SESA2023 Propulsion

Lecture 0: Module Information and Organization

Ivo Peters
i.r.peters@soton.ac.uk

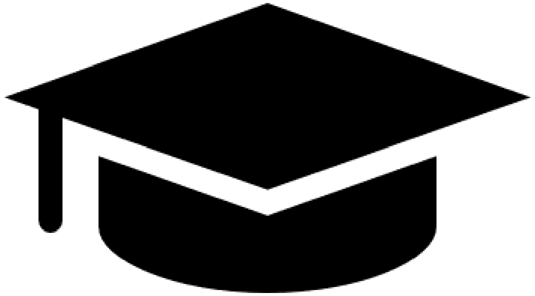
PROPULSION CONTENT OVERVIEW

Section 1: Introduction and Fundamentals	3 weeks, Ivo Peters
Section 2: Ramjets, Combustion, Rockets	3 weeks, Ivo Peters
Section 3: Gas Turbines, Turbojets, and Turbofans	2 weeks, Ed Richardson
Section 4: Turbomachinery and Propellers	3 weeks, Ed Richardson

YOUR FINAL MARK

- **5 Summative courseworks (20%)**
  - Three quizzes (3% each)
  - Two Labs (5.5% each)

- **Exam (80%)**
  - Sit down(!) exam



A WEEK IN SESA2023…

15 CATS = 150 hours

150 / 12 = 12.5 hours / week

• Lectures: Concepts and examples	3 hours
• Reading: Lecture notes	2 hours
• Practice material: Weekly problem sheet	5 hours
• Formative or summative assessment submission	2.5 hours

PROPULSION LABS

- Nozzle Lab: Compressible flow
- Propulsion Lab: Ramjet, (rocket), combustion
- Can’t attend at your timetabled slot? Agree to switch with a colleague.
- Assessment: Summative Blackboard Tests
- **Questions: Discussion Board**

BLACKBOARD OVERVIEW

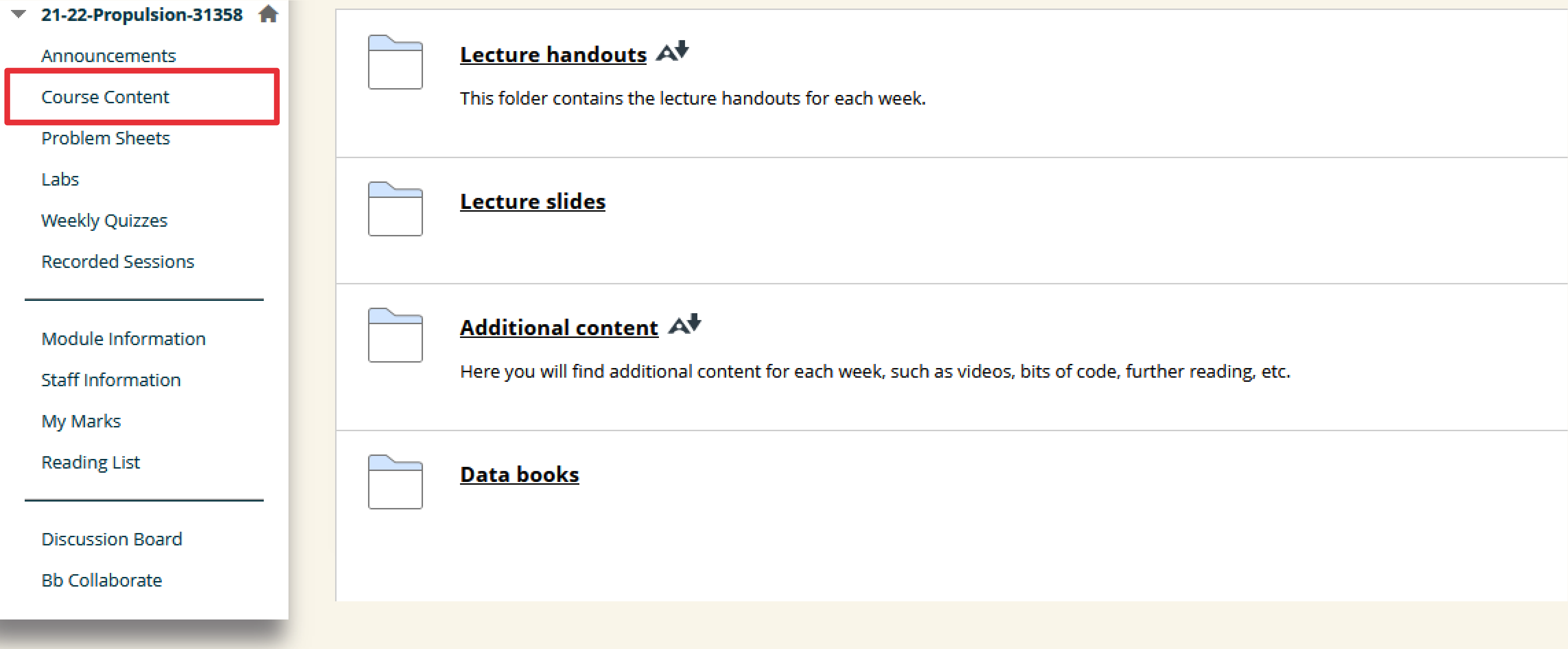
21-22-Propulsion-31358

- Announcements
- Course Content
- Problem Sheets
- Labs
- Weekly Quizzes
- Recorded Sessions

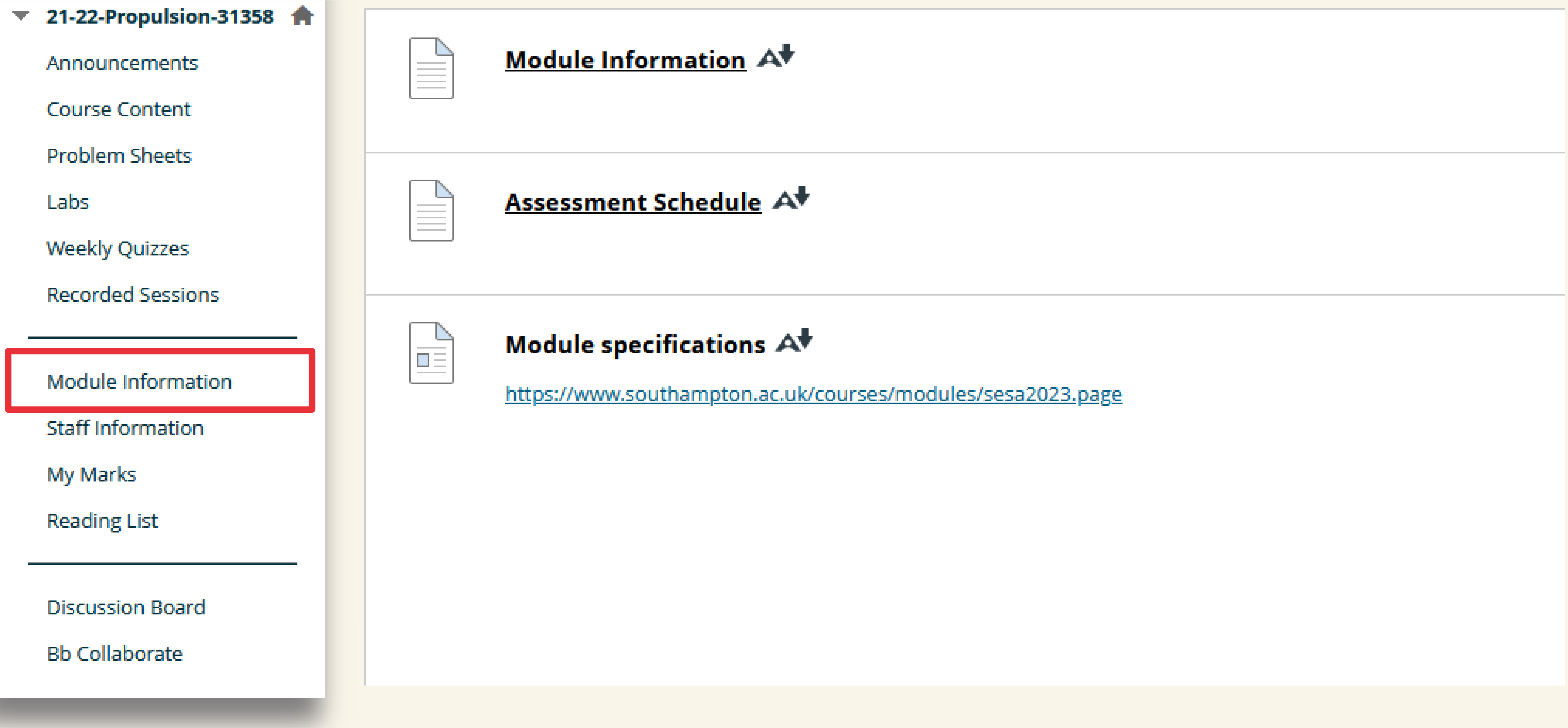
- Module Information
- Staff Information
- My Marks
- Reading List

- Discussion Board
- Bb Collaborate

BLACKBOARD: COURSE CONTENT



BLACKBOARD: MODULE INFORMATION



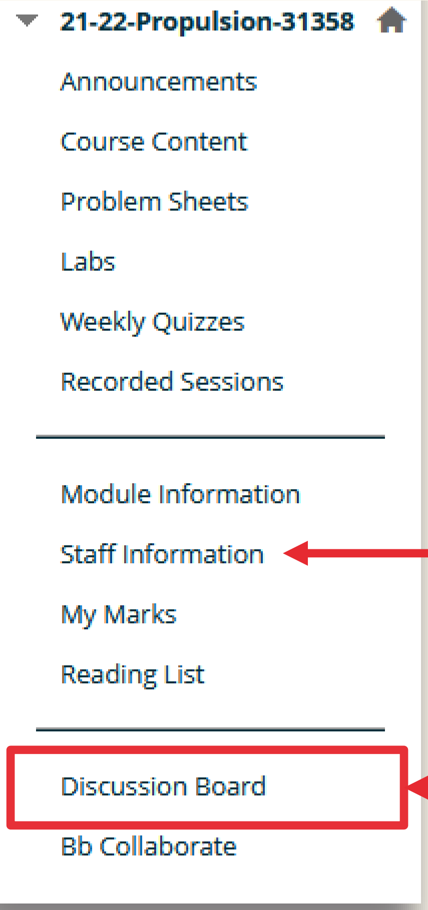
BLACKBOARD: MODULE AND ASSESSMENT SCHEDULE

- **21-22-Propulsion-31358**
  - Announcements
  - Course Content
  - Problem Sheets
  - Labs
  - Weekly Quizzes
  - Recorded Sessions
  - Module Information
  - Staff Information
  - My Marks
  - Reading List
  - Discussion Board
  - Bb Collaborate

Semester week	Week/c	Uni week	Section	Quiz	Lab coursework	Weight
1	30/1/2023	18	1			
2	6/2/2023	19	1	Summative		3%
3	13/2/2023	20	1	Formative		
4	20/2/2023	21	2	Summative		3%
5	27/2/2023	22	2	Formative		
6	6/3/2023	23	2	Formative	Nozzle	5.5%
7	14/3/2023	24	3	Formative		
8	20/3/2023	25	3	Formative	Propulsion	5.5%
EASTER BREAK						
9	24/4/2023	30	4	Formative		
10	1/5/2023	31	4	Summative		3%
11	8/5/2023	32	4	Formative		
12	15/5/2023	33	Revision	Formative		

#	Assessment	Set Date	Due Date	Feedback Date	Weighted Mark
1	Quiz Week 1	30/01/2023	10/02/2023	17/02/2023	3%
2	Quiz Week 3	13/02/2023	24/02/2023	03/03/2023	3%
3	Nozzle Lab	13/02/2023	10/03/2023	24/03/2023	5.5%
4	Propulsion Lab	27/02/2023	24/03/2023	07/04/2023	5.5%
5	Quiz Week 9	24/04/2023	05/05/2023	12/05/2022	3%
6	Exam				80%

I NEED HELP!



Ask questions during lectures

Office hours / drop-in

Almost all questions

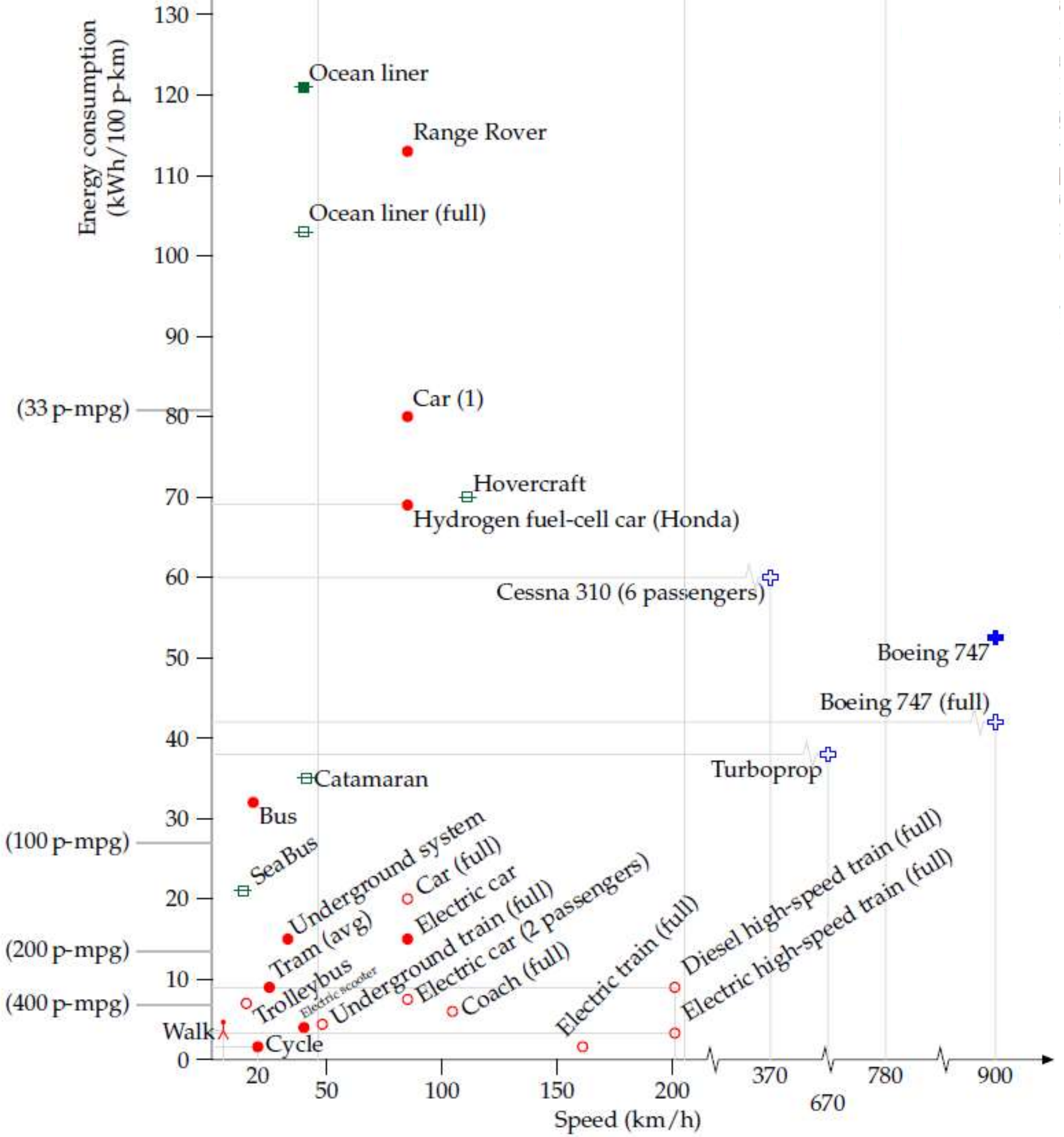
SUMMARY

- Content in 4 sections
- Weekly set of material (hand-out, problem sheet, quiz)
- Mark: 20% coursework, 80% exam
  - Quizzes: 9%
  - Labs: 11%
- Questions on Discussion Board
- Any feedback is much appreciated!

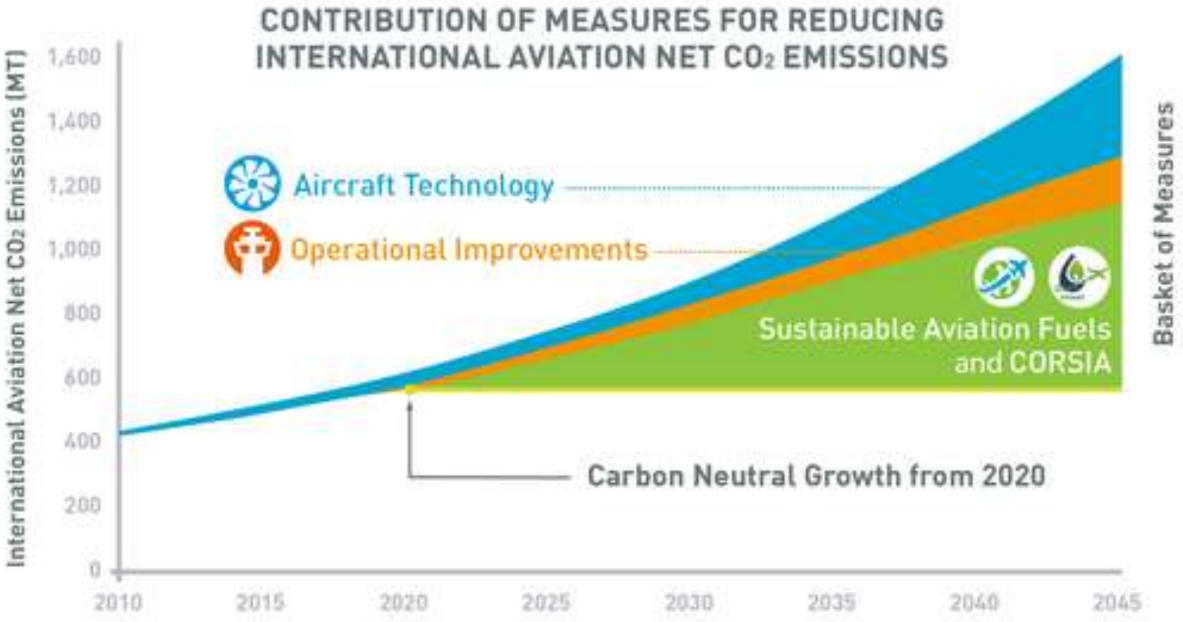
SESA2023 Propulsion

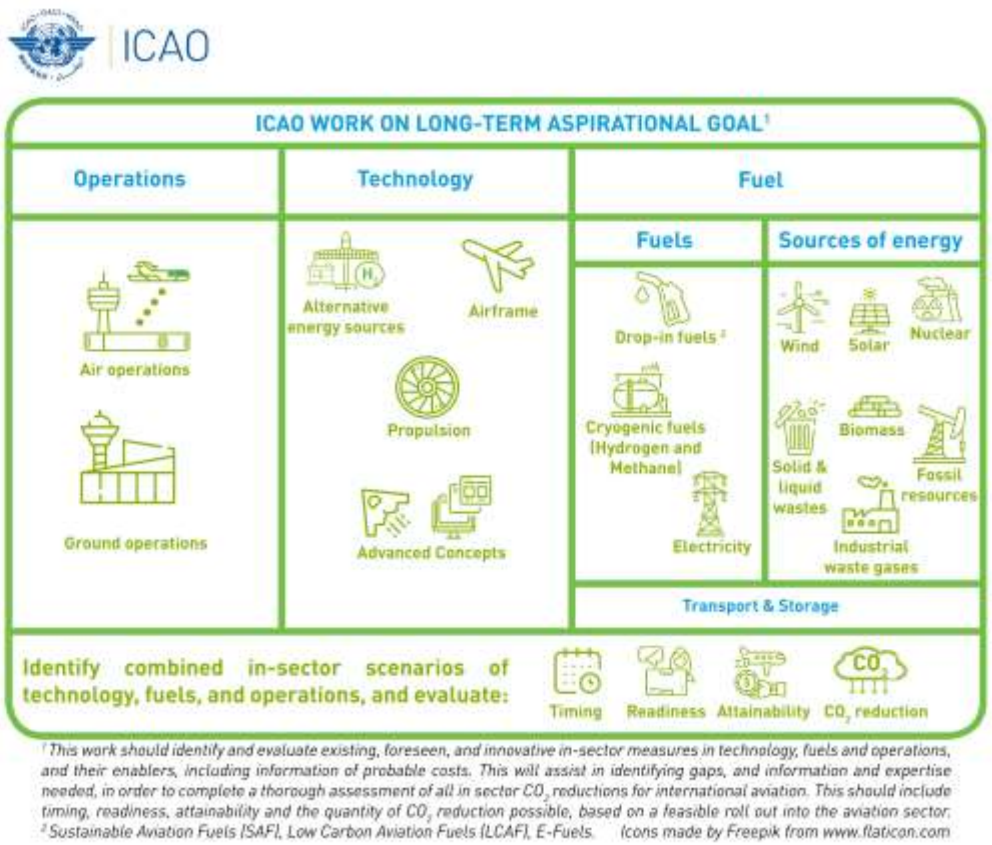
Lecture 1: Introduction & Brief History

Ivo Peters
i.r.peters@soton.ac.uk



Source: “Sustainable energy without the hot air” by David MacKay





Source: ICAO (International Civil Aviation Organization)

WHAT IS PROPULSION?

- Drive “something” forward
- Aircraft propulsion:
  - Accelerate a working fluid (air)
- Momentum conservation

METHODS OF PROPULSION

- Air breathing

- Non air breathing

ROCKET PROPULSION

- No momentum in:
  - Momentum out is pure thrust!

- Disadvantage:
  - Carry all the oxidizer

AIR-BREATHING PROPULSION

- Capture mass (air) and accelerate it
- Carry only fuel

Brief History

18 & 19TH CENTURY

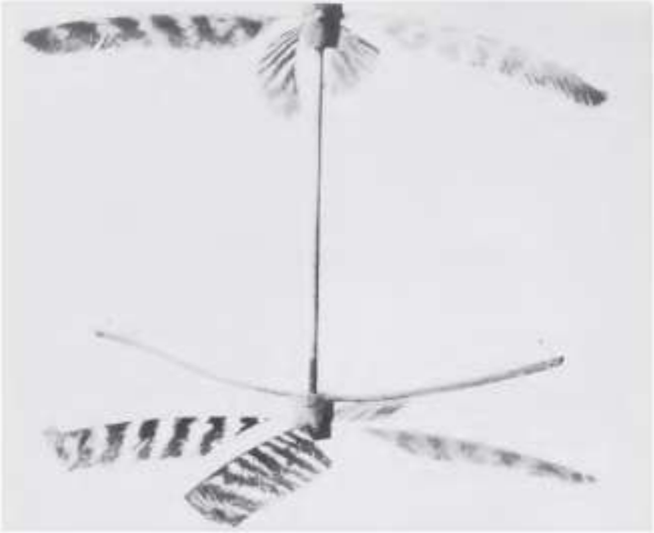


Figure 1.—Reproduction of Launoy and Bienvenue helicopter (NASM 1930-15), using bent-bow propulsion, 1784. (*Photo A-18232*)

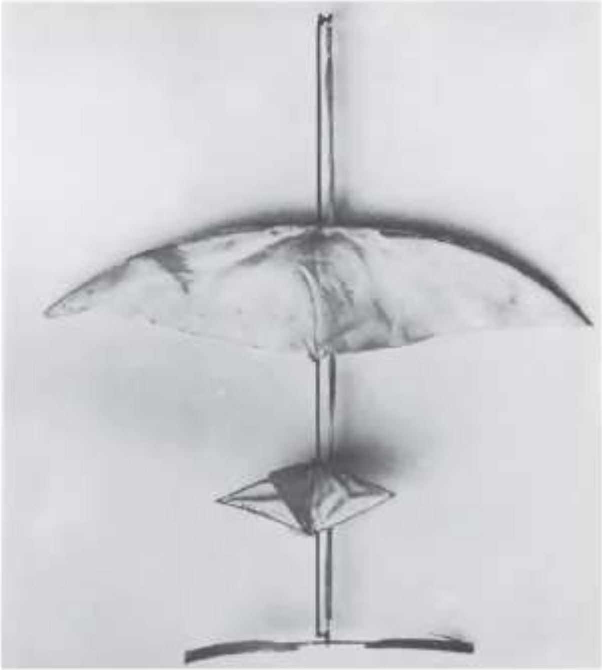


Figure 2.—Pénaud's Planaphore (NASM 1930-17), using rubber-band propulsion, 1871. (*Photo A-19627*)

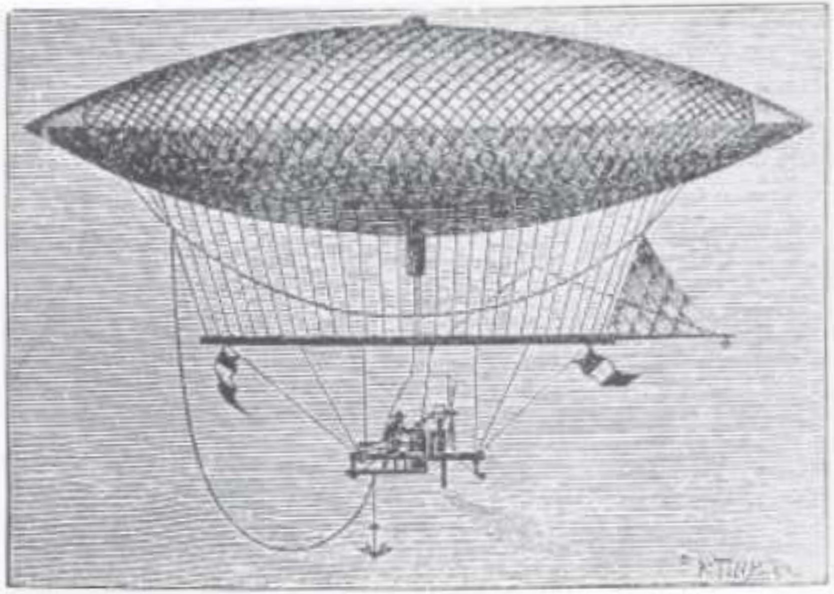


Figure 4.—Giffard airship, steam-engine powered, 1852. (*Photo A-19889*)

Source: Smithsonian Annals of Flight

THE EARLY YEARS

1903: The Wright Flyer

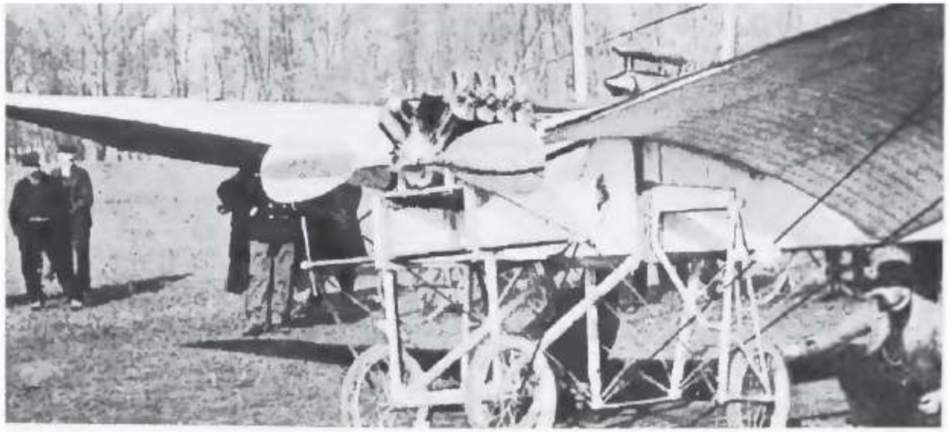
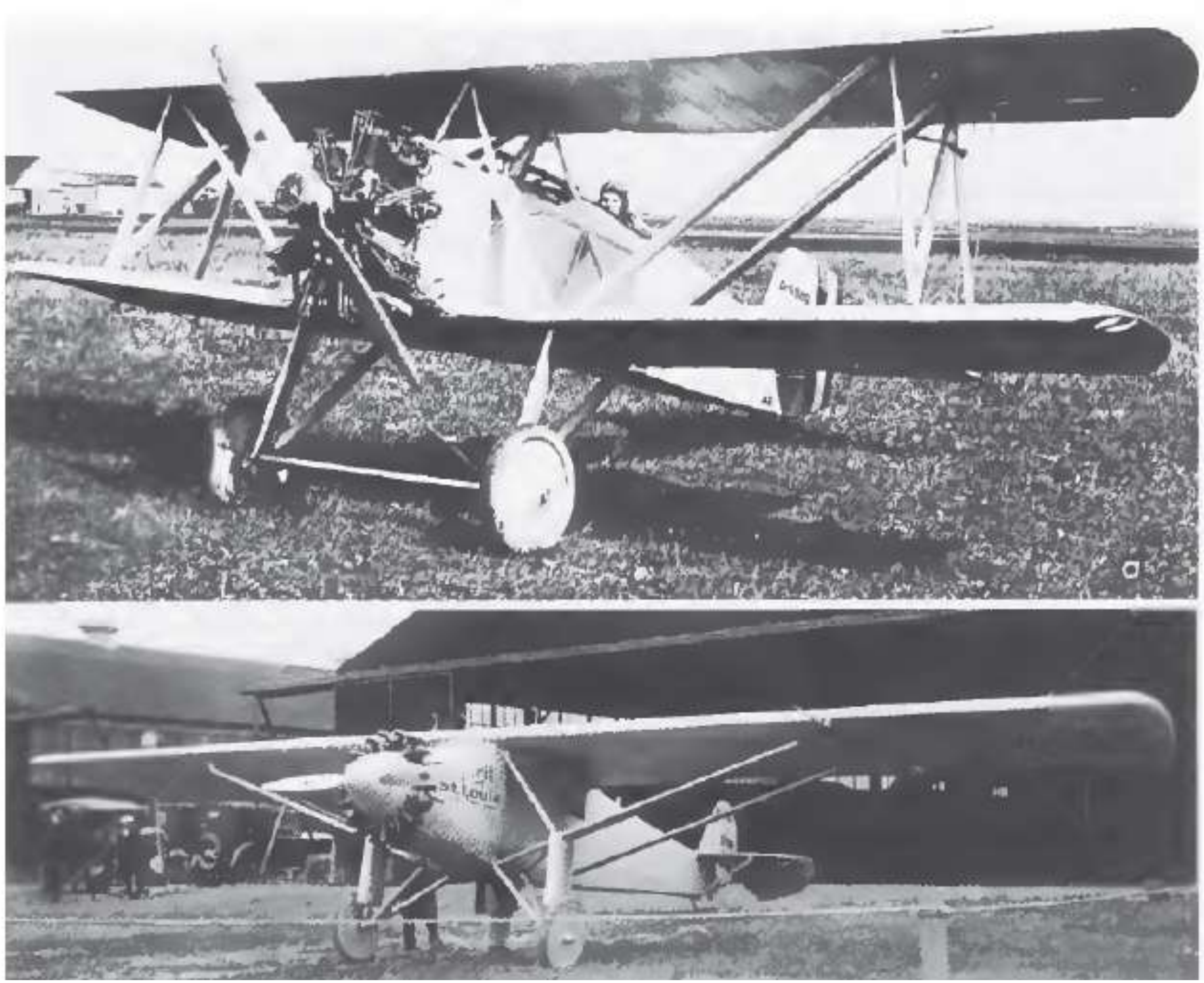


Figure 15.—Antoinette monoplane with Levavasseur Antoinette engine, 1909. (Photo A-3099)

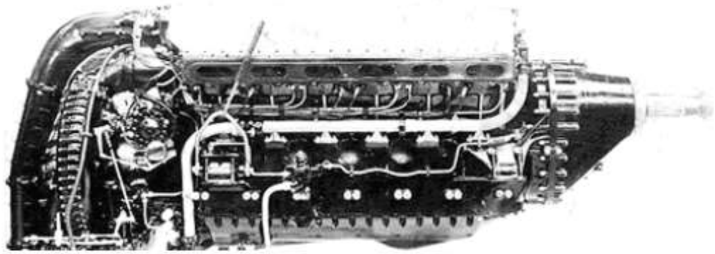
1909: Antoinette monoplane

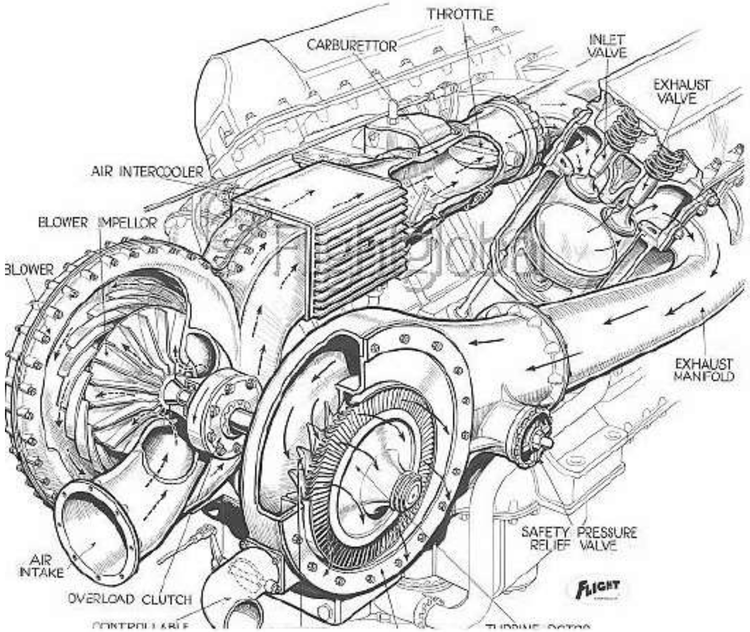
Source: Smithsonian Annals of Flight

1920’s: PROPELLER PROPULSION



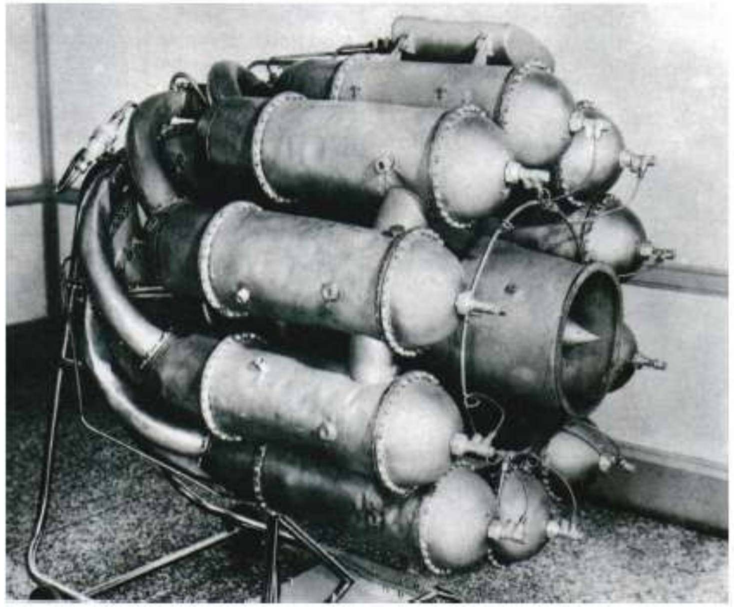
1930's: SUPERCHARGING

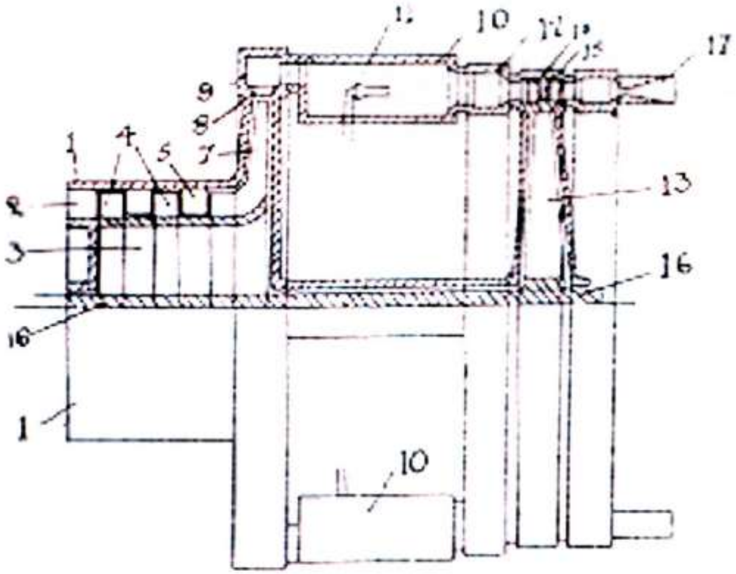




- Focus on increasing power
- Evolutionary advancements on traditional engines

WHITTLE ENGINE





Whittle's 1930 Patent Application, allowed to lapse in 1935

EXPERT OPINIONS

*"Scientific investigation into the possibilities of jet propulsion has given **no indication that this method can be a serious competitor** to the airscrew/engine combination."*

British Under-Secretary of State for Air, 1934

*"In its present state, and even considering the improvements possible when adopting the higher temperatures proposed for the immediate future, the gas-turbine engine **could hardly be considered a feasible application to airplanes**."*

Committee on Gas Turbines, US National Academy of Sciences, June 1941

FIRST FLIGHT IN THE UK

Gloster E28/39 powered by the W1 ~ 15th May 1941

… NOW

- Speed
- Capacity
- Distance
- Efficiency
- Pollution
- Noise

SESA2023 Propulsion

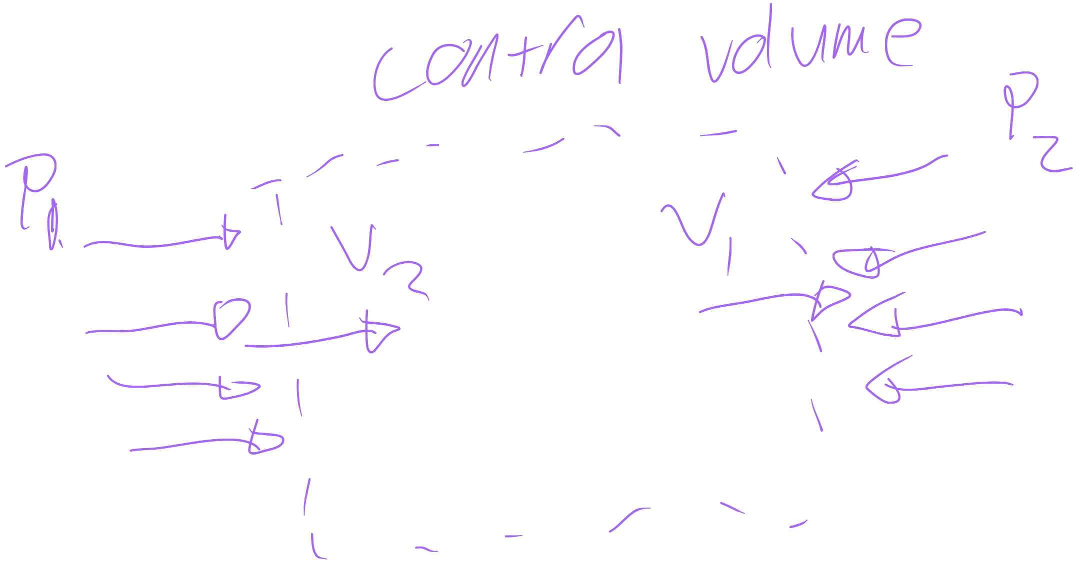
Lecture 2: Thrust, fuel consumption and range

Ivo Peters
i.r.peters@soton.ac.uk

THIS LECTURE

- Apply momentum conservation to rockets and gas turbines
- Investigate the significance of fuel flow in thrust
- Derive the Breguet range equation

MOMENTUM CONSERVATION



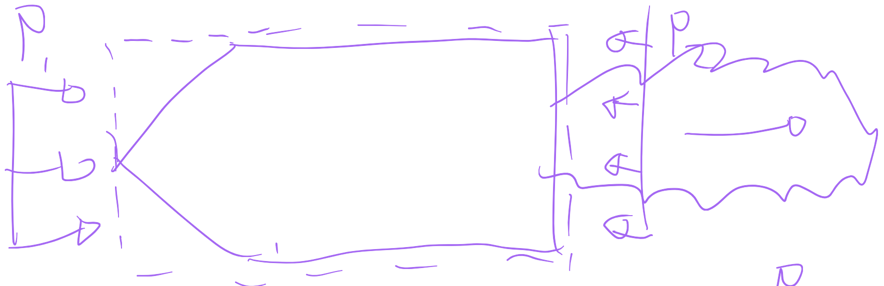
RECAP:
- Pressure acts normal to control volume
- Mass flow

All needed for momentum conservation

This is the starting point we'll use for most engine analysis

Rocket engine analysis

let $V_\infty = 0$ $\quad \xleftarrow{\;x\;}$



$\underbrace{P_2 = P_j}_{\text{jet}} \qquad \underbrace{P_1 = P_A}_{\text{atm}}$

note: rockets contain all prop
∴ no inflow mass

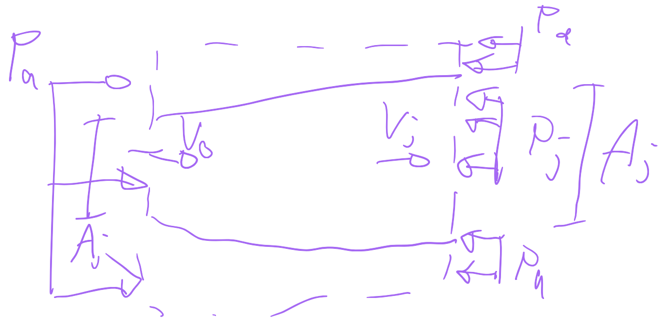
$$\dot{M}_{x\,out} - \cancel{\dot{M}_{x\,in}} = \sum F_x$$

thrust

$$T = \dot{m}_p V_j + A_j (P_j - P_A)$$

jet area

Jet engine



$V_{in} = V_0$

$V_{out} = V_j$

$\dot{m}_{in} = \dot{m}_a$ — mass air in

$m_{out} = \dot{m}_a + \dot{m}_f$ — fuel

$$M_{x\,out} - M_{x\,in} = \sum F_x$$

$$V_j(\dot{m}_a + \dot{m}_f) - V_0 \dot{m}_0 = \underbrace{A_j(P_A - P_j)}_{\text{pressure net force}} + T$$

new variable: fuel to air ratio: $f = \frac{\dot{m}_f}{\dot{m}_a}$

$$T = \dot{m}_a\left[(1+f)V_j - V_0\right]$$

often $f \ll 1$

BREGUET RANGE EQUATION

assumptions:

- steady flight ($L=W$, $\underbrace{F=D}$, $V_0=\text{const}$)

using F instead of T for thrust (cringe)

- fuel consumption: $\frac{dW}{dt} = \dot{m}_f g$
- Thrust specific fuel consumption $TSFC = \frac{\dot{m}_f}{F}$ $\rightarrow$ $\therefore \frac{dW}{dt} = -TSFC \times F \times g$

$W = L$
$= D\left(\frac{L}{D}\right)$
$= F\left(\frac{L}{D}\right)$ $\rightarrow$ $F = W\left(\frac{D}{L}\right)$

$\frac{dW}{dt} = -g\,TSFC\,W\left(\frac{D}{L}\right)$

$ds = V\,dt$

$\int \frac{1}{W}\,dW = \int -g\,TSFC\,W\left(\frac{D}{L}\right)dt$

assume constants

$\ln\left(\frac{W_2}{W_1}\right) = -g\,TSFC\,W\left(\frac{d}{L}\right)V \times s$

$s = \left(\frac{L}{D}\right)\frac{V}{g \times TSFC}\ln\left(\frac{W_1}{W_2}\right)$

use $W_1 = W_f + W_0$ $\quad W_2 = W_0$

$s_{max} = \left(\frac{L}{D}\right)\frac{V}{g\,TSFC}\ln\left(\frac{W_f + W_0}{W_0}\right)$

University of Southampton

777 RANGE

$\frac{W_1}{W_2} \approx 2$

$s_{max} = \left(\frac{L}{D}\right)_g \frac{V}{TSFC} \ln\left(\frac{W_f + W_o}{W_o}\right) = \ln\left(\frac{W_1}{W_2}\right)$

$TSFC = \frac{L}{D} \frac{V}{g s_{max}} \ln(2)$

- Empty mass: 145,150 kg
- Fuel capacity: 145,538 kg
- Cruise speed: 248 m/s
- Range: 15,843 km
- L/D: 25

Estimate the following:

- Mass flow rate of fuel
- Thrust-specific fuel consumption
- Thrust

$\dot{m}_f = 2.28\ \mathrm{kg/s}$

$TSFC = 2.77 \cdot 10^{-5}\ \mathrm{kg\ s^{-1} N^{-1}}$

$F = 82.2\ \mathrm{kN}$

SUMMARY

- Momentum conservation

$$\dot{M}_{x,out} - \dot{M}_{x,in} = \Sigma F_x$$

  - Rockets:

$$F = \dot{m}V_j + A_j(P_j - P_A)$$

  - Air-breathing propulsion systems:

$$F = \dot{m}_a\left[(1+f)V_j - V\right]$$

- Breguet range equation

$$s = -\frac{L}{D}\frac{V}{g_0 \times \mathrm{TSFC}}\ln\left(\frac{W_2}{W_1}\right)$$

SESA2023 Propulsion

Lecture 3: Efficiency, altitude tables

Ivo Peters
i.r.peters@soton.ac.uk

THIS LECTURE

- Define efficiency parameters for propulsion systems
  - Thermal efficiency
  - Propulsive efficiency
  - Overall efficiency

- How does efficiency concerns influence engine design?

- Usage of altitude tables + computational tool

EFFICIENCY

Heat

Thermal Efficiency

Jet Power

Propulsive Efficiency

Aircraft Power

Overall Efficiency

Overall efficiency

$$\underbrace{\eta_o}_{\text{overall}} = \underbrace{\eta_p}_{\text{Prop}} \times \underbrace{\eta_{th}}_{\text{Thermal}}$$

Propulsive efficiency

$$\eta_p = \frac{\dot{W}_{aircraft}}{\dot{W}_{jet}}$$

$\dot{W}_{aircraft} = F \times V_0$ } engine work by thrust

$\dot{W}_{jet} = (E_{k,out} - E_{k,in})\frac{d}{dt}$ KE equation

$= \frac{1}{2}(\dot{m}_a + \dot{m}_f)V_j^2 - \frac{1}{2}\dot{m}_a V_0$

using fuel ratio f

$= \frac{1}{2}\dot{m}_a\left((1+f)V_j^2 - V_0^2\right)$

~~KE~~ work of thruster

KE due to thruster

use $f \ll 1$

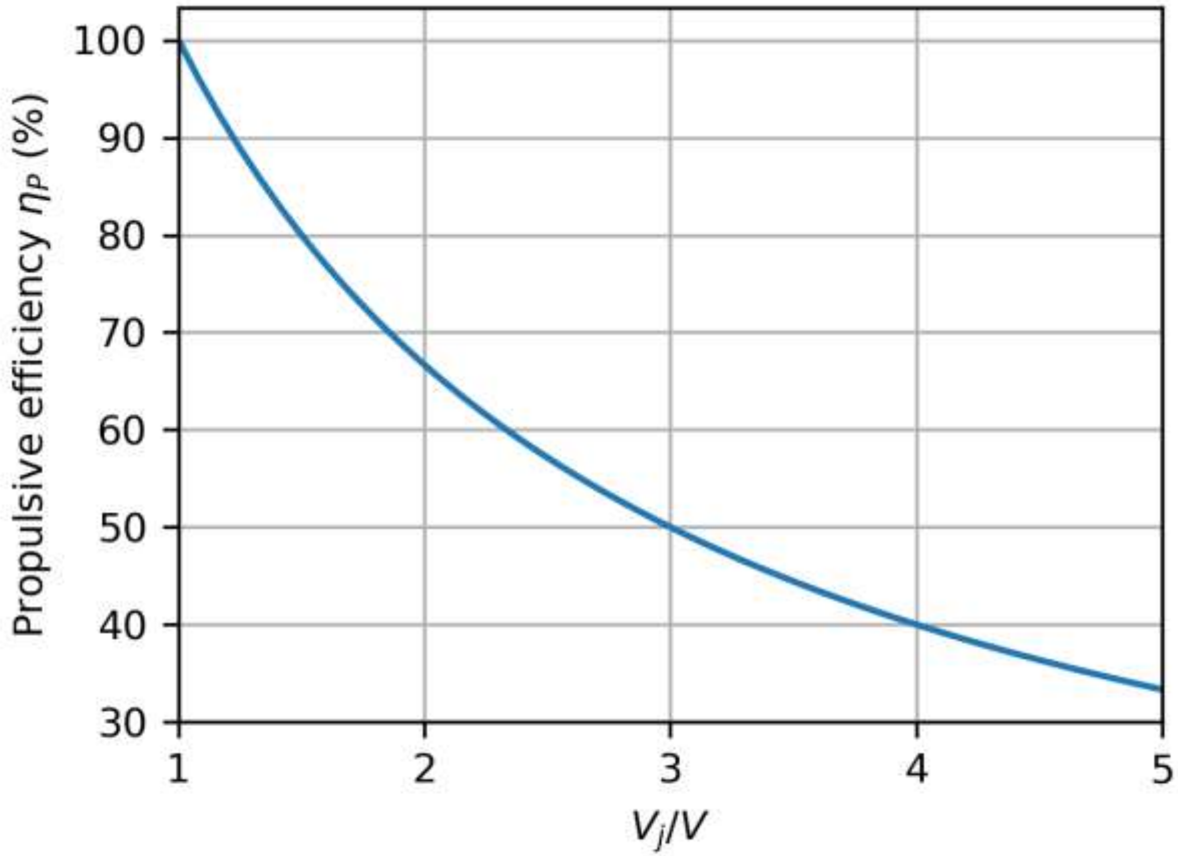
$$\eta_p = \frac{F \times V_0}{\frac{1}{2}\dot{m}_0\left[(1+f)V_j^2 - V_0^2\right]} = \dots = \frac{2V_0}{V_{jet} + V_0} = \frac{2}{\underbrace{\frac{V_j}{V_0}}_{} + 1}$$

reason why $V_j > V_0$ often, because of min thrust requirements

efficient engines have high mass flow rate

PROPULSIVE EFFICIENCY

PROPULSIVE EFFICIENCY

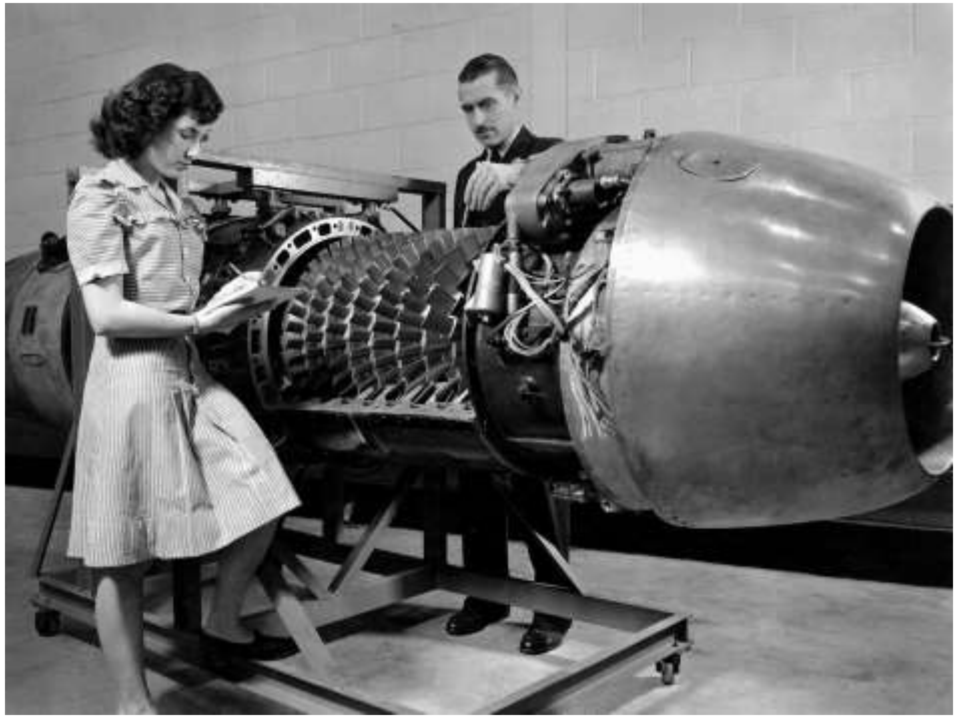


$$\eta_P = \frac{2}{\frac{V_j}{V} + 1}$$

$$F = \dot{m}_a (V_j - V)$$

PROPULSIVE EFFICIENCY: INCREASE MASS FLOW RATE

$$F = \dot{m}_a(V_j - V)$$



Junkers Jumo 004 (1940)

General Electric GE90 (1993-current)

THERMAL AND OVERALL EFFICIENCY

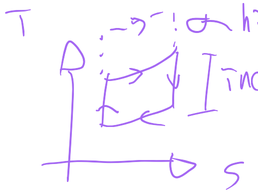
$\eta_{th} = \frac{W}{Q_{in}}$ effeciency of heat in → work useful

$= \frac{\dot{W}_{jet}}{\dot{Q}_{in}}$ $Q_{in} = \dot{m}_f \times LCV$ → energy from burning ~ 45 MJ/kg typical

$$\eta_{th} = \frac{\frac{1}{2}\dot{m}_a (V_j^2 - V_0^2)}{\dot{m}_f \times LCV}$$

combine $\eta_0 = \eta_{th} \times \eta_p$ → $\eta_0 = \frac{(V_j + V_0) V_0}{f \; LCV} = \underbrace{\frac{F}{\dot{m}_f}}_{\frac{1}{TSFC}} \frac{V_0}{LCV} = \frac{V_0}{TSFC \times LCV}$

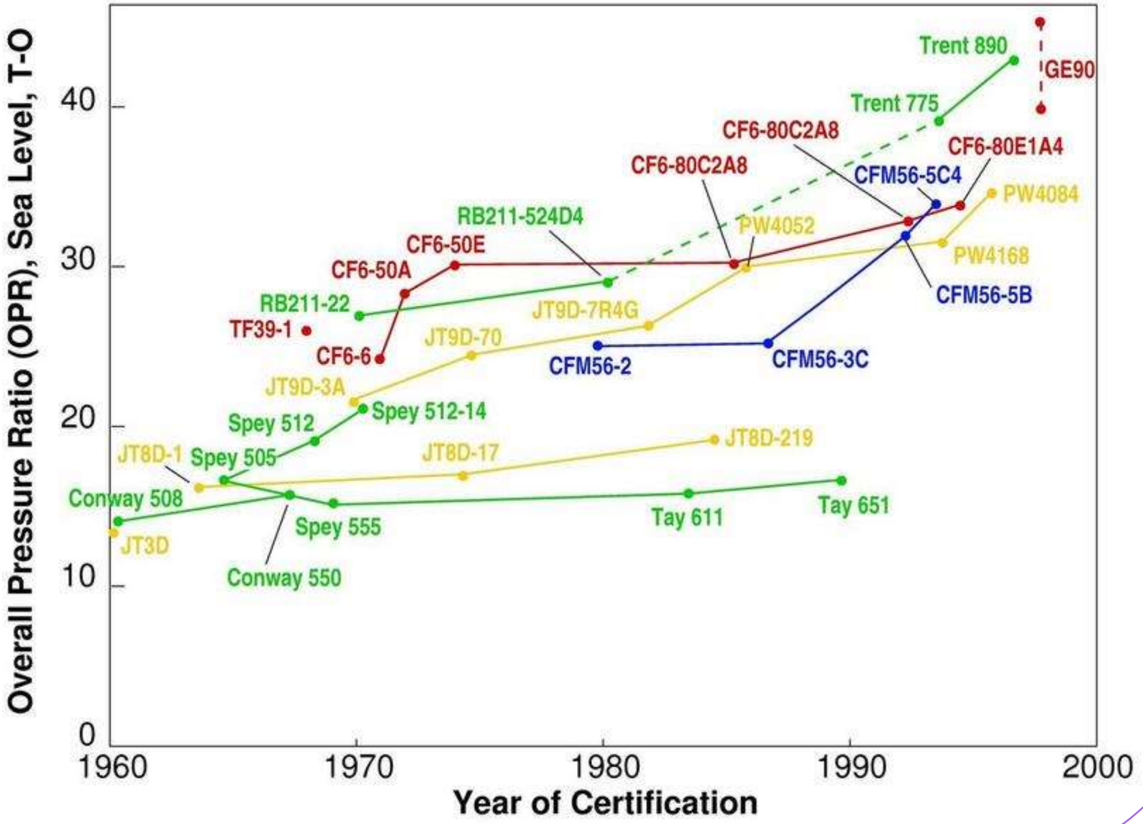
Breyton cycle (gas turbine engine)

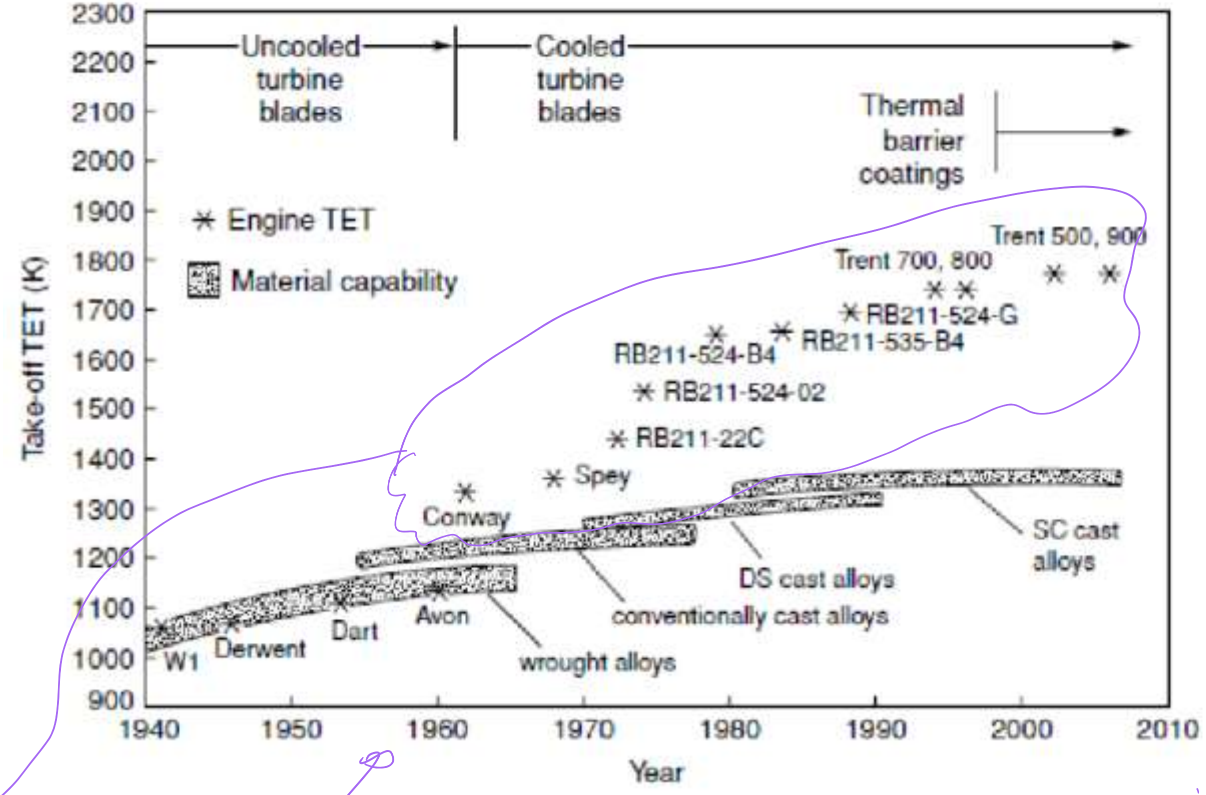


→ higher compression

Increase temp diff for better η_{th} by increasing compression ratio as seen in industry

THERMAL EFFICIENCY: PRESSURES AND TEMPERATURES





cooling blades
so they operate beyond exhaust temp

increase limited by material science

BOEING 777 EFFICIENCY

Cruise speed: 905 km/h
Unit cost: $259–315m

Engine - PW4098 $24 million
General characteristics

- Type: Two spool high bypass ratio Turbofan
- Length: 4.14 m Diameter: 2.8 m (fan)
- Compressor: 1 stage fan, 5 stage low pressure compressor, 15 stage (5 variable) high pressure compressor
- Combustors: Annular
- Turbine: 2 stage high pressure turbine, 5 stage low pressure turbine
- Overall pressure ratio: 32.0:1 – 35.4:1
- Bypass ratio: 5.3:1

Performance

- Air consumed: 1295 kg per second
- Lower calorific value of = 44.65 MJ/kg
- Aircraft velocity at cruise V = 251 m/s
- Jet velocity at cruise V_j = 299 m/s
- Fuel flow at cruise = 0.58kg/s

ALTITUDE TABLES

- Engine design for use at altitude
- Atmospheric conditions change (temperature & pressure)
- International Standard Atmosphere (ISA) provides a consistent approach

h, km	δ, P/P_{std}	Standard day θ, T/T_{std}	Cold day θ, T/T_{std}	Hot day θ, T/T_{std}	Tropical day θ, T/T_{std}	h, km
0	1.0000	1.0000	0.7708	1.0849	1.0594	0
0.25	0.9707	0.9944	0.7925	1.0788	1.0534	0.25
0.50	0.9421	0.9887	0.8142	1.0727	1.0473	0.50
0.75	0.9142	0.9831	0.8358	1.0666	1.0412	0.75
1.00	0.8870	0.9774	0.8575	1.0606	1.0352	1.00
1.25	0.8604	0.9718	0.8575	1.0545	1.0291	1.25

notable values

[a]Density: $\rho = \rho_{std}\ \sigma = \rho_{std}(\delta/\theta)$. Speed of sound: $a = a_{std}\sqrt{\theta}$.
Reference values: $P_{std} = 101{,}325\ \mathrm{N/m^2}$; $T_{std} = 288.15\ \mathrm{K}$; $\rho_{std} = 1.225\ \mathrm{kg/m^3}$; $a_{std} = 340.3\ \mathrm{m/s}$.

ISA: COMPUTATIONAL

- See pages after the altitude tables
- Implementation in Jupyter notebook on blackboard (additional material)

Comparison to table values at 15.0 km

In [13]:
```
h = 15000
delta = P(h)/P_0
theta = T(h)/T_0
print('delta = %0.4f' % delta)
print('theta = %0.4f' % theta)
```

```
delta = 0.1195
theta = 0.7519
```

SUMMARY

- Overall efficiency
  - Propulsive efficiency, engine design
  - Thermal efficiency, engine design
- International Standard Atmosphere
  - Tables and computational methods