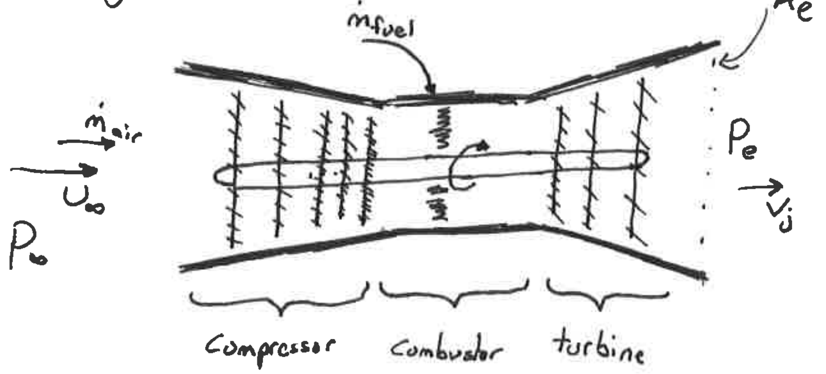
Lesson 7

Turbojet Engines
+
Turbofan Engines
+
Turboprop Engines

Turbojet



Details of how to design and determine the operational characteristics are left to a propulsion class AEM 408

Thrust

$$T = \underbrace{\dot{m}_{air}(V_j - V_\infty)}_{\text{momentum as seen in ideal thrust actuator}} + \underbrace{\dot{m}_{fuel} V_j}_{\text{fuel addition}} + \underbrace{(P_e - P_\infty) A_e}_{\text{pressure forces at exit}}$$

or as in the book

$$T = \underbrace{(\dot{m}_{air} + \dot{m}_{fuel}) V_j}_{\text{exiting momentum}} - \underbrace{\dot{m}_{air} V_\infty}_{\text{entering momentum}} + \underbrace{(P_e - P_\infty) A_e}_{\text{pressures}}$$

Fuel Consumption

$$\underbrace{\text{Thrust Specific Fuel Consumption}}_{TSFC \neq C_t} \equiv C_t \equiv \frac{\text{Weight fuel per time}}{\text{thrust}}$$

units $= \left[\frac{1}{s}\right]$

TSFC has units $\left[\frac{1}{hr}\right]$

$$TSFC = 3600\, C_t$$

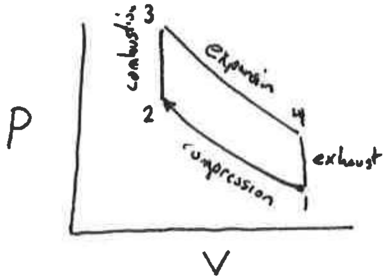
Ex: A jet engine develops 20000 lbf of thrust for 40 minutes while burning 7000 lbf of fuel. What is the TSFC?

$$TSFC = \frac{\#}{T \cdot t} = \frac{7000\,\text{lbf}}{20000\,\text{lbf}} \cdot \frac{1}{40\,\text{min}} \cdot \frac{60\,\text{min}}{\text{hr}} = 0.525$$

(very low for a turbojet)

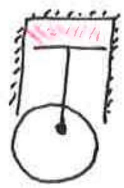
Thermodynamics of piston vs Turbine ~~g~~ engines.

Piston:



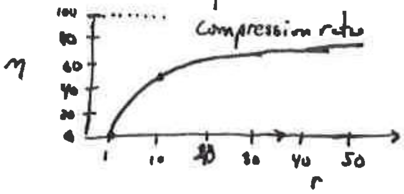
This is an Otto cycle

Notice that combustion is almost a constant volume process



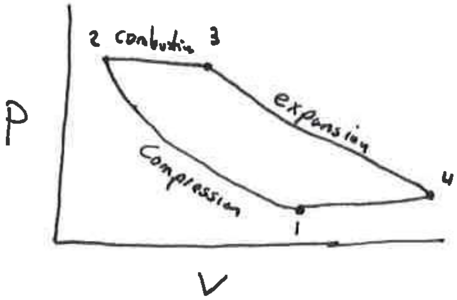
$$\eta \approx 1 - r^{-(\gamma-1)}$$

$\uparrow$ compression ratio



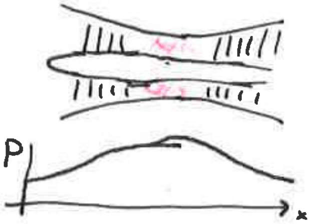
Highest efficiency at high compression ratios ... this is why aircraft use high octane fuels.

Turbine



This is a Brayton cycle

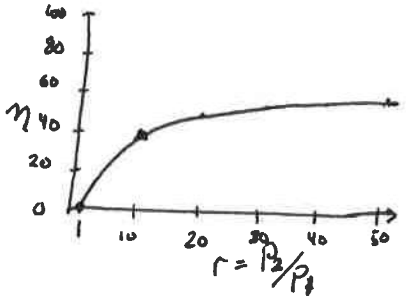
Combustion is a constant pressure process



$$\eta \approx 1 - \frac{T_1}{T_2} = 1 - \left(\frac{P_1}{P_2}\right)^{\frac{\gamma-1}{\gamma}}$$

$\gamma_{air} \approx 1.4$

$\gamma_{air} \approx 1.3$



Highest η at largest r.

High r requires many stages in the compressor and a strong case.

Also, the Brayton cycle is always less efficient given the same pressure ratio comparing to an Otto cycle engine.

Variation of Thrust and TSFC with flight conditions

- Thrust relatively constant wrt V_∞
- Thrust ratio proportional to density ratio

$$\frac{T}{T_0} = \frac{\rho}{\rho_0}$$

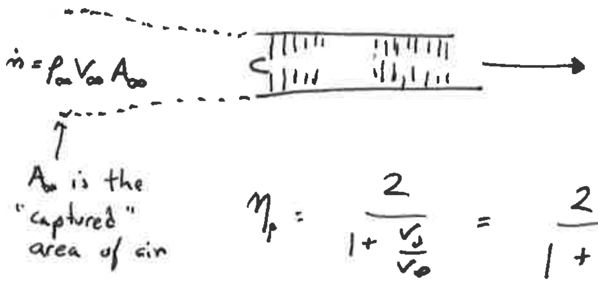
- TSFC relatively constant wrt altitude.
- TSFC relatively constant wrt Mach number

Turbofan

The efficieny of a thrust system is $\eta = \dfrac{2}{1 + \frac{V_J}{V_\infty}}$

The thrust of turbine is approximately $T \approx \dot{m}_{air}(V_J - V_\infty)$

What is the efficieny problem with a turbojet?



$$\longrightarrow V_j = \frac{T}{\dot{m}} + V_\infty$$

$$\eta_p = \frac{2}{1+\frac{V_J}{V_\infty}} = \frac{2}{1 + \frac{T}{\dot{m}V_\infty} + \cancel{\frac{V_\infty}{V_\infty}}^{1}} = \frac{2}{2 + \frac{T}{\dot{m}V_\infty}}$$

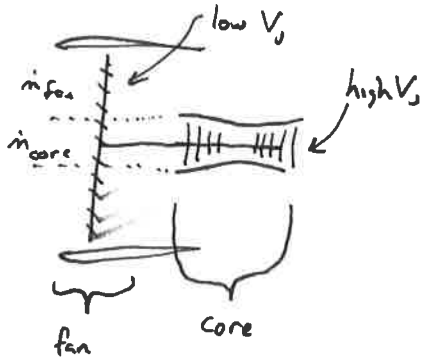
$$= \frac{2}{2 + \frac{T}{\rho V_\infty A_\infty V_\infty}} = \frac{2}{2 + \frac{\frac{1}{2}T}{\frac{1}{2}\rho V^2 A}} = \frac{1}{1 + 4C_T}$$

where C_T is a thrust per dynamic pressure and area.

- When the thrust is high, η is low.
- <u>All</u> of the air is combusted. (passing through the combustion section is lossy)

Solution:

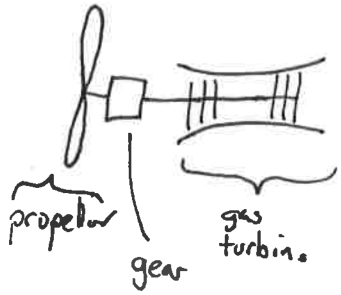
Low V_J portion of flow path driven by core



Bypass ratio $\equiv \dfrac{\dot{m}_{fan}}{\dot{m}_{core}}$

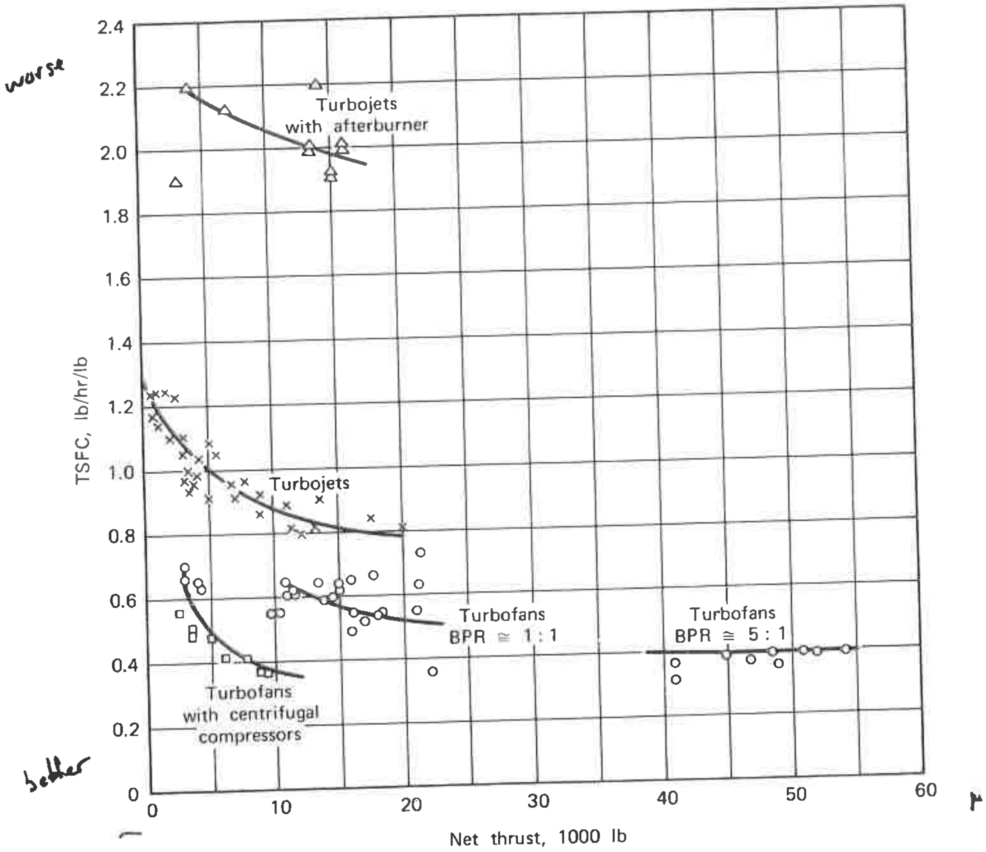
Since V_J is on average lower, η is higher

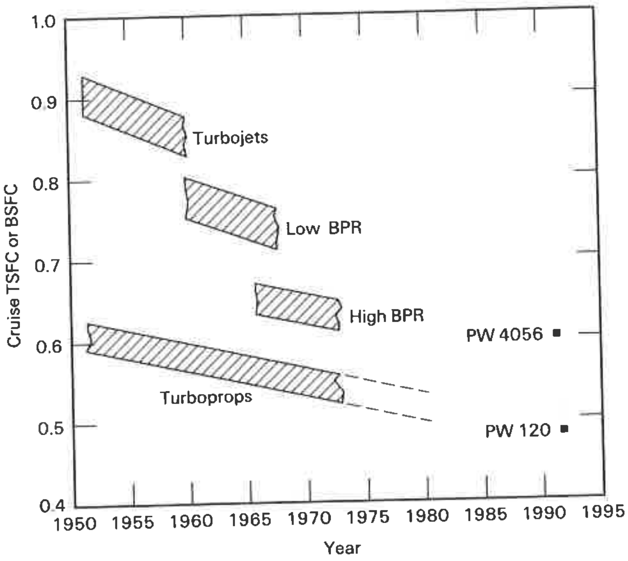
Turbo prop



High power of turbine engine combined with high efficiency at lower speeds (b/c propellor)

Higher specific fuel consumption than piston engine, but ~~[illegible]~~ higher shaft power is available





Aircraft Propulsion

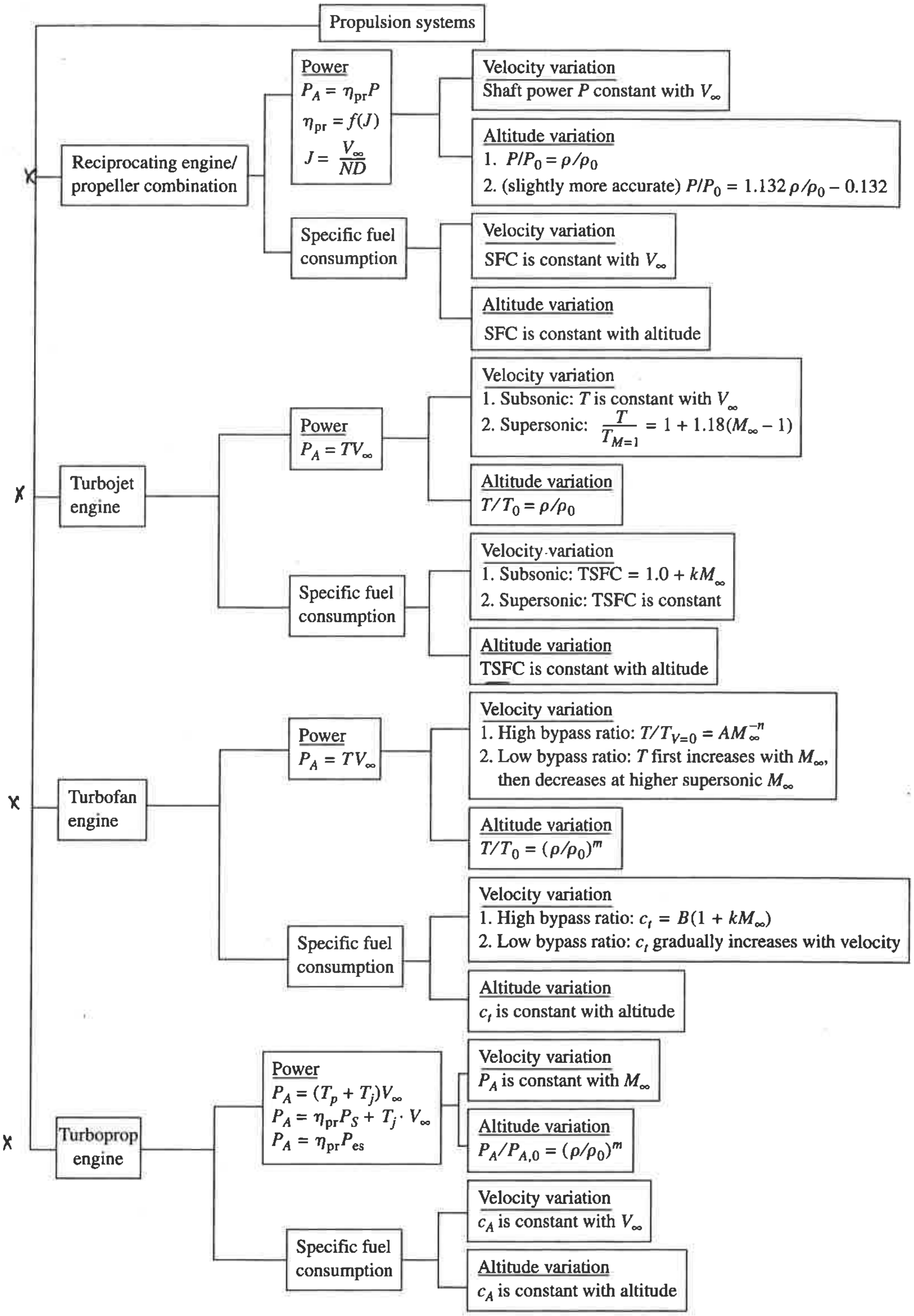


Figure 3.29 Block diagram summary.

Source: APD, Anderson

Problem 3.1

$T = 10000\ \text{lbf}$ @ SSL $\qquad A \approx 3.19\ \text{ft}^2 \qquad V_\infty = 1000\ \text{ft/s}$

a) Estimate V_J.

$$T = \dot m (V_J - V_\infty) \quad \Rightarrow \quad V_J = \frac{T}{\dot m} + V_\infty$$

$$\dot m = \rho V A = \frac{0.00237\ \text{slug}}{\cancel{\text{ft}^3}}\Bigg|\frac{1000\ \cancel{\text{ft}}}{\text{s}}\Bigg|\frac{3.19\ \cancel{\text{ft}^2}}{} = 7.56\ \frac{\text{slug}}{\text{s}}$$

$$V_J = \frac{10000\ \cancel{\text{lbf}}}{7.56\ \cancel{\text{slug}}}\Bigg|\frac{\cancel{\text{s}}}{}\Bigg|\frac{\cancel{\text{slug}}\ \text{ft}}{\cancel{\text{lbf}}\ \cancel{\text{s}^2}\ \text{s}} + 1000\ \frac{\text{ft}}{\text{s}}$$

$$\boxed{V_J = 2322\ \text{ft/s}}$$

b) Estimate η_p

$$\eta_p \approx \frac{2}{1 + \frac{V_J}{V_\infty}} = \frac{2}{1 + \frac{2322\ \text{ft/s}}{1000\ \text{ft/s}}} = 0.60$$

$$\boxed{\eta_p \approx 0.60}$$

Problem 3.2

Two 285^{hp} engines @ 2700 rpm. Prop diameter is 6.27^{ft} and are variable pitch

The aircraft top speed is 238 mph @ SSL.

Estimate the power available. (using Fig 3.7)

$$\eta_p \approx 0.87$$

$$P_A \approx 0.87 \cdot 2 \cdot 285^{hp} \approx 495^{hp}$$