Design Point & Off-Design Performance 1

Objective ~ Lecture 3

To outline the way that the performance of a propulsion system can be characterised

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Design Point & Off-Design Performance

- The Design Point of an Engine is where all of the components are matched at their *Design Conditions* - often where each unit is achieves design pressure ratio & peak efficiency at maximum flow.

  Also sometimes called *Synthesis Matching Point*

- The Altitude & Mach Number conditions are usually those which are critical for the Aircraft/Engine Requirements.

- Typically the Design Point for a Subsonic Passenger Aircraft will be at the top of Climb i.e. M = 0.7, 35,000 ft. – T_{01} = 240K.

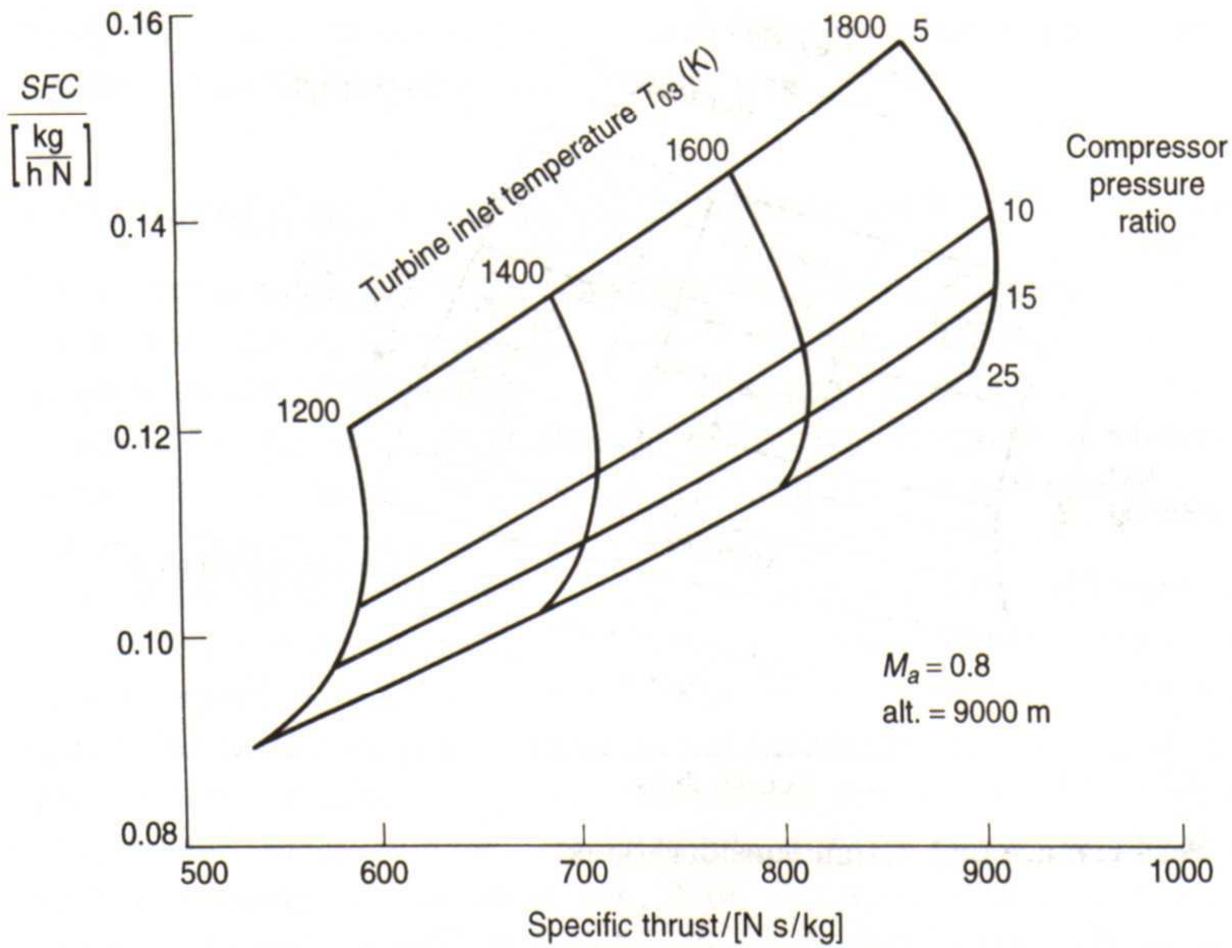
- For a Military Aircraft, the Design Point will be at the critical condition for manoeuvring in Combat i.e. M = 1.8, 40,000 ft. - T_{01} = 357K.

- For a Helicopter the Design Point will be at M = 0 at Sea level - T_{01} = 288 K.

- All other conditions are *Off-Design* where the pressure ratio, efficiency and flow are different from those at the design point.

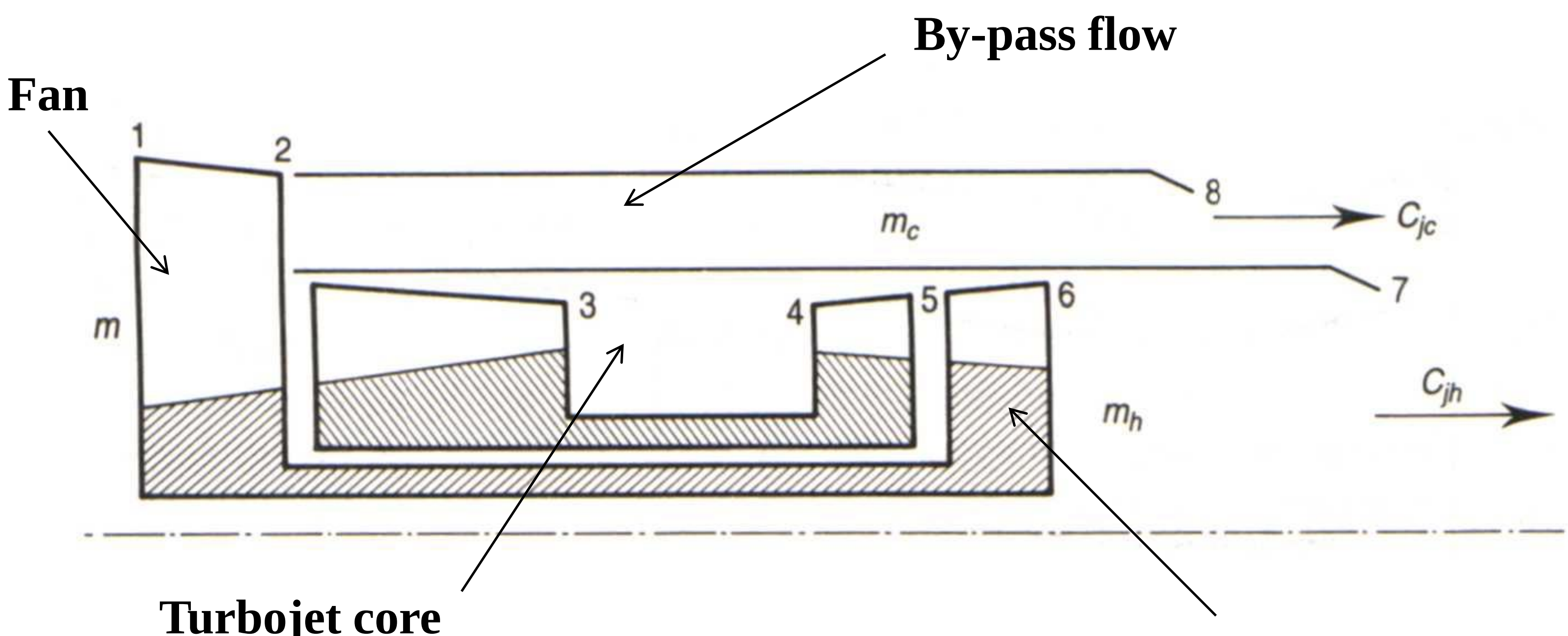
Performance of a range of Typical Turbojet Cycles

Choice of Cycle characteristics at the Design Point



√ ***Design Point calculations ~ each point is a different engine***

Most "Jet" Engines are By-pass Engines
Unmixed Two Spool Turbofan engine

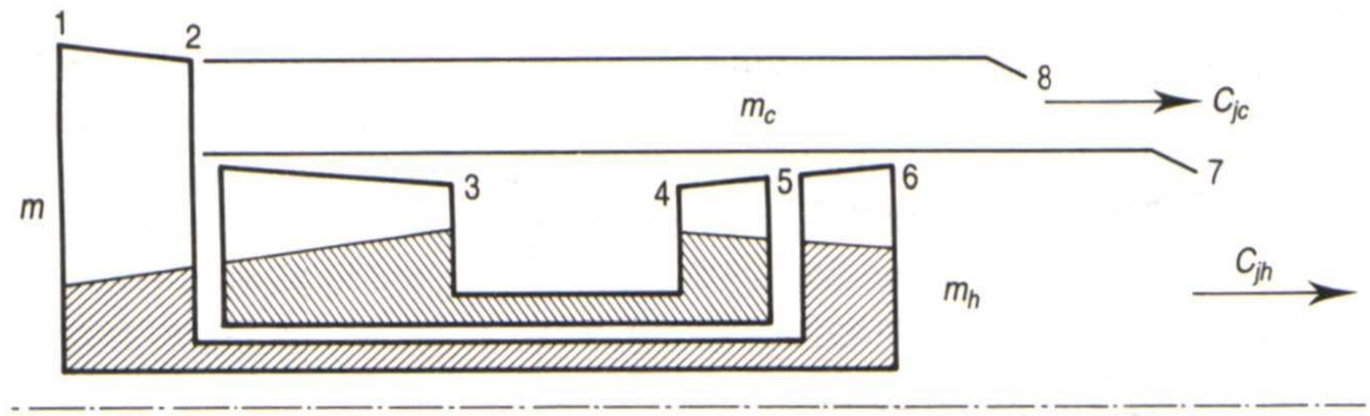


$$\textbf{Bypass ratio } \lambda = \frac{\dot{m}_c}{\dot{m}_h}$$

$$\dot{m} = \dot{m}_c + \dot{m}_h$$

Unmixed Two Spool Turbofan engine

Key Cycle Parameters at the Design Point

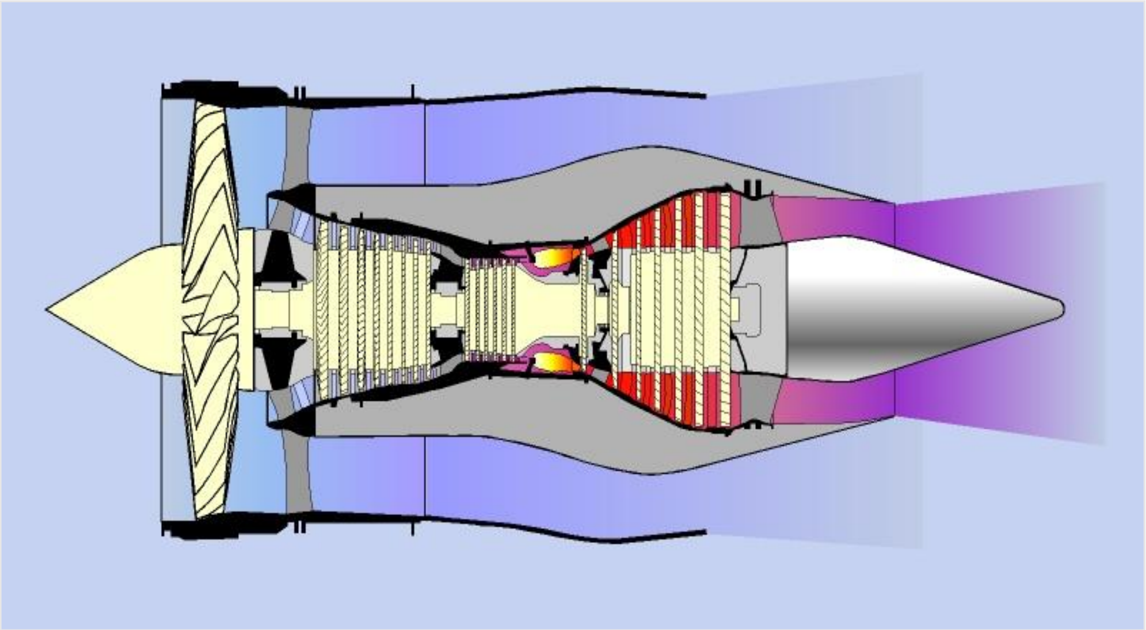


- Overall Pressure Ratio $OPR = P_{03}/P_{01}$
- Fan Pressure Ratio $FPR = P_{02}/P_{01}$
- Stator Outlet Temperature $SOT\ K = To_4$
- Specific Thrust $ST = F/\dot{m}$
- By-pass Ratio $\lambda = \dfrac{m_c}{m_h}$ (by-pass flow/core flow)

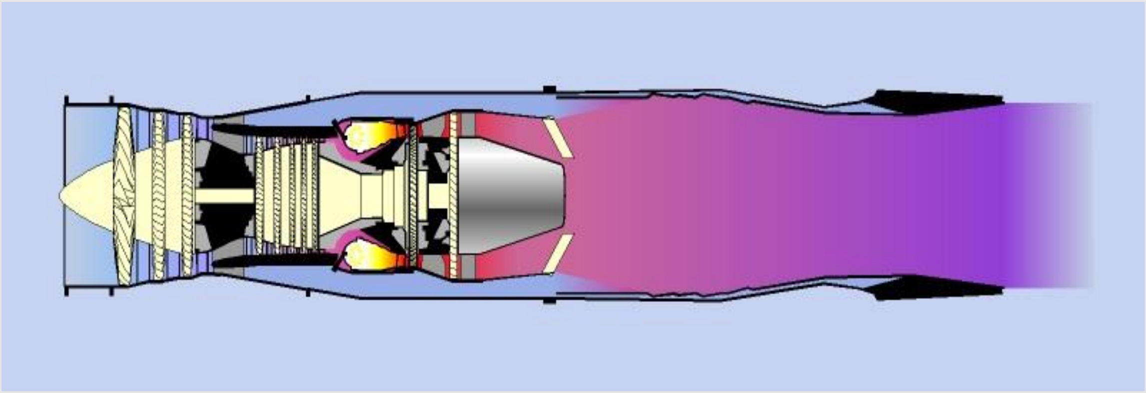
Note for mixed flow engines p_{sh}/p_{sc} is also important

Different Turbofan Types

Civil Turbofan~ Trent



Military Turbofan ~ EJ200



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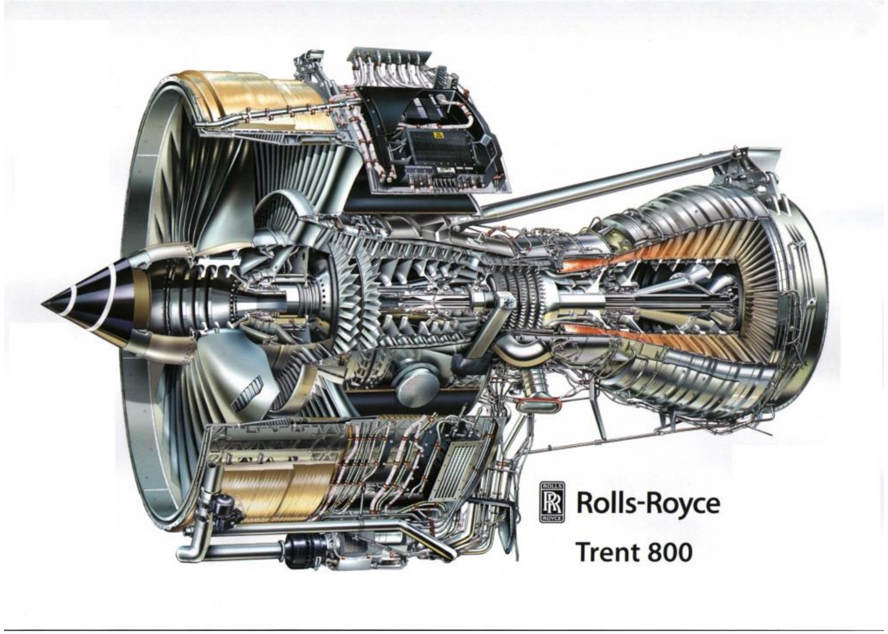
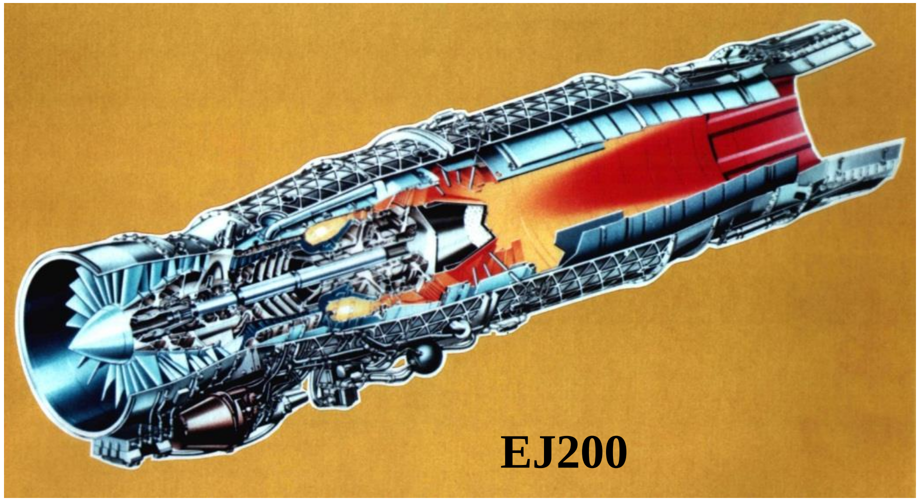
Propulsion Systems for Transport & Combat Aircraft





High by-pass ratio Turbofan

Thrust ~2000 to 100,000 lb
By-pass ratio 4 – 10
OPR ~ 40
Fan PR ~ 1.9
Specific Thrust ~ 25 – 35 lb/lb/sec

Low by-pass ratio Reheated Turbofan

Thrust ~10,000 to 40,000 lb (inc R/H)
By-pass ratio 0.3 – 1
OPR ~ 25 – 30
Fan PR ~ 3 – 5
Specific Thrust ~ 120 lb/lb/sec (inc R/H)

Cycle Design Point ~ Main Parameters

Turbofan Engine

- **Overall Pressure Ratio:**
  - Total pressure at compressor delivery divided by that at entry to first compressor stage

- **Stator Outlet Temperature:**
  - Temperature of gas which does work at first turbine rotor
  - Also called Rotor Inlet Temperature or Turbine Inlet Temperature

- **Fan pressure ratio:**
  - Total pressure at fan delivery divided by that at fan entry

Cycle Design Point ~ Main Parameters

Turbofan Engine

- **By-pass ratio:**
  - Ratio of mass flow of by-pass stream to that passing though combustion system
- **Component performance parameters:**
  - The characteristics of each component in terms of efficiency, flow capacity, pressure etc.
- **Pressure balance in exhaust jets:**
  - The ratio of the static pressure in the two stream should be close to unity.

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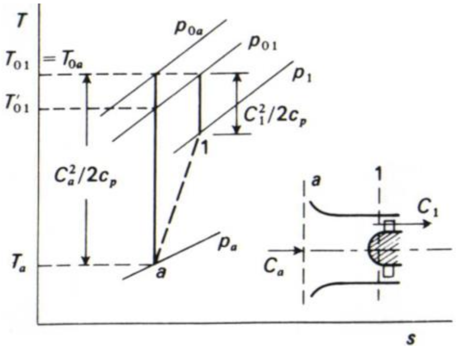
Intake Efficiency



- The **Intake** can be considered to be an **Adiabatic Duct** with no heat or work transfer.

- **Total Temperature remains constant**.

- The **losses** due to friction, shock waves etc. will be seen as a **reduction in total pressure**

- The two main ways of defining Intake Efficiency are:
  - ***Isentropic*** (defined in terms of temperature)
  - ***Ram*** (defined in terms of pressure)

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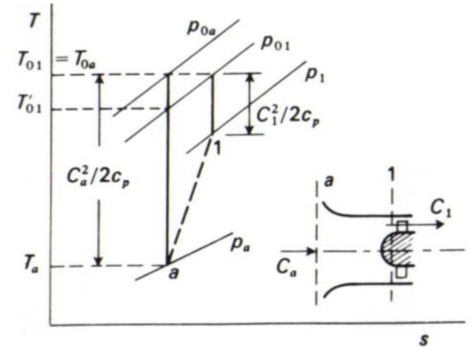
Intake Efficiency



ISENTROPIC EFFICIENCY:

From T – s diagram:

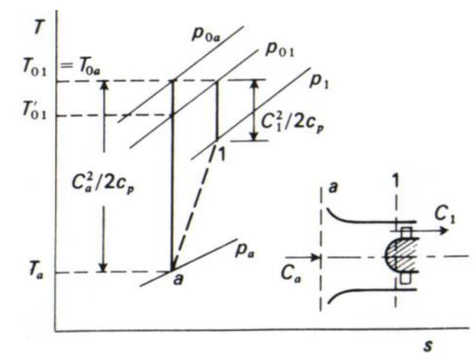
$$T_{01} = T_{oa} = T + \frac{C_{FE}^2}{2C_P} \quad \& \quad \frac{P_{o1}}{P_a} = \left(\frac{T'_{o1}}{T_a}\right)^{\frac{\gamma}{\gamma-1}}$$

Where T'_{o1} is the temperature that would have been reached after an isentropic compression to P_{01}.

T'_{o1} can be related to T_{01} by Isentropic Efficiency:

$$\eta_{isen} = \frac{T'_{o1} - T_{o2}}{T_{o1} - T_{o2}} \quad \& \quad (T'_{o1} - T_a) = \eta_{isen}\frac{C_a^2}{2C_p}$$

Intake Efficiency



ISENTROPIC EFFICIENCY:

$$\frac{P_{01}}{P_a} = \left[1 + \frac{T'_{01} - T_a}{T_a}\right]^{\frac{\gamma}{\gamma-1}} \qquad \frac{P_{01}}{P_a} = \left[1 + \eta_{isen}\frac{C_a^2}{2C_pT_a}\right]^{\frac{\gamma}{\gamma-1}}$$

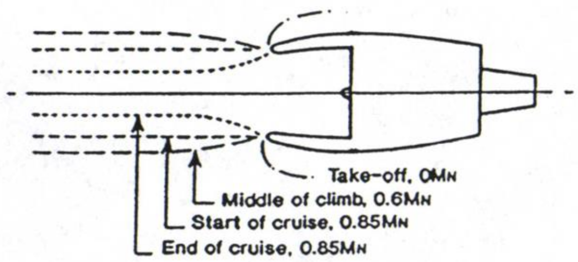
$$M = \frac{C}{\sqrt{\gamma RT}} \quad \& \quad \gamma R = C_p(\gamma - 1) \quad \rightarrow \quad \frac{P_{01}}{P_a} = \left[1 + \eta_{isen}\frac{(\gamma-1)}{2}M^2\right]^{\frac{\gamma}{\gamma-1}}$$

RAM EFFICIENCY:

$$\eta_r = \frac{P_{01} - P_a}{P_{0a} - P_a}$$

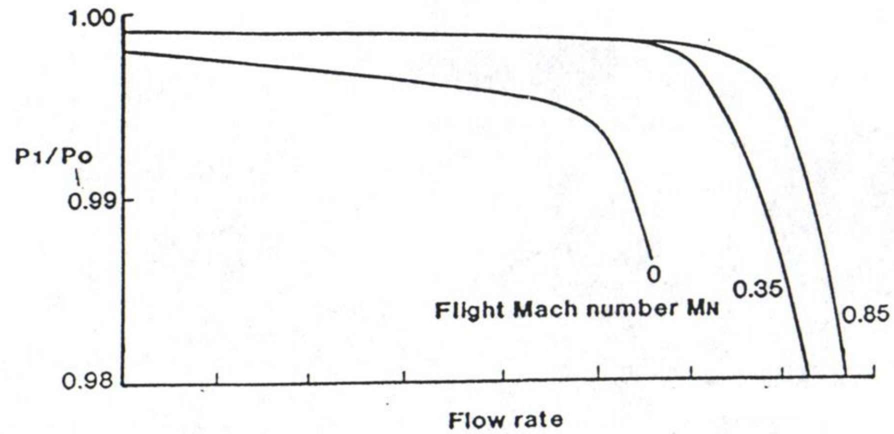
Intake performance is often quoted in terms of a pressure recovery factor $\frac{p_{01}}{p_{0a}}$ i.e. stagnation pressure ratio.

Intake Performance

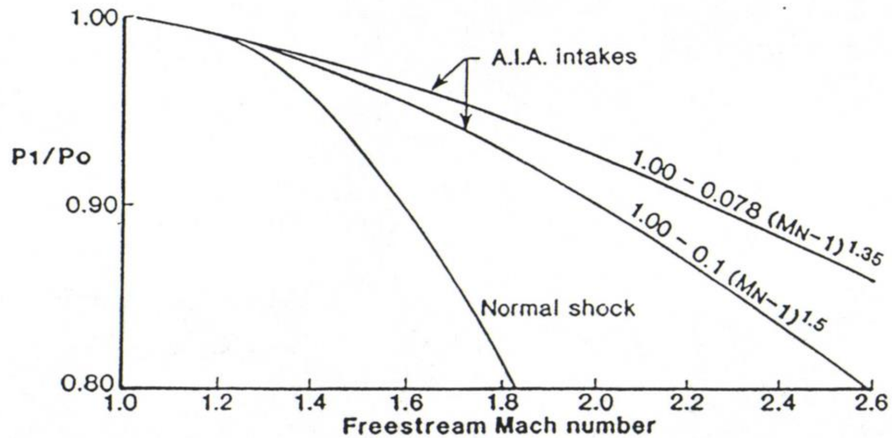


Intake flow stream tubes

(typical subsonic transport)

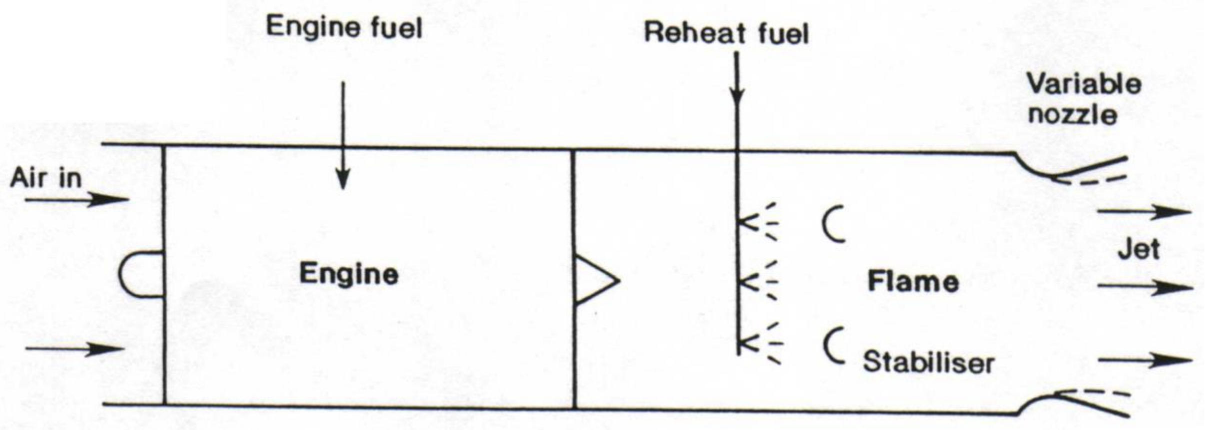


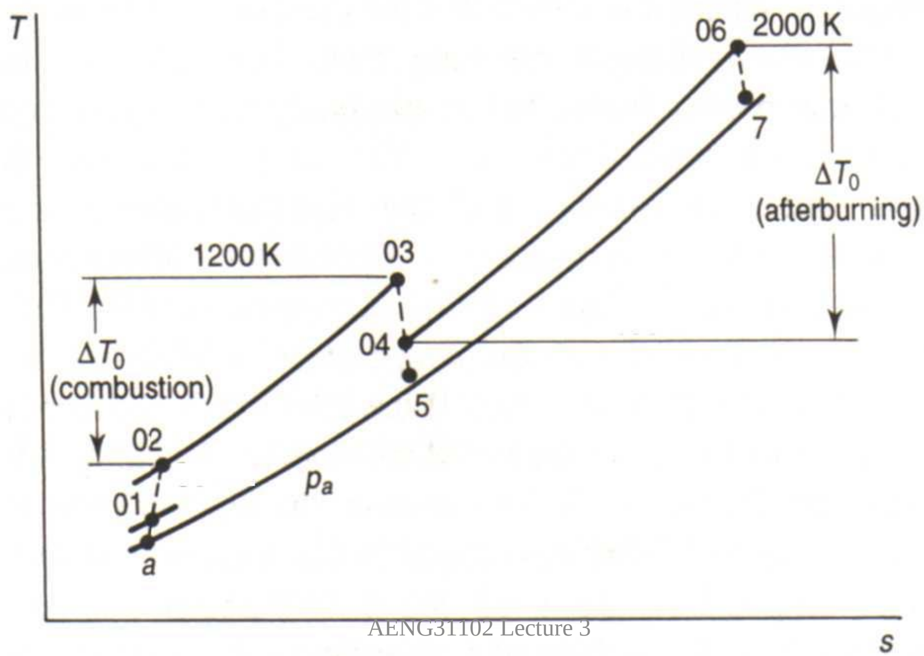
Subsonic flight intake recovery (typical) – Fixed geometry



Supersonic flight intake recovery – Variable geometry

Thrust Augmentation





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Nozzle Performance

- $\boldsymbol{Net\ Thrust} = Nozzle\ Gross\ Thrust - Momentum\ Drag$

- **NOZZLE GROSS THRUST:**

$$\boldsymbol{F_{N_{gross}} = \dot{m}_j \cdot C_j + A_j \cdot \left(P_j - P_a\right)}$$

For a Convergent-Divergent or an un-choked Convergent Nozzle, the static pressure at the nozzle exit is equal to the ambient static pressure i.e. $P_j = P_a$. Hence the pressure term is 0.

- **IDEAL GROSS THRUST:**

  - The ideal gross thrust assuming that the flow entering the nozzle is expanded adiabatically & reversibly to the ambient static pressure i.e. a convergent-divergent nozzle with no losses.

Nozzle Performance

- **GROSS THRUST COEFFICIENT OR EFFICIENCY**:
  - Ratio of Actual Gross Thrust from nozzle to Ideal Gross Thrust from the nozzle.
  - Takes account of pressure losses, shock losses, leakage etc. Sometimes quoted as an Isentropic Efficiency.
- **DISCHARGE COEFFICIENT**:
  - Ratio of the actual mass flow discharged by the nozzle to the ideal mass flow. Equal to the ratio of the ideal one-dimensional flow area to pass the actual nozzle flow to the actual geometric nozzle area.
  - Takes account of non-uniformity of flow, boundary layers etc.

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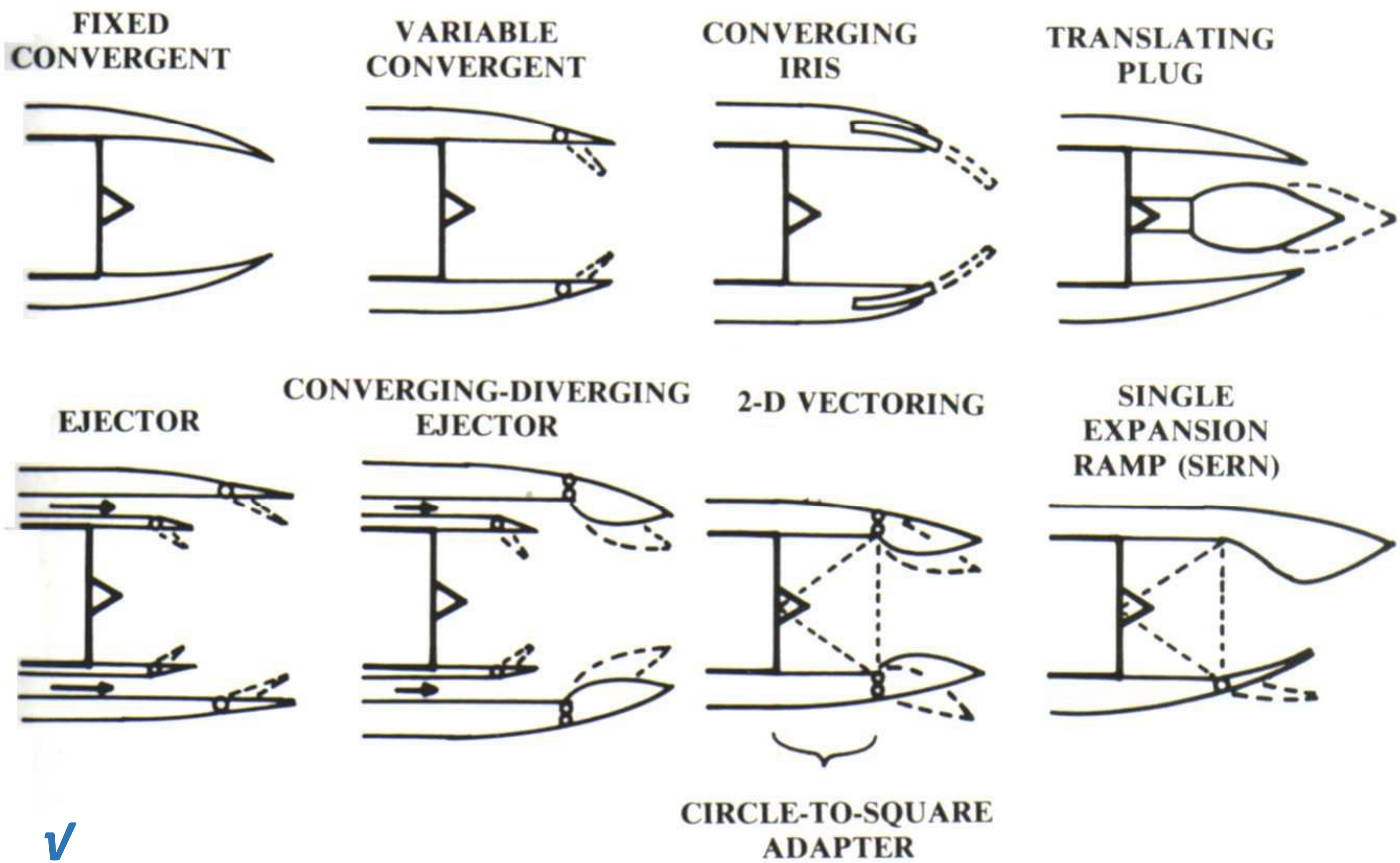
Types of Nozzles



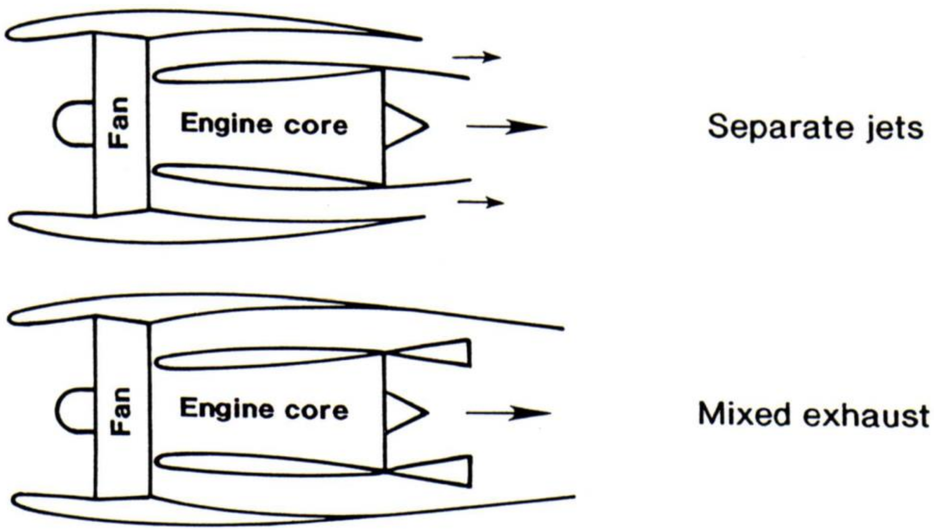
Nozzles ~ Supersonic Combat Aircraft

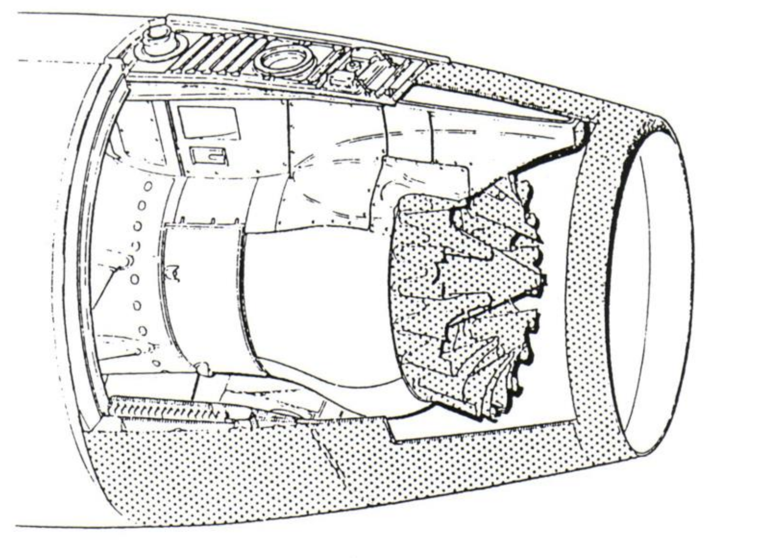
RB199 with Convergent Nozzle

EJ 200 with Con-di Nozzle

F35 with vectoring final Nozzle

Types of Nozzle
Subsonic High By-pass Ratio Engines





Typical practical mixer

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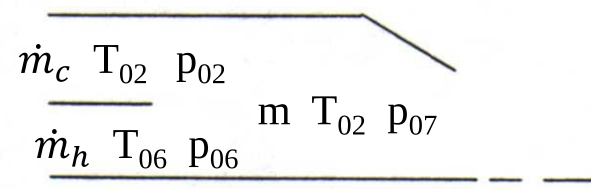
Mixing of Hot & Cold Streams



Enthalpy Balance:

$$\dot{m}_c \cdot C_{p_c} \cdot T_{o2} + \dot{m}_h \cdot C_{p_h} \cdot T_{o6} = \dot{m} \cdot C_{p_m} \cdot T_{o7}$$

$$\dot{m} = \dot{m}_c + \dot{m}_h$$

$$\lambda = \dot{m}_c \ / \ \dot{m}_h$$

The properties of a mixture of gases to those of its constituents can be written as:

$$C_{p_m} = \frac{\dot{m}_c \cdot C_{p_c} + \dot{m}_h \cdot C_{p_h}}{\dot{m}_c + \dot{m}_h} \quad \& \quad \left(\frac{\gamma}{\gamma - 1}\right)_m = \frac{R_m}{C_{pm}}$$

$$R_m = \frac{\dot{m}_c \cdot R_c + \dot{m}_h \cdot R_h}{\dot{m}_c + \dot{m}_h}$$

Momentum Balance:

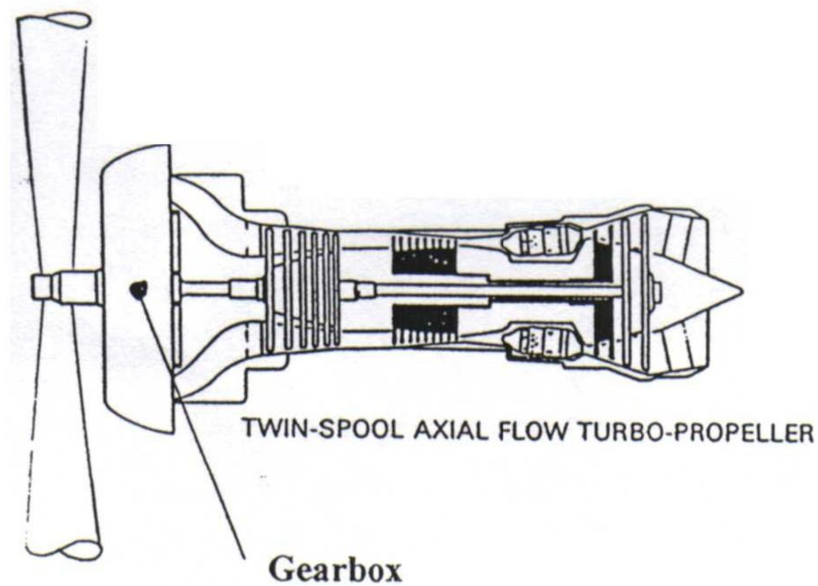
$$(\dot{m}_c \cdot C_c + P_2 \cdot A_2) + (\dot{m}_h \cdot C_h + P_6 \cdot A_6) = \dot{m} \cdot C_7 + P_7 \cdot A_7$$

(If there is no swirl in the duct then the static pressure will be uniform i.e. $P_2 = P_6$)

Continuity gives: $\dot{m} = \rho_7 \cdot C_7 \cdot A_7$

- p_{07} is required for the cycle calculation & this is best done using an iterative procedure.

The Turboprop Engine



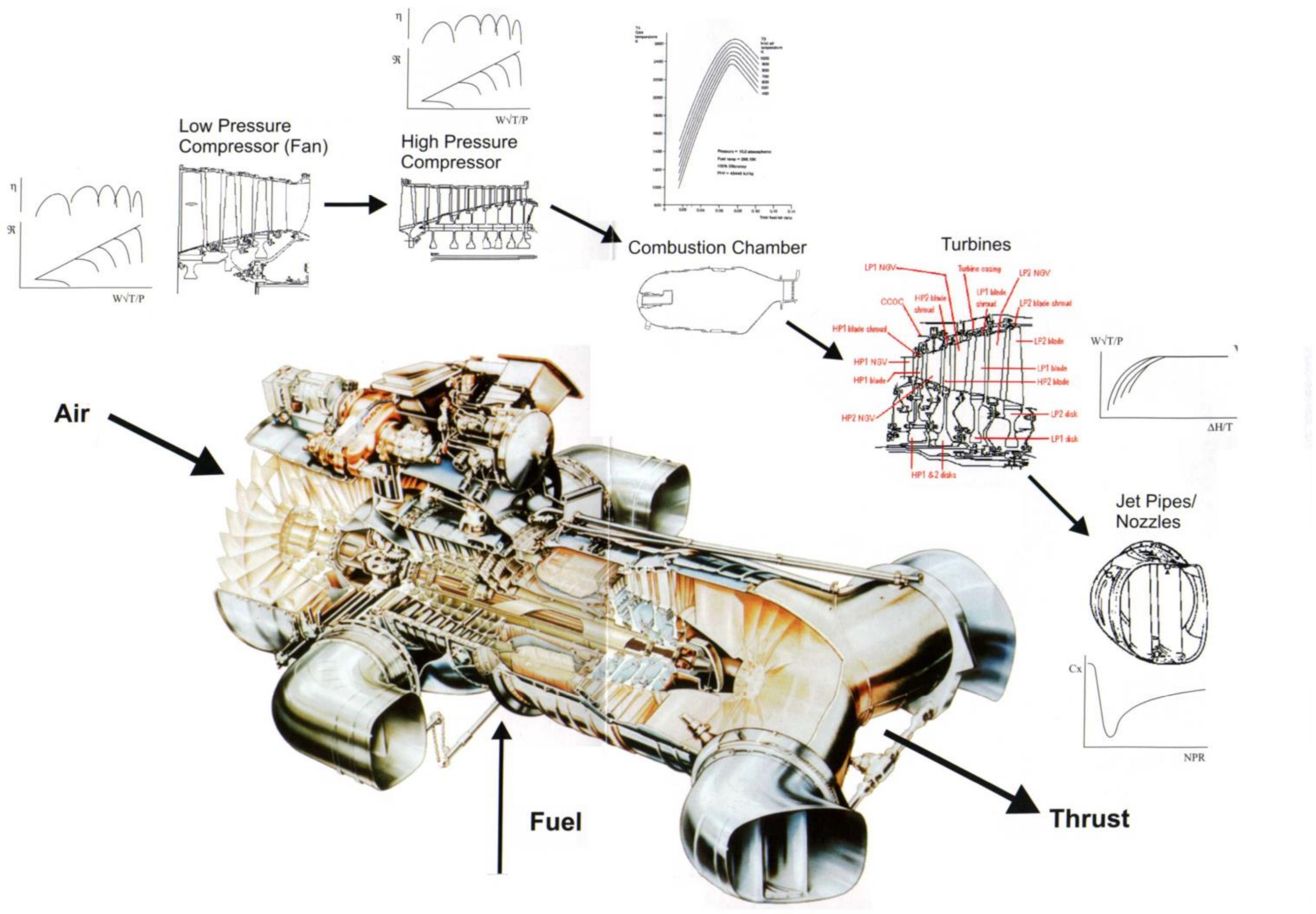
Total Thrust:
Thrust from propeller plus jet thrust

Power:
Shaft Power x Propeller efficiency + Jet thrust x Aircraft Velocity
To compare with a piston engine which has no jet thrust the following is used:

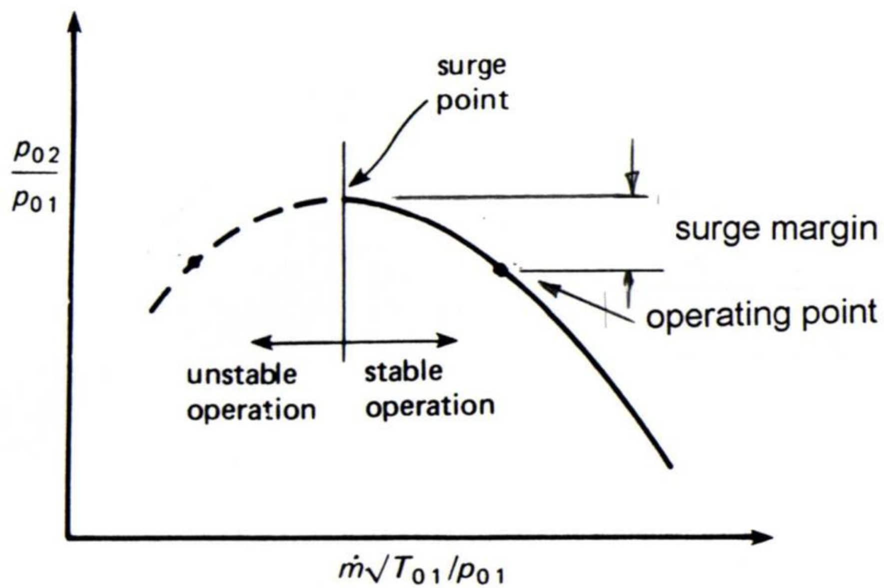
Equivalent Shaft Power:

Shaft Power + (Jet thrust x Aircraft Velocity)/Propeller efficiency

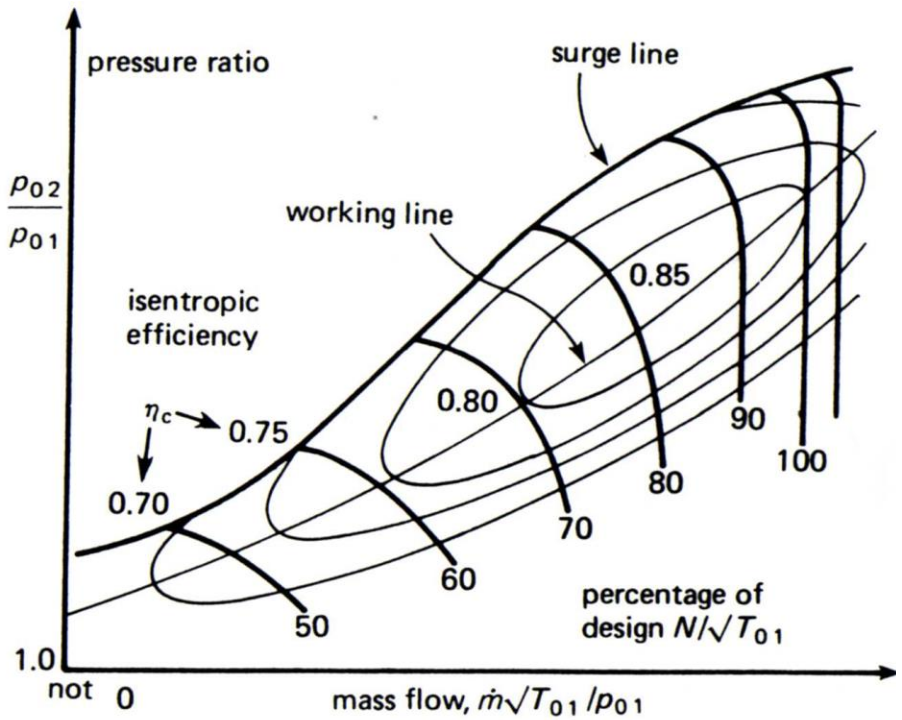
Detailed Performance Estimation



Overall Compressor Characteristics



Simplified constant speed characteristic



Idealised Characteristic

Mechanical Design Parameters

For a given Design Point a number of mechanical design parameters must be kept within limits

- Shaft Speeds
- Compressor delivery temperature & pressure
- Fan flutter
- Vibration levels of rotating components
- Disc and blade stress levels
- Cyclic and creep life of major components
- Oxidation levels of components
- Rotating flow instabilities

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Key Points from Lecture 3

- The difference between Design Point & Off-design Performance
- The key parameters for a Turbofan Engine
- How Intake Performance is characterised.
- Nozzle types & how their performance is calculated
- Turbo-prop & shaft power performance
- The data required for a full performance analysis
- The main Mechanical Design parameters.

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Design Point & Off-Design Performance ~ 2

Objective ~ Lecture 4

To show how the detailed performance of a propulsion system can be analysed.