LECTURE 1

Aircraft Propulsion AENG 31102

Aircraft Gas Turbine Performance & Design

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Aircraft Propulsion

- **Objectives**
  - ➢ *To describe the basic features of aircraft propulsion, engine performance and design.*
- **Learning Outcomes**
  - ➢ *On successful completion of the unit the student will have an introductory knowledge of the propulsion concepts used in aircraft and be able to apply this knowledge to set problems.*
- **Prerequisites**
  - ➢ *Fluids and Thermodynamics (AENG11100)*
  - ➢ *Aerodynamics (AENG 21100)*

Aircraft Propulsion

- **Learning Objectives Lecture 1**
  - Introduce the topic
  - Detail useful textbooks
  - Outline the units & nomenclature
  - Describe the possible propulsion units for aircraft propulsion
  - Revision of the necessary Thermodynamics
  - Examples of Airframe / Engine combinations
  - Introduction of Joule or Brayton Cycle & the practical turbojet cycle.

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Aircraft Propulsion

- Introduction
- Cycle Calculations & Design Point Performance
- Off-design performance
- Engine Airframe Integration
- Choice of Engine Cycle for different applications
- Compressors
- Combustion
- Turbines
- Control of Engine behaviour
- High Speed propulsion
- Propeller & Propfan Design & Performance (a)

20 Lectures, with (a) by Dr Rezgui

√ ***Plus Example & Revision sheets***

Lectures & Text Books

A full set of the lecture slides can be found on Blackboard. Copies of the key lecture slides (marked with a √) are provided in booklet. This material is aimed at providing the basic information necessary to fulfil the overall learning objectives and should be amplified with your own notes. Students should refer to textbooks for a fuller description and for further background reading.

- **Recommended:**

Gas Turbine Theory ***Saravanamuttoo, Rogers & Cohen*** ***Longman***
3rd , 4th , 5th or 6th Edition

- **Other Titles:**

Fundamentals of Jet Propulsion with applications ***Flack*** ***Cambridge***

Jet Propulsion ***Cumpsty & Heyes*** ***Cambridge University Press***

Aircraft Propulsion & Gas Turbine Engines ***Ahmed F. El-Sayed*** ***CRC Press***

Jet Engines ***Hunecke*** ***Airlife***

Gas Turbine Performance ***Walsh & Fletcher*** ***Blackwell Science***

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Units

- **Basic Units:** **Preferred SI** **Imperial**

(Mass, length, time & temperature)

	Preferred SI	Imperial
Mass	kg	slug
Length	m	ft
Time	s	s
Temperature	C/K	(F/R)

Derived units:

	Preferred SI	Imperial
Force	Kilonewton kN	lbf
Pressure	Kilopascal kN/m2 or kPa	lb/in2
Work or Energy	Kilojoule kJ or kNm	ft lb
Power	Kilowatt kW or kJ/s	hp

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Symbols

Mass Flow	$\dot{\boldsymbol{m}}$	kg/s
Thrust / Force	$\boldsymbol{F}$	Kn
Absolute Velocity	$\boldsymbol{C}$	m/s
Relative Velocity	$\boldsymbol{V}$	m/s
Mach Number	$\boldsymbol{M}$	
Total Temperature	$\boldsymbol{T_o}$	C/K
Static Temperature	$\boldsymbol{T}$	C/K
Total Pressure	$\boldsymbol{P_o}$	kPa / bar
Static Pressure	$\boldsymbol{P}$	kPa / bar
Work / Energy	$\boldsymbol{W}$	kJ
Power	$\boldsymbol{P_{ow}}$	kW

Subscripts/Superscripts

a ambient

‘ Ideal

N at nozzle throat

N^* static conditions @ nozzle throat

c Bypass flow

h LP turbine exit flow

j Mixed flow at jet exit

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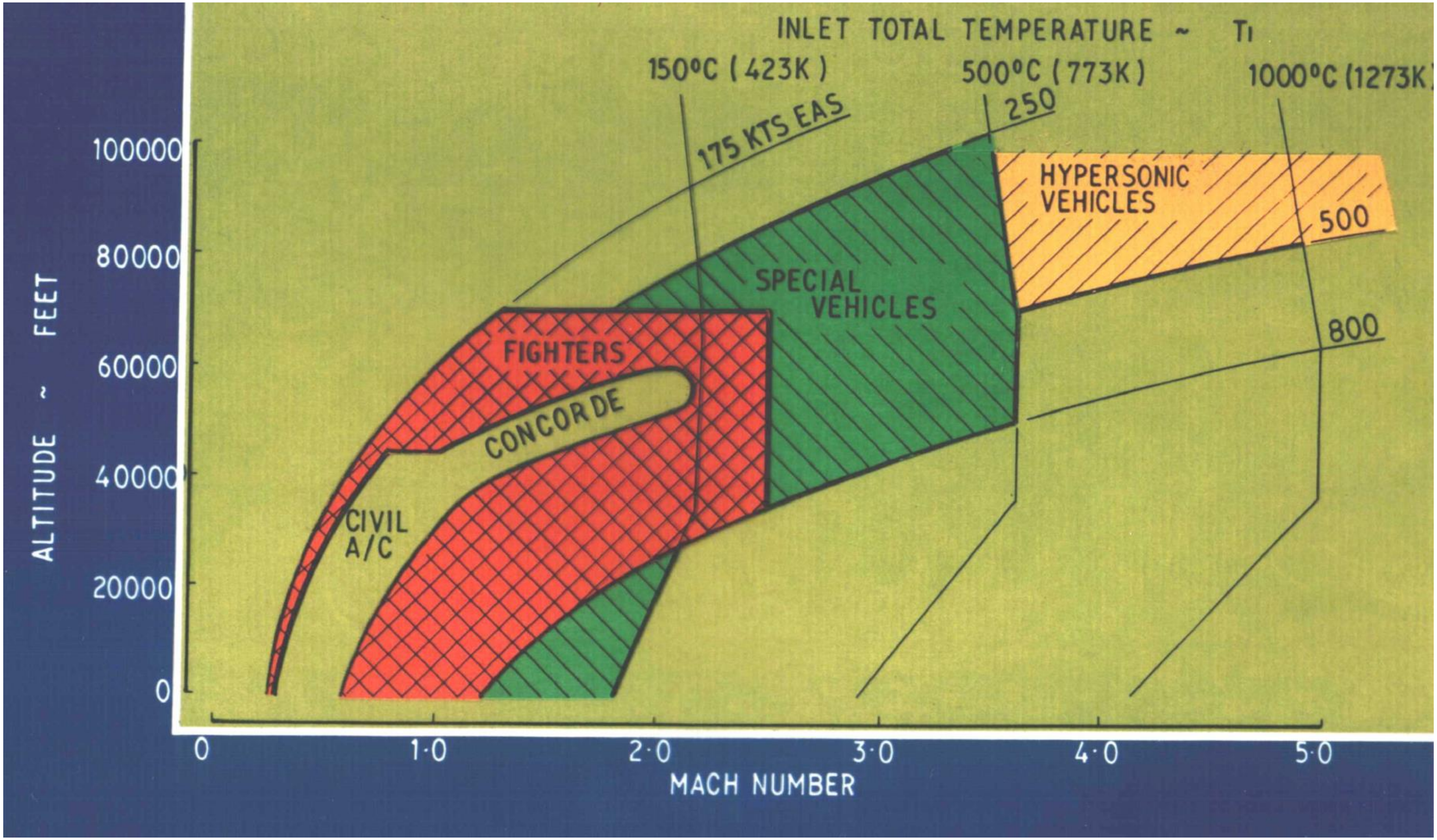
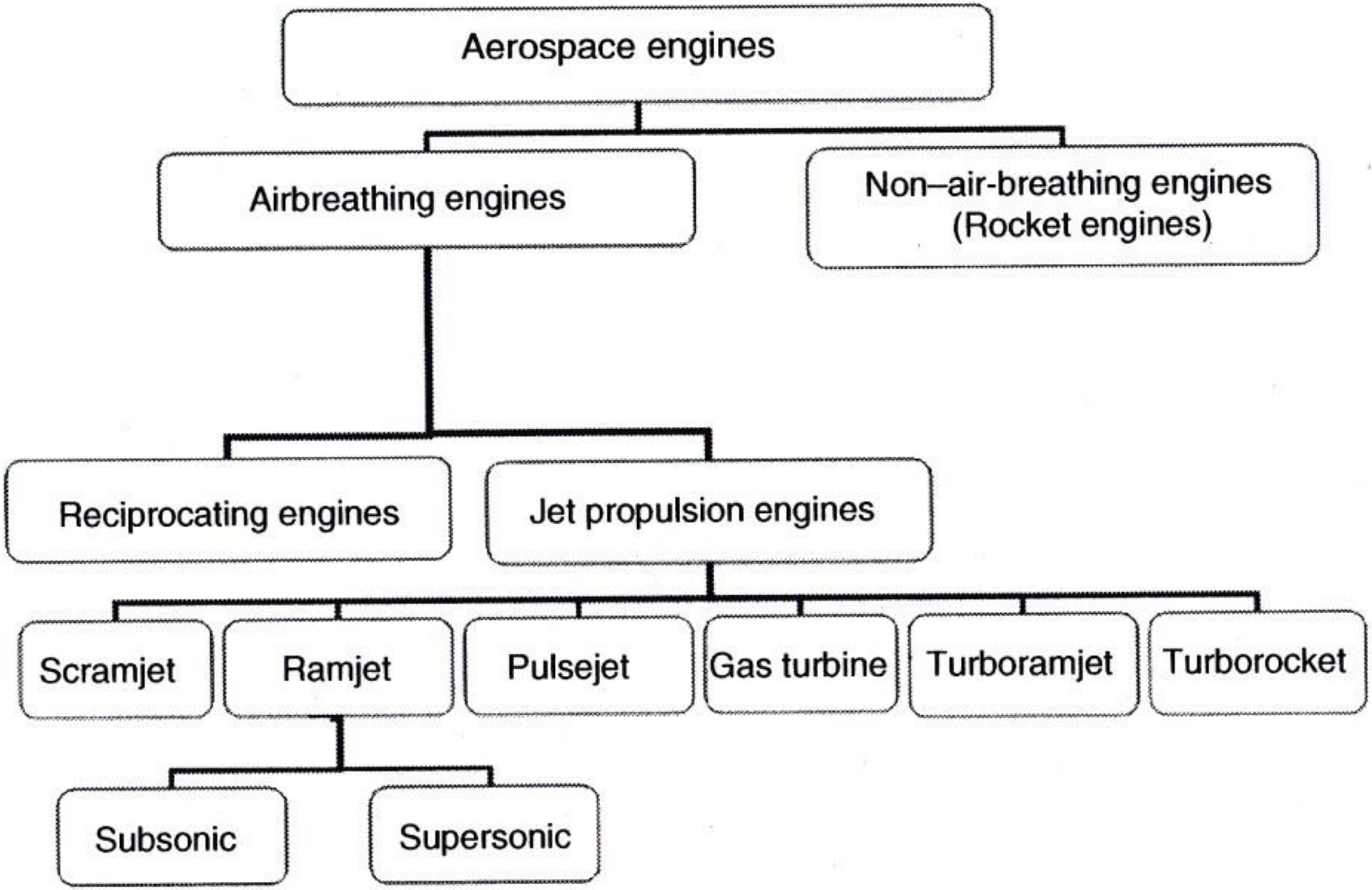
Aircraft Flight Envelope

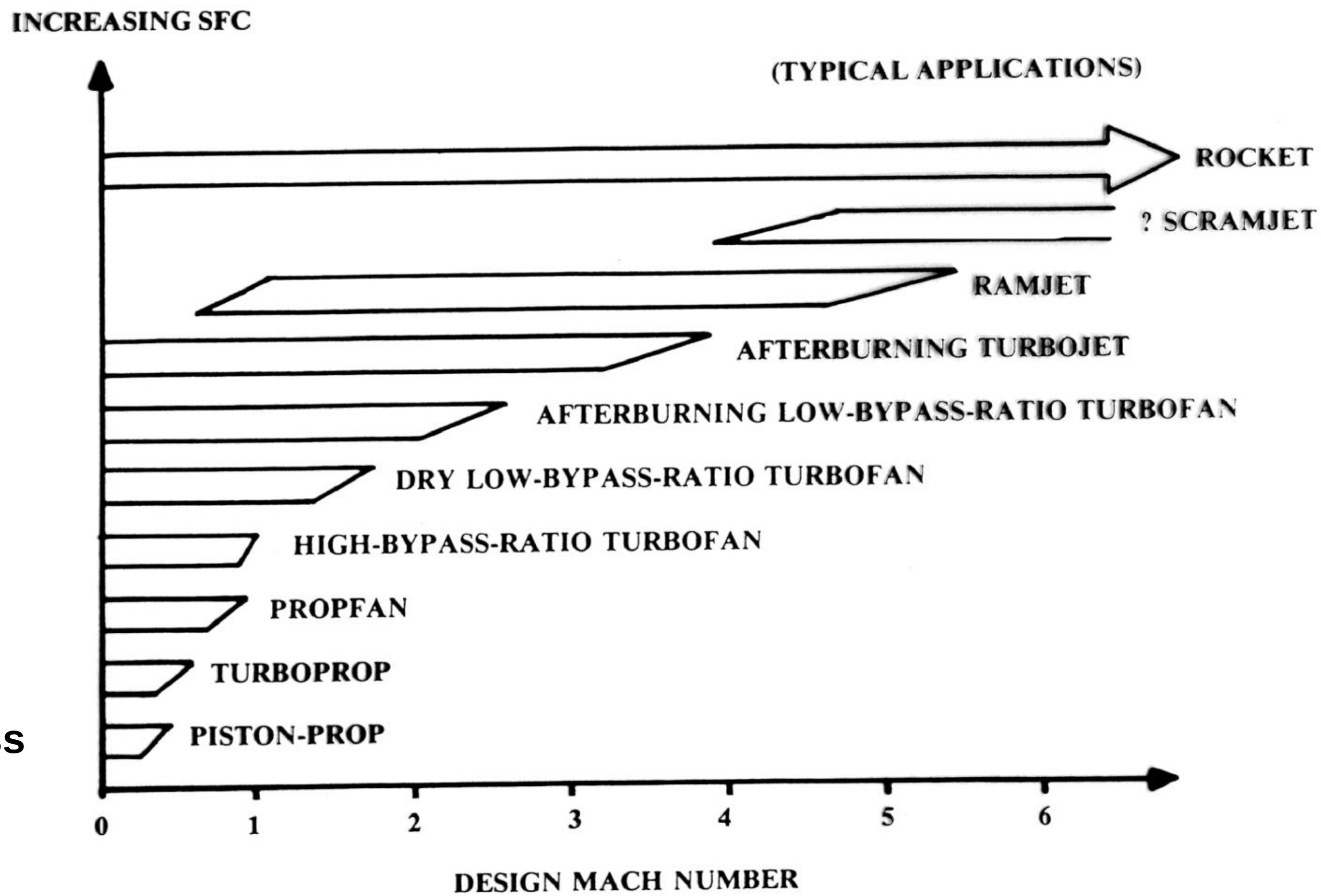


Propulsion System Classification



Propulsion system speed limits

Specific Fuel Consumption ~ Fuel flow per unit thrust ~ kg/hr/N or lb/hr/Lb



Mass

What is Thermodynamics?

- **Thermodynamics -** the interrelationship and the conversion of different forms of energy

- **Energy -** the potential capacity to do work

- ***For Example***
  - Gravitational energy (weight driven clock escapement)
  - Kinetic energy
  - Elastic energy
  - Heat - the transmission of energy by temperature difference
  - Electrical energy
  - Nuclear energy
  - Mass as an energy source - $E = mc^2$

What relevance does it have to this course?

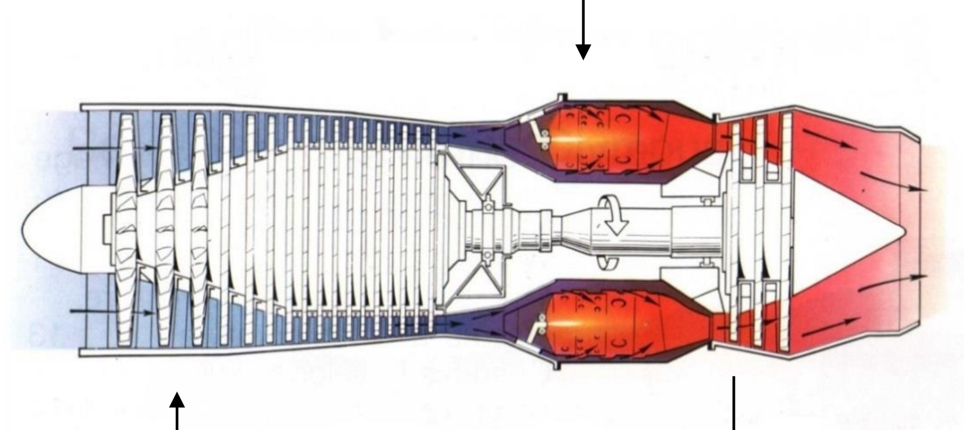
The turbojet engine - an energy converter

Hydrocarbon energy into air

Useful work in form of a jet

$\dot{m}_{in}$

V_{in}



$\dot{m}_j$

V_{out}

Work into air

Extract thermal energy from air to produce power to drive compressor

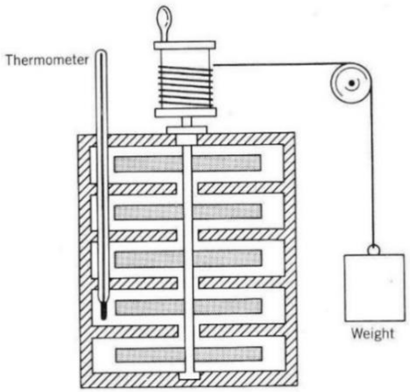
Via shaft

$$Thrust \rightarrow F = (\dot{m}_j \cdot V_{out} - \dot{m}_{in} \cdot V_{in})$$

$$Propulsive\ Efficiency \rightarrow \eta_{prop} = \frac{2}{1 + \frac{V_{out}}{V_{in}}}$$

First Law of Thermodynamics (1)

- The first law is essentially a statement of conservation of energy - “energy in a closed system may change in form but it is neither created nor destroyed”.
- *First postulated by a German naval surgeon in a paper in 1842 but not accepted as he was an “unknown”. Also postulated mechanical equivalent of heat.*
- Experimental paper by Joule (published in 1843) verified that work could be totally converted into thermal energy – usually called ‘mechanical equivalent of heat’.



First Law of Thermodynamics (2)

- Further work by Joule, together with that by Helmholtz in Germany led to the acceptance of the conservation of energy and the first law of thermodynamics.
- By implication Joule had shown in his experiments that ***mechanical work could be converted completely into thermal energy.***
- However, the known efficiency (useful work out/ thermal energy in) of steam engines was only of the order of 5% at that time.
- ***Is there a physical limit to the conversion of thermal energy to useful work or were designers poor engineers ?***

Maximum Efficiency of a Thermal Energy Machine (1)

- **Sadi Carnot** - a French engineer - had already looked at this theoretically in the early 19th century and built on the work of James Watt. He concluded that

$$\eta \propto \mathbf{T_{hot} - T_{cold}}$$

  and that it was independent of whether it was a steam engine or any other kind of engine.

- However he had used ‘caloric’ theory which was later shown to be wrong in concept. The steps in the thinking were correct but effectively violated the first law of thermodynamics.

Maximum Efficiency of a Thermal Energy Machine (2)

- Rudolf Clausius, a German physicist, updated Carnot's ideas. Using the cycle Carnot had proposed he showed that the maximum efficiency an ideal, frictionless heat engine could achieve would be:

$$\eta_{ideal} = 1 - (T_c/T_h)$$

where T_h is the temperature at which the thermal energy is put into the cycle and T_c is the temperature at the lowest point of the cycle.

Moral: For maximum efficiency, build your power stations in outer space!

Maximum Efficiency of a Thermal Energy Machine (3)

- In reaching this formula Clausius developed a new concept which he called **'entropy'**.

- The name was from two Greek words and meant 'transformation content'. His concept was that an **increase in entropy** resulted in **reduced availability of thermal energy** for conversion into **useful work.**

- He realised that **changes in entropy** were more important than the absolute level of entropy and that entropy changes were proportional to the thermal energy added to the system and inversely proportional to the temperature at which the thermal energy was added to the system.

- Mathematically he defined this as $\Delta s = \Delta Q/T$

- From this he was able to deduce: $\eta_{ideal} = 1 - (T_c/T_h)$

Limiting Thermal Efficiencies

- **Using the formula developed by Clausius the following 'ideal' efficiencies result :**

1. Early steam engine - ideal 20% (actual ≈ 5%)

$$\eta_{lim} = 1 - (300/373) = 0.20$$

2. Modern steam turbine - ideal 65% (actual ≈ 38%)

$$\eta_{lim} = 1 - (300/850) = 0.65$$

3. Steam turbine with recuperator - ideal 75% (actual ≈ 56%)

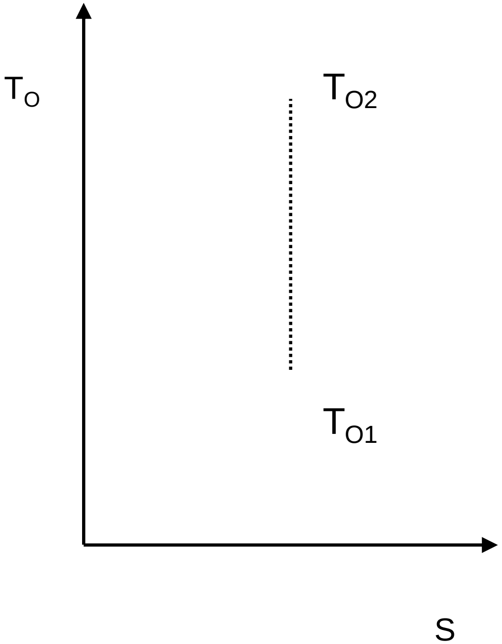
Entropy & the 2nd Law of Thermodynamics

- Clausius, using this concept of entropy (1865) had shown that **it is impossible to convert heat (thermal energy) completely into useful work**, as did Lord Kelvin around the same time.

- This is one statement of what became known as the **Second Law of Thermodynamics**.

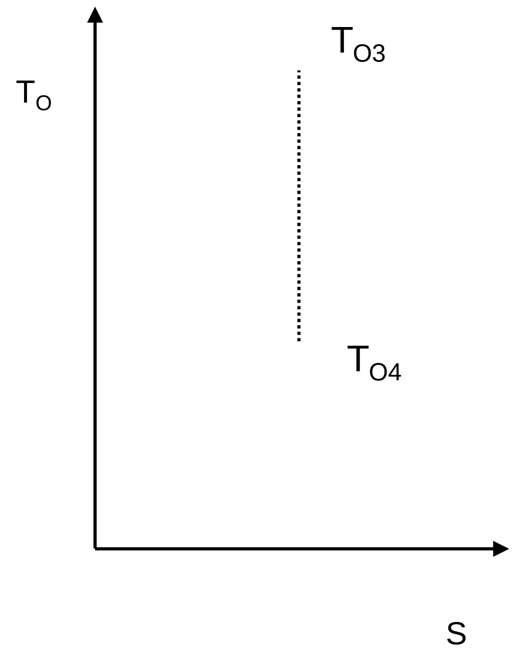
- The Second Law is odd in that there are a number of alternative ways of stating it. The reason for this is that there is a ‘circle’ of ‘causes’ and ‘effects’ contributing to the law. Dependent on where you start in the circle you can define an appropriate statement for the Law - they are complementary.

Isentropic Compression and Expansion



Compression

Increase in Total Temperature (Enthalpy) exactly balances decrease due to volume effect.



Expansion

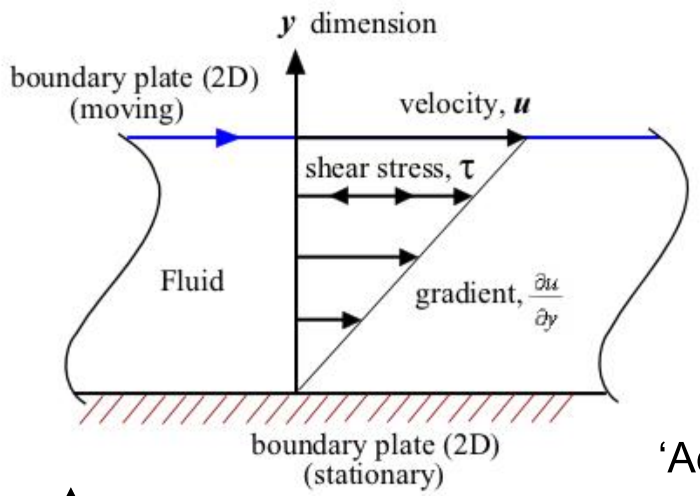
Decrease in Total Temperature (Enthalpy) exactly balances increase due to volume effect

Enthalpy = $\dot{m} \cdot Cp \cdot \Delta T$

“Inefficiencies in a turbomachine are like a person with an illness - they make the machine (person) run at a higher temperature”

Sir Stanley Hooker

Viscosity and Efficiency

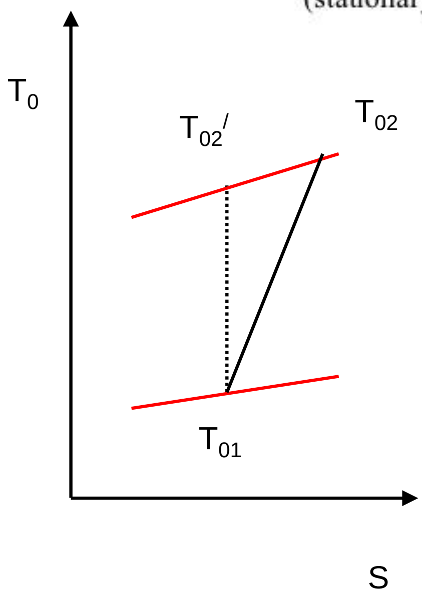


Viscosity produces a stress at the boundary $\tau = \mu \frac{\delta u}{\delta y}$ where 'μ' is the coefficient of viscosity. So, for instance, there is resistance to flow in a pipe due to the 'drag' at the walls.

'Actual' work in compressor = 'Ideal' work + (friction, etc)

$(\dot{m} \cdot Cp \cdot \Delta T)_{actual} = (\dot{m} \cdot \mathrm{C_p} \cdot \Delta \mathrm{T})_{ideal}$ + (Irreversible Work)

The (Irreversible Work) is almost entirely due to viscosity.



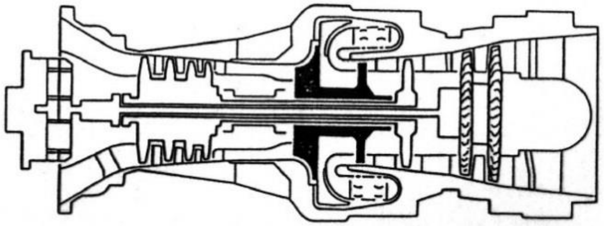
ISENTROPIC EFFICIENCY

Isentropic Total Temperature rise/ Actual Total Temperature rise.

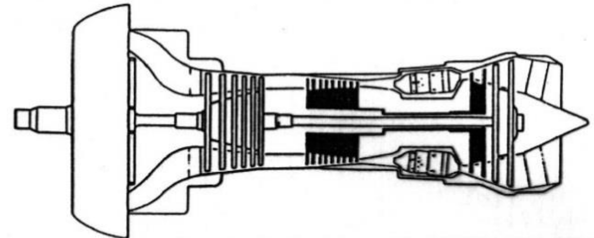
$$\eta = \frac{T'_{02} - T_{01}}{T_{02} - T_{01}}$$

** Note there is another way of defining the efficiency of a process i.e. Polytropic Efficiency ~ see lecture on Compressors*

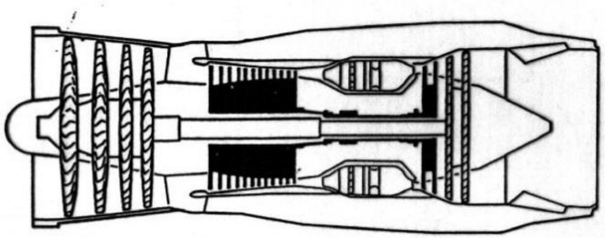
Mechanical Arrangements of Gas Turbines



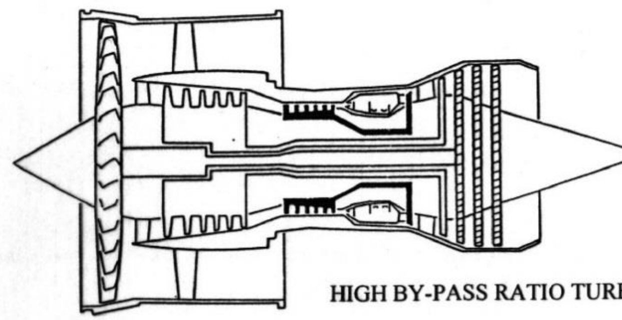
TWIN-SPOOL TURBO-SHAFT (with free-power turbine)



TWIN-SPOOL AXIAL FLOW TURBO-PROPELLER



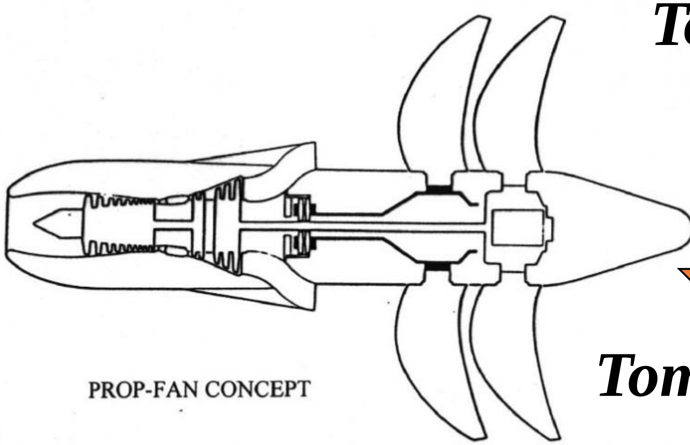
LOW BY-PASS RATIO TURBOFAN



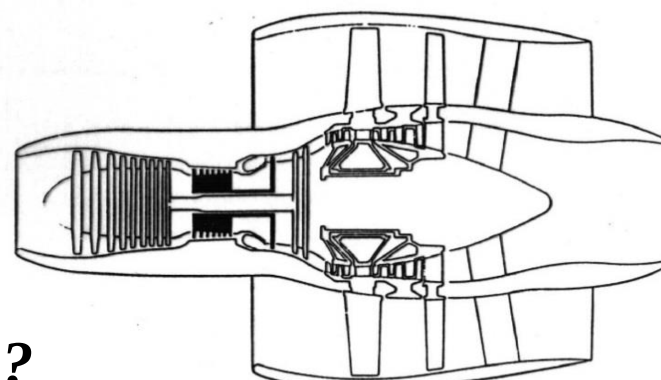
HIGH BY-PASS RATIO TURBO-FAN

Today

Tomorrow ?

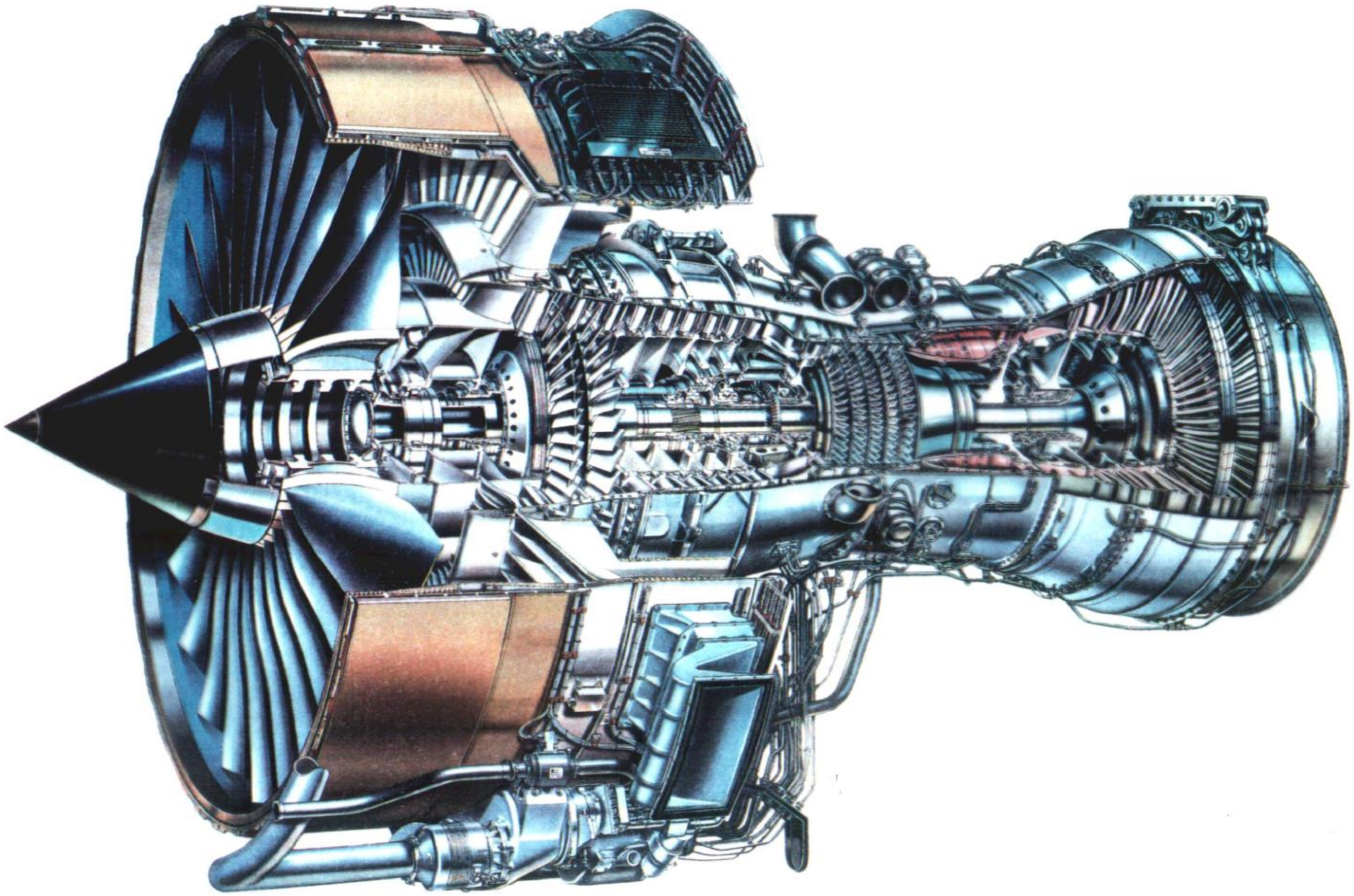


PROP-FAN CONCEPT



ULTRA HIGH BY-PASS RATIO (Contra-rotating fans)

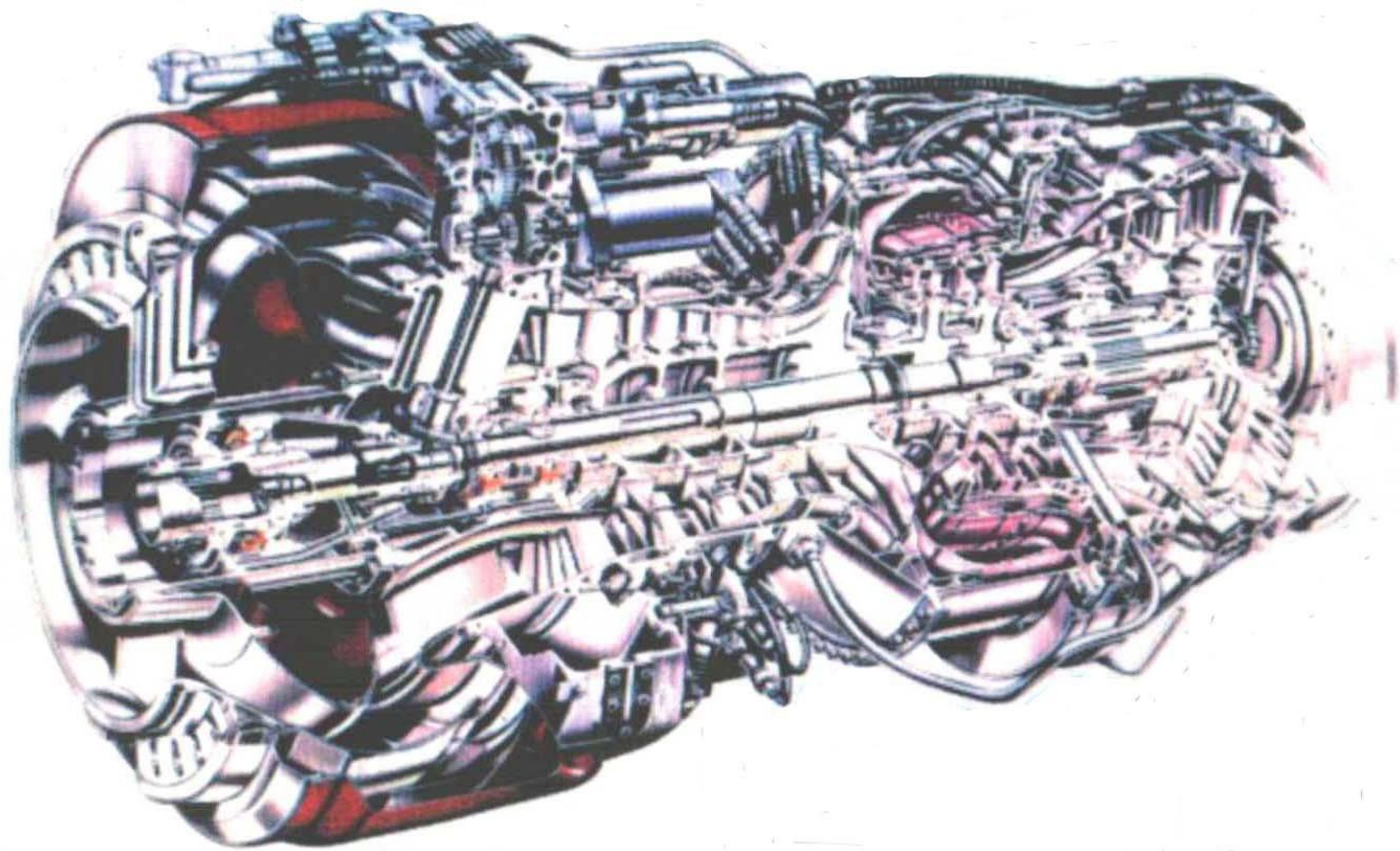
Rolls Royce ~ Trent



Rolls-Royce plc Data

RTM 322

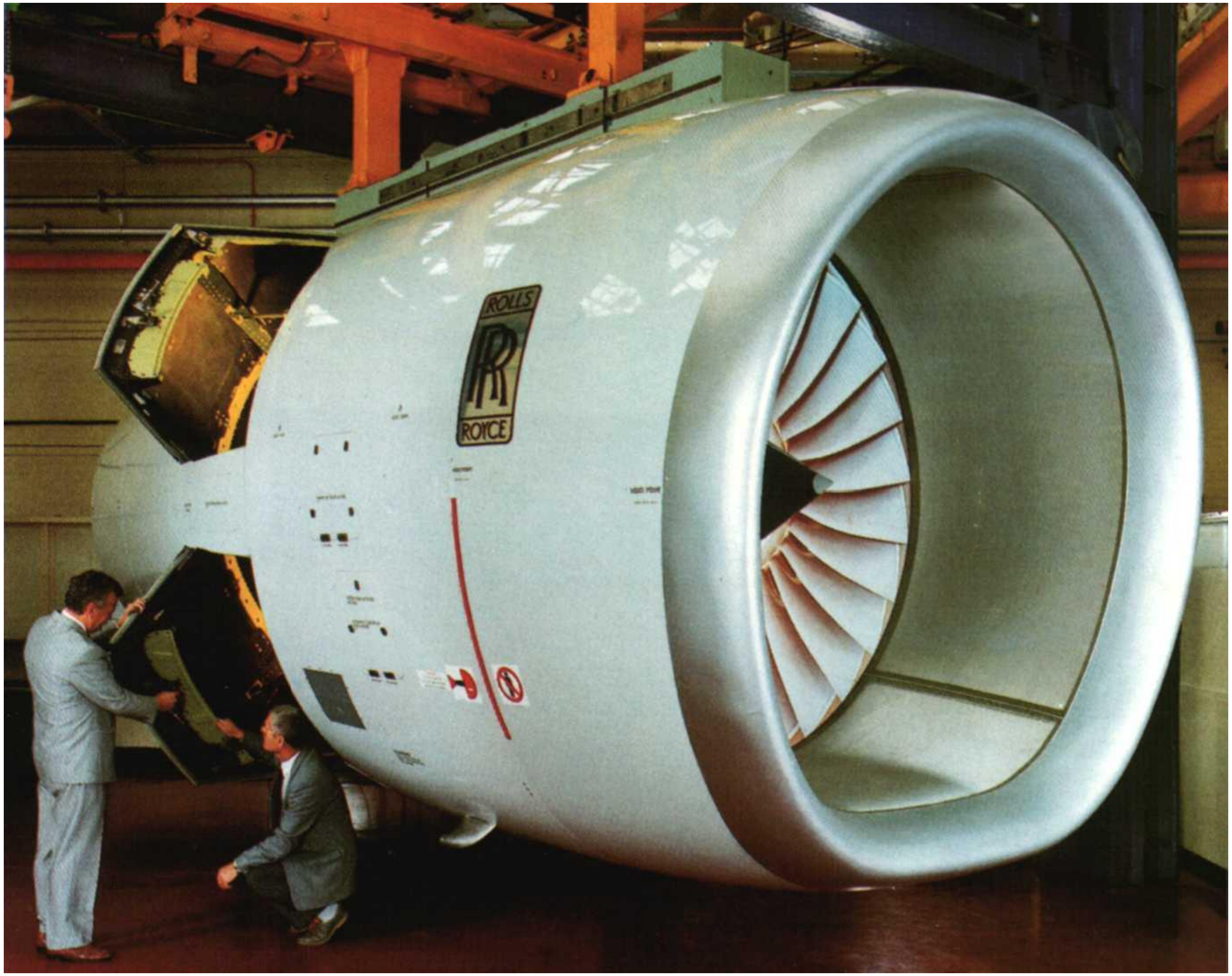
Turboshaft Engine



EJ 200

Military Reheated Turbofan

Rolls Royce ~ Trent 700



Rolls Royce Trent

Airbus A350

Boeing B787

A320 with CFM 56

Feederliners and Business Jets

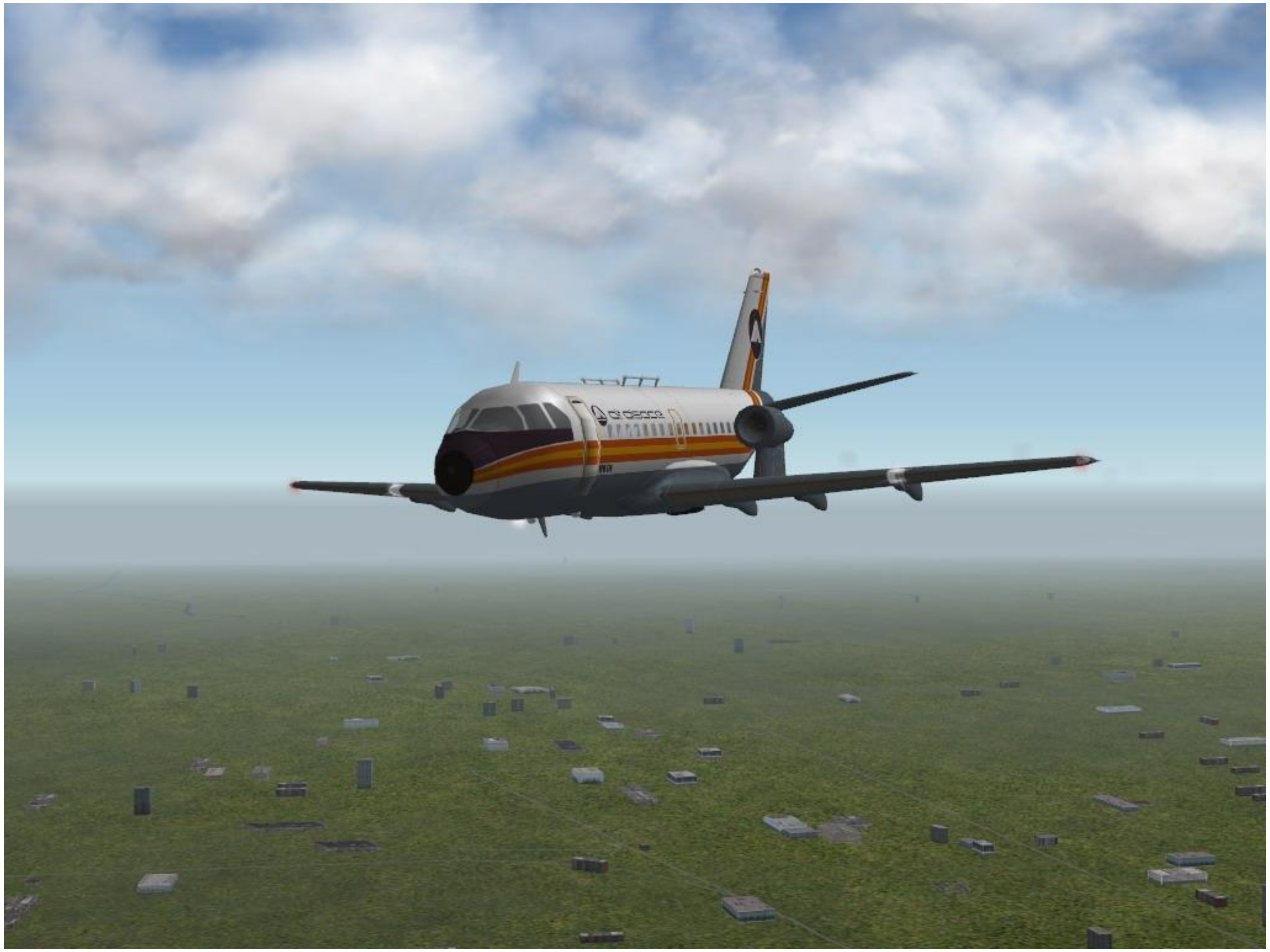
Hs146

Bomdardier Global Express

Embraer 145

Embraer 170/175

VFW 614 powered by Rolls Royce M45H



Engine Comparison

		RB211	Trent 1000
Design era		**(1970's)**	**(2011 EIS)**
Aircraft		L1011	B787
Thrust	kN (Lb)	185 (43,000)	335 (75,000)
SFC * @ cruise	kg/hr/N	0.063	0.055
Mass	kg	4200	5400
Mass flow	kg/s	625	1210
Fan Diameter	m	2.15	2.85
Overall pressure ratio		25	52
By-pass ratio		5	11
Turbine Entry Temperature TET	K	1500	1800
Specific thrust	N/kg/s m/s)	300	280
Thrust/Weight		5	6

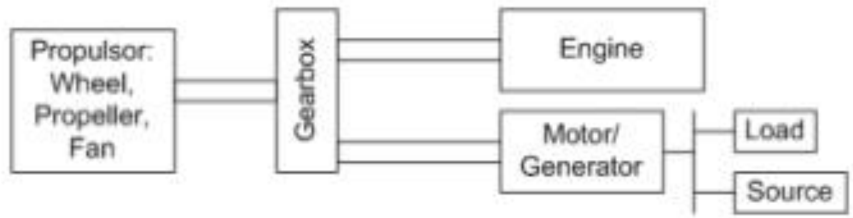
** ~ SFC Specific Fuel Consumption at M=0.8 35,000 ft*

Hybrid & Electric Propulsion – Overview

Conventional:
Electrical system not propulsive

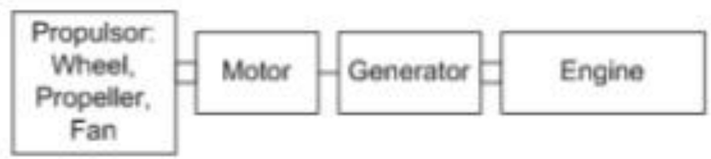
Hybrid Electric Propulsion:
Both engine and motor can directly drive the propulsor

- Also called a parallel hybrid
- May or may not have batteries

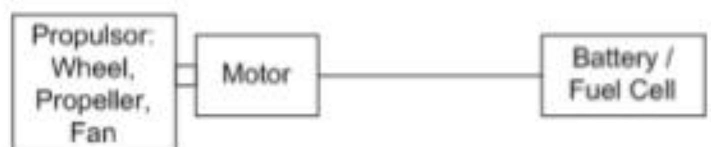


Diesel-Electric / Turbo-Electric Propulsion:
All propulsion power transmitted electrically from the engines

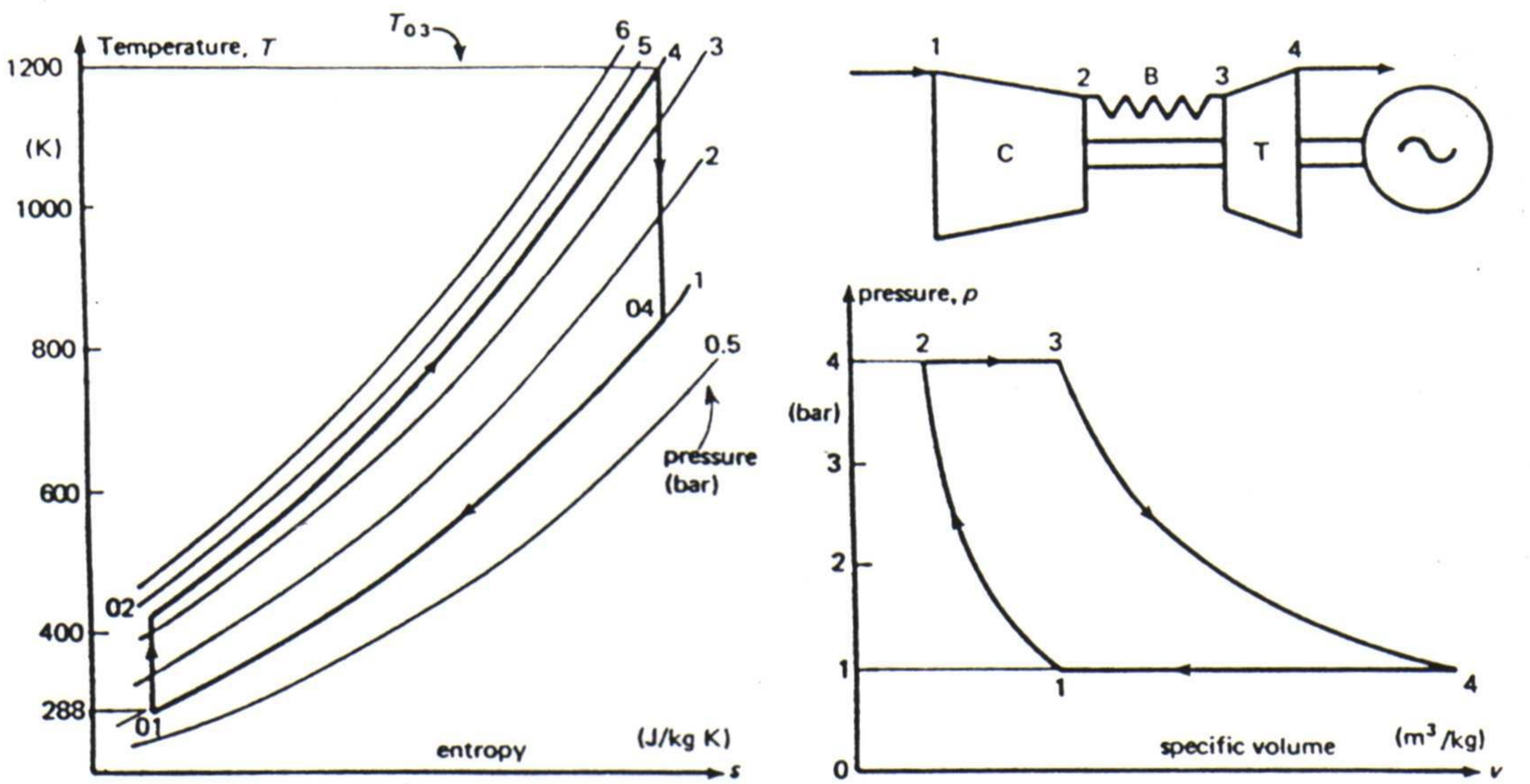
- Also called a series hybrid
- May or may not have batteries



Electric Propulsion: No engines



Joule or Brayton Cycle for a Gas Turbine



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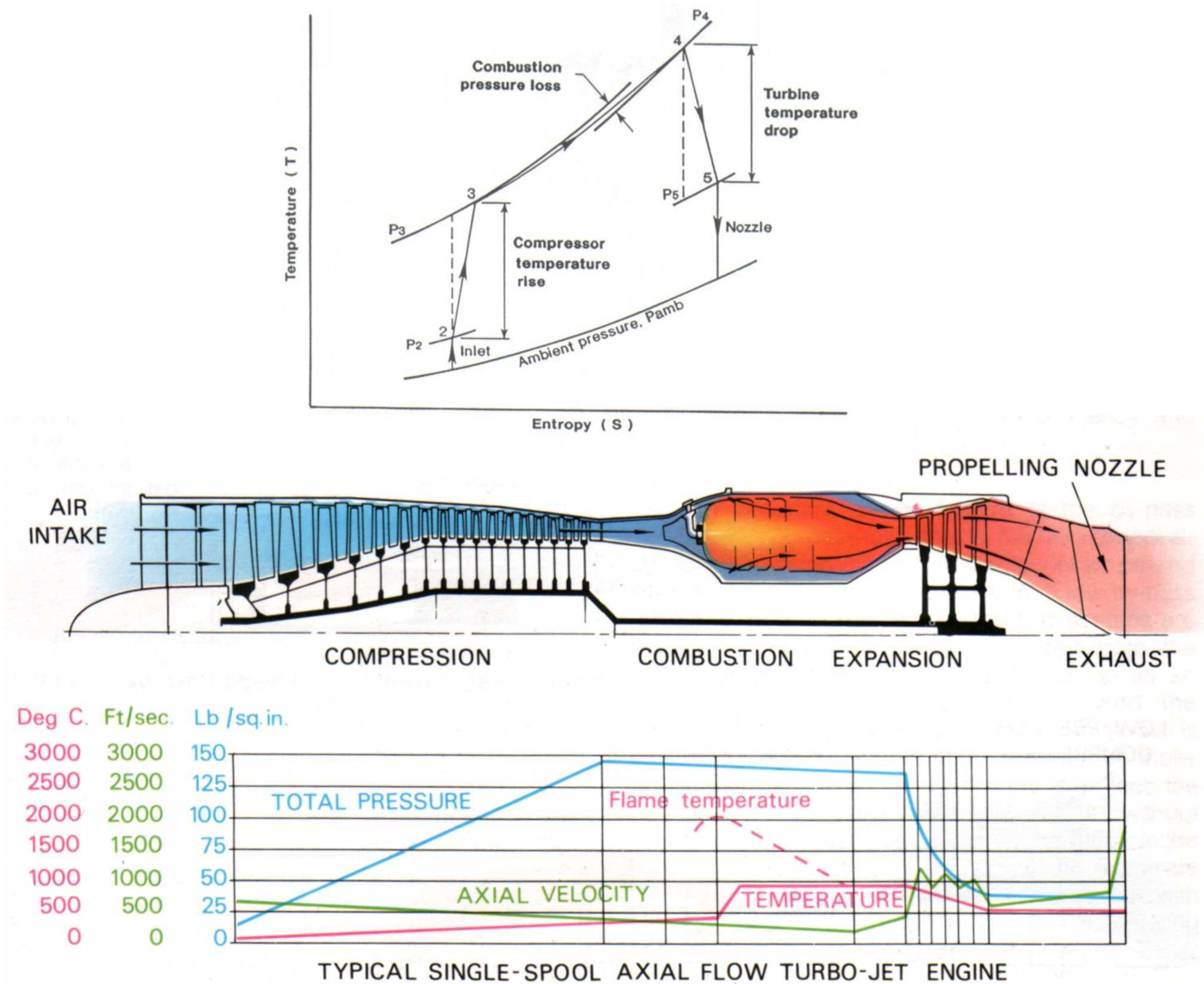
$$\eta = 1 - \{1/(p_2/p_1)\}^{\gamma - 1/\gamma}$$

The Practical Turbojet Cycle



Key Points from Lecture 1

- Outline of contents of Unit
- Revision of Basic Thermodynamics
- Details of the types of Propulsion Systems currently used in aviation
- A brief description of the Joule or Brayton Cycle and its relevance to gas turbines.

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Objectives ~ Lecture 2

- To describe the International Standard Atmosphere and its significance.
- To show the ideal efficiency of the Joule or Brayton Cycle.
- To calculate the main characteristics of a practical turbojet.