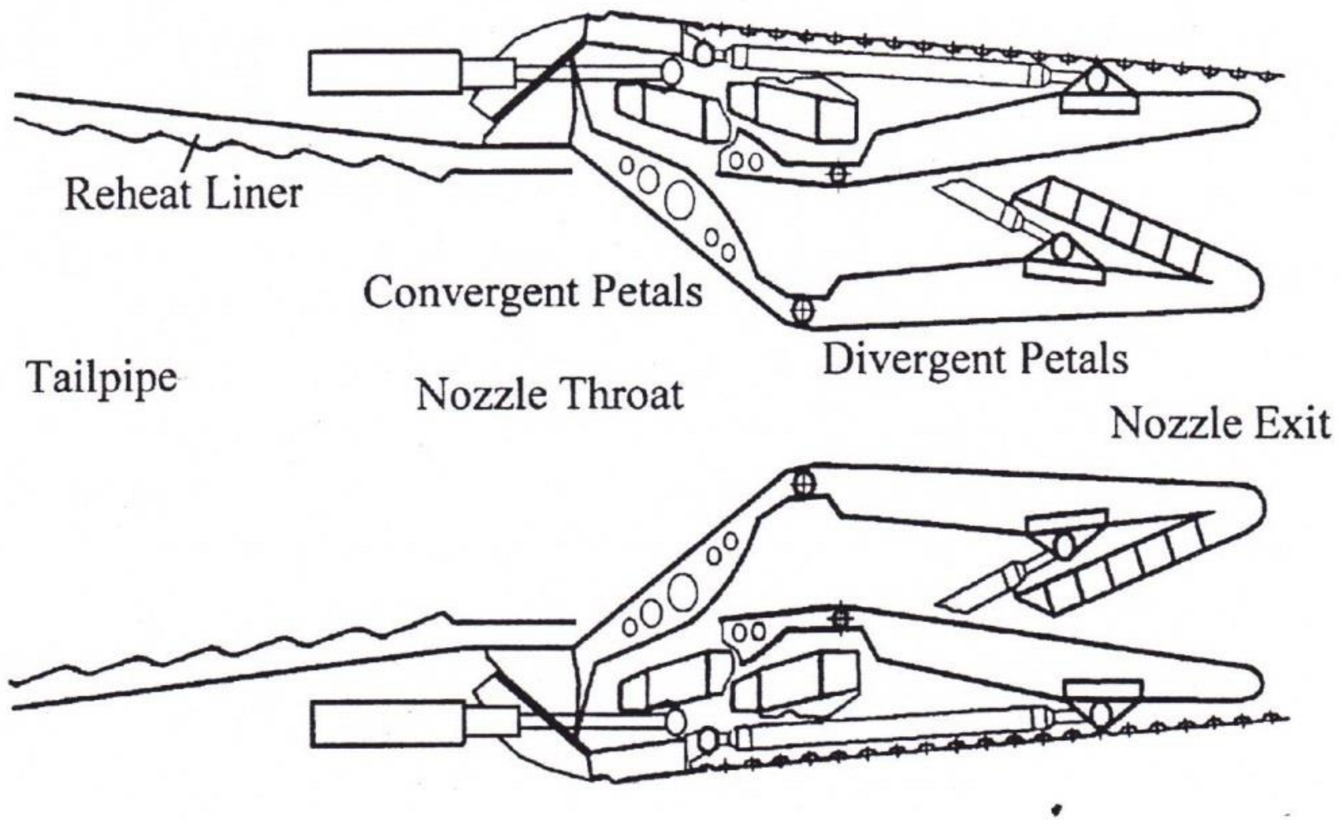
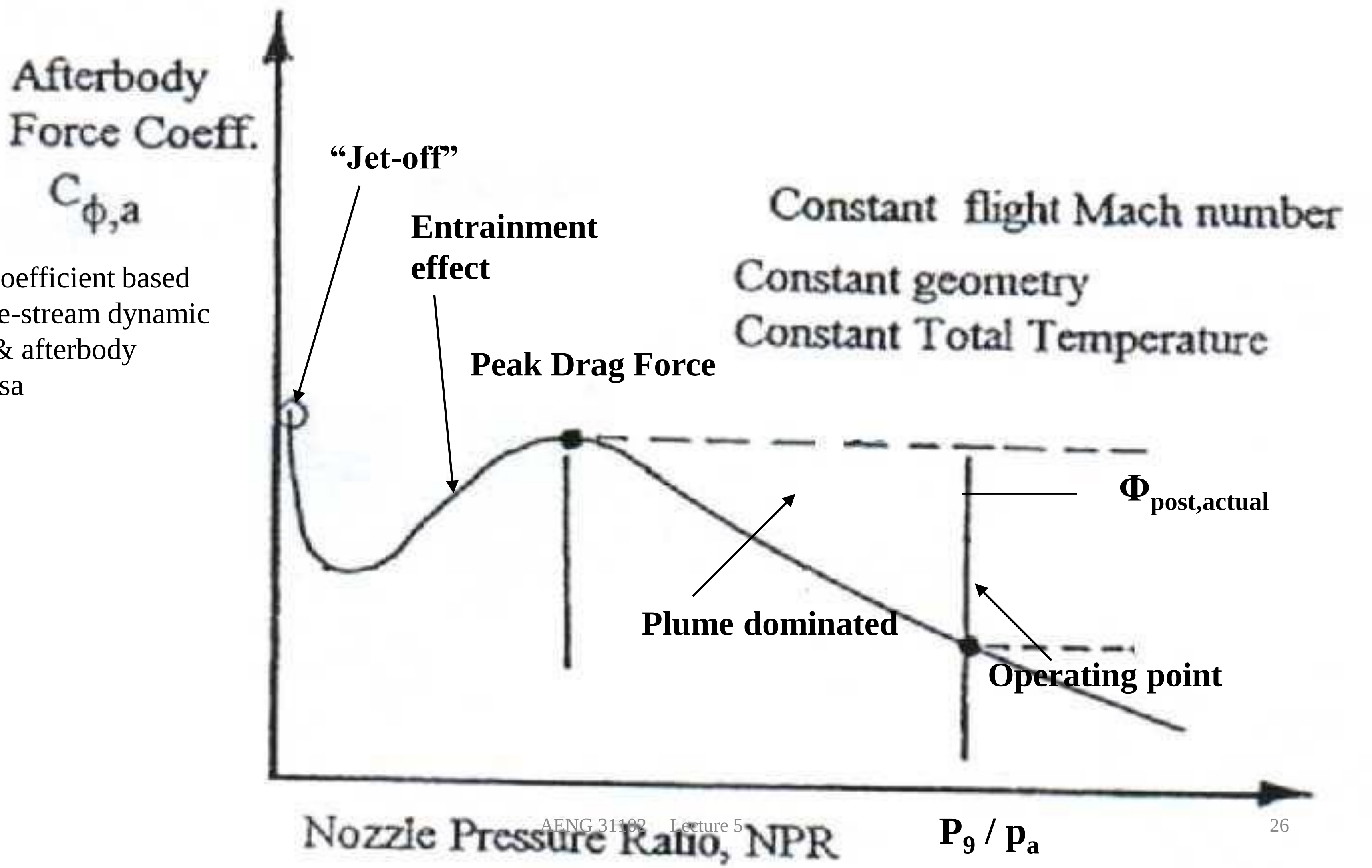
## Con-Di Nozzle



# Afterbody Force Co-efficient

*Typical Empirical Data*

$C_{\Phi,a}$ coefficient based on free-stream dynamic head & afterbody max csa

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# Key Points from Lecture 5

- Though often treated as separate entities – the airframe affects the engine & the engine effects the airframe.
- There is a "standard" Thrust Drag accounting method to ensure consistency in the overall analysis of platform performance. √
- A proper understanding of the interaction between the engine & airframe is essential for the design of the optimum engine installation.

√

**Typical Underwing Installation**
**RB211 – 524 on a Boeing 747**

**Lecture 6**

# Engine Placement

## Objective ~ Lecture 6

***To examine the issues arising from installing the propulsion system into a vehicle.***