Case for a bypass engine (page 70):

To make efficient use of the high work output from the core:

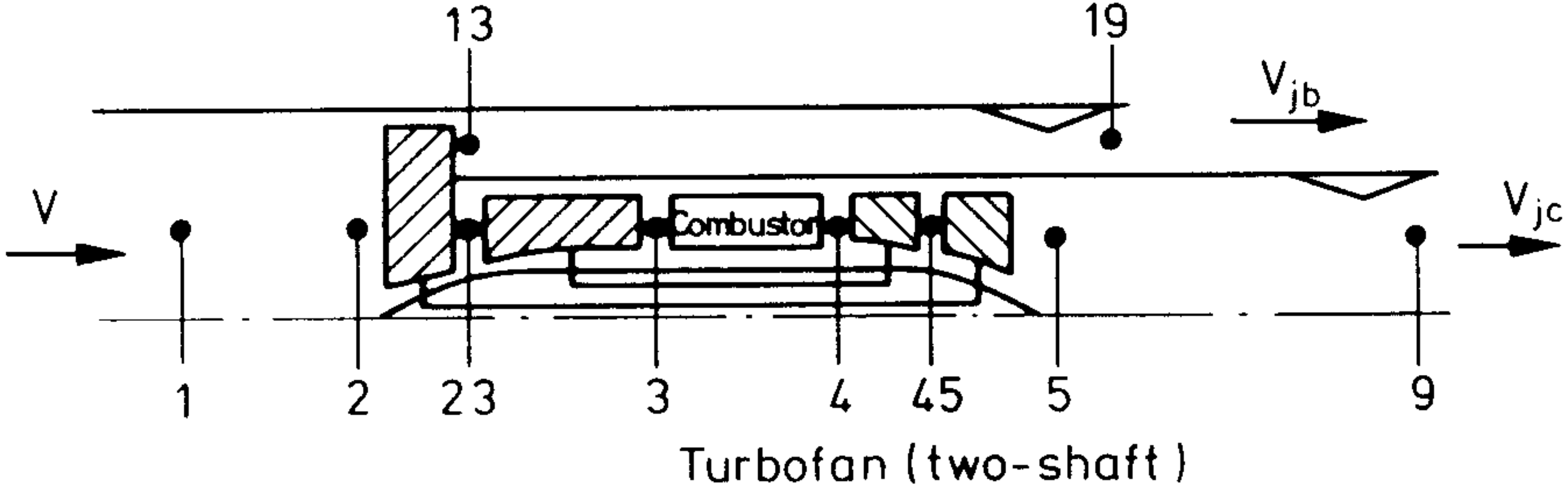
Expand core flow through a low-pressure turbine (LPT).

Use low-pressure turbine to drive a fan (fan pressure ratio $\approx$ 1.6).

Fan produces a low bypass jet velocity (eg 400 m/s) which is only a little higher than the flight speed of 256 m/s.

This gives a better match of the aeroengine to the aircraft and yields a higher propulsive efficiency.

Standard numbering system for locations within a bypass engine (page 70):



Turbofan (two-shaft)

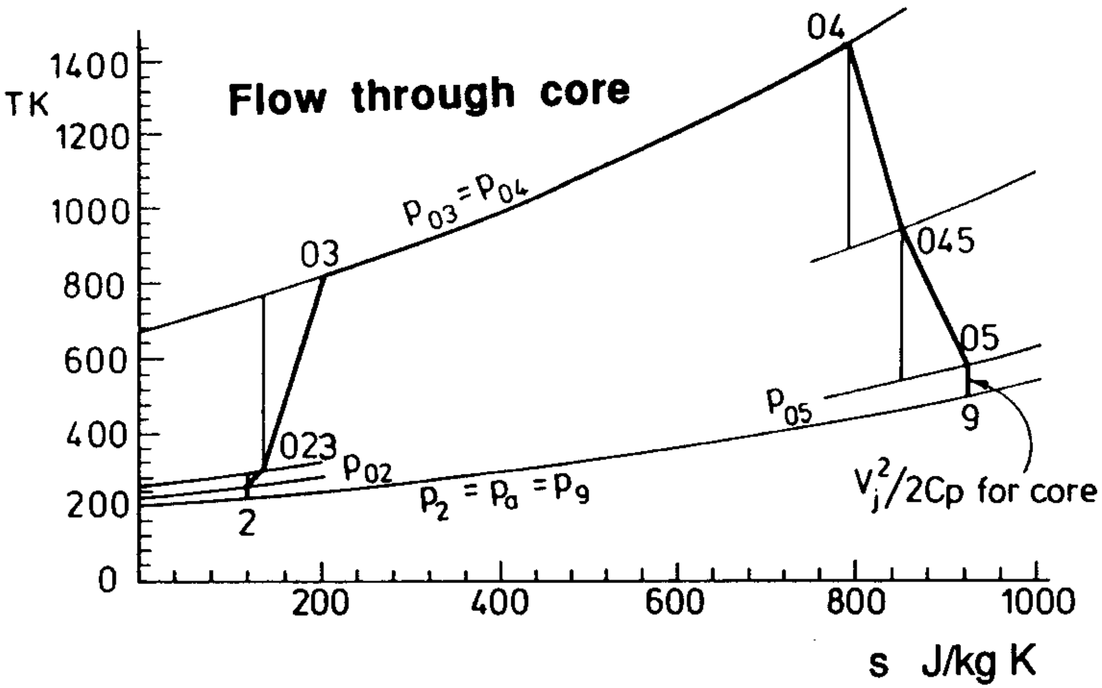
Note that the key locations have the same numbers as for the single-shaft turbojet.

We will assume that the core and bypass jet velocities are equal.

Thermodynamic cycle for core flow (page 71):

Since the core flow now passes through the inner portion of the fan before entering the core compressor, the overall pressure ratio of 40 is split between the two.

For this example:



Fan-core pressure ratio = 1.25

Core compressor ratio = 32.0

Overall pressure ratio = 40.0

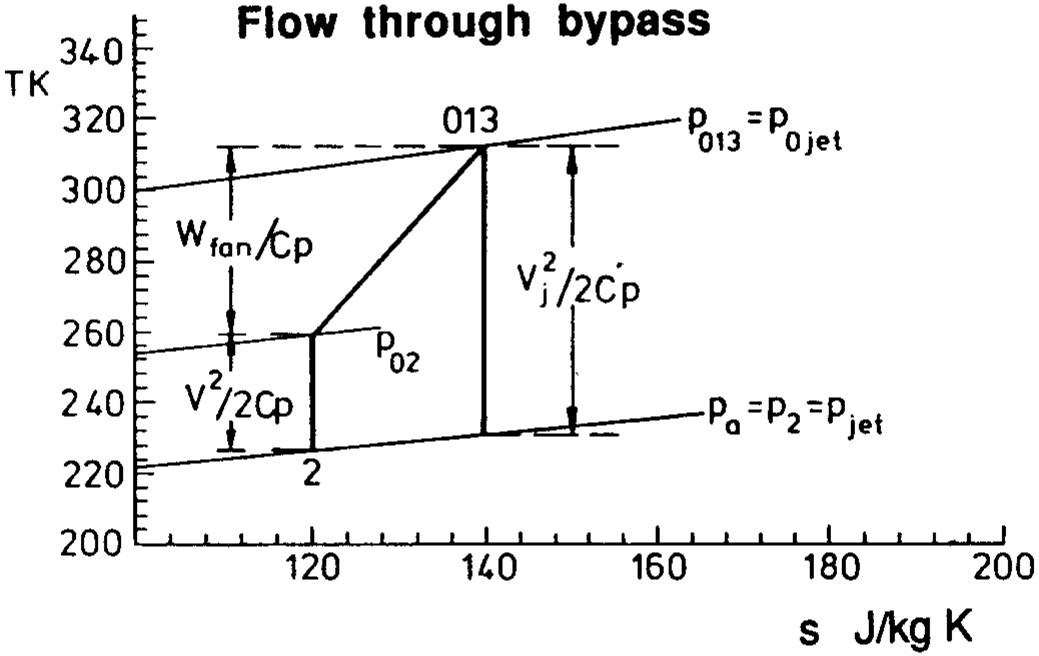
Note: Exercises differ.

Thermodynamic cycle for bypass flow (page 71):

The pressure ratio for the fan-bypass flow depends on the bypass jet velocity required. This in turn depends upon the bypass ratio and the low-pressure turbine work.

If the fan were isentropic:

$$T_{013isen} - T_{02} = \frac{V_j^2 - V^2}{2C_p}$$



Define fan efficiency:

$$T_{013} - T_{02} = \frac{V_j^2 - V^2}{2C_p\eta_{fan}}$$

(Not quite an isentropic efficiency)

Solution method for bypass ratio and jet velocity (page 72):

Given temperature T_{045} and pressure p_{045} at exit from core (Ex 5.1: 946 K, 333 kPa)

1) Guess drop in T_0 across low-pressure turbine, hence calculate LPT work

$$\dot{W}_{LPT} = \dot{m}_c C_p \Delta T_{0LPT} = \dot{m}_c C_p (T_{045} - T_{05})$$

2) Given low-pressure turbine efficiency and know T_{05}/T_{045} calculate p_{05}/p_{045}

3) Knowing T_{05} and p_{05} in the core jet pipe find the core jet velocity

$$V_{jc} = \sqrt{2C_p T_{05}\left(1 - \left(p_9/p_{05}\right)^{(\gamma-1)/\gamma}\right)}$$

(Again assuming isentropic expansion: would require con-di nozzle.)

4) Assume bypass jet velocity is the same as the core jet velocity

$$V_{jb} = V_{jc}$$

5) Calculate the required fan-bypass work input

$$C_p(T_{013} - T_{02}) = (V_{jb}^2 - V^2)/2\eta_{fan}$$

6) For the low-pressure shaft calculate the energy balance

$$\text{LPT work} = \text{fan-bypass work} + \text{fan-core work}$$

$$\dot{m}_c C_p(T_{045} - T_{05}) = \dot{m}_b C_p(T_{013} - T_{02}) + \dot{m}_c C_p(T_{023} - T_{02})$$

7) Solve for the bypass ratio.

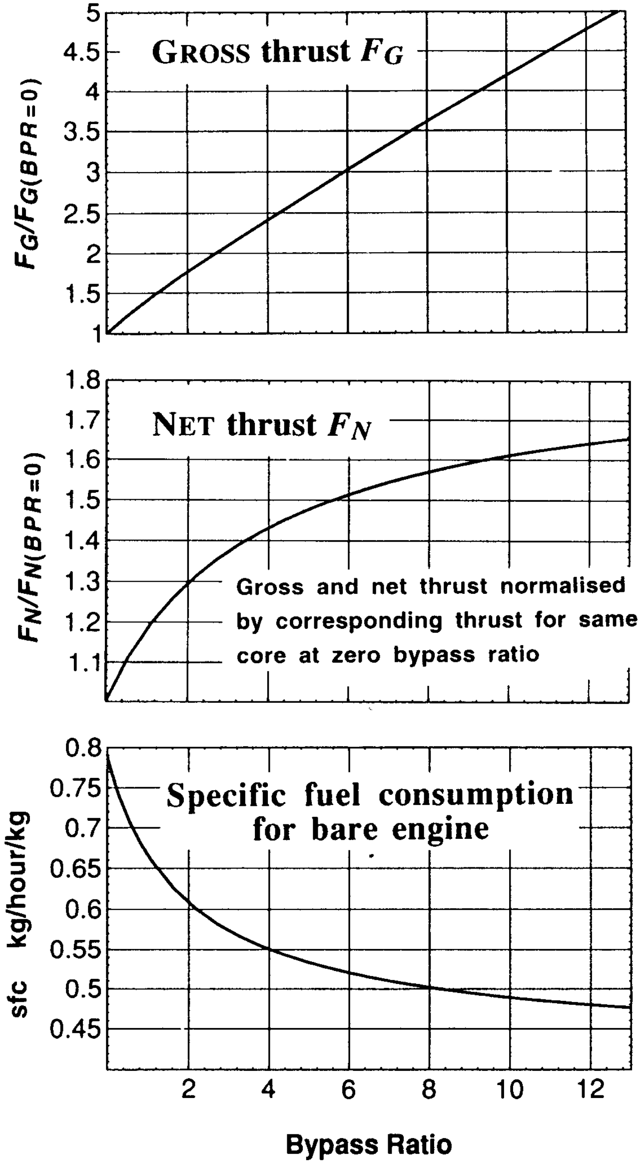
$$\text{BPR} = \dot{m}_b/\dot{m}_c$$

May then calculate all other variables (sfc, propulsive efficiency etc.).

Variation of thrust and sfc with bypass ratio (page 74)

As the bypass ratio is increased the gross thrust rises almost linearly but the net thrust (which is the more important) rises more slowly for high bypass ratio engines.

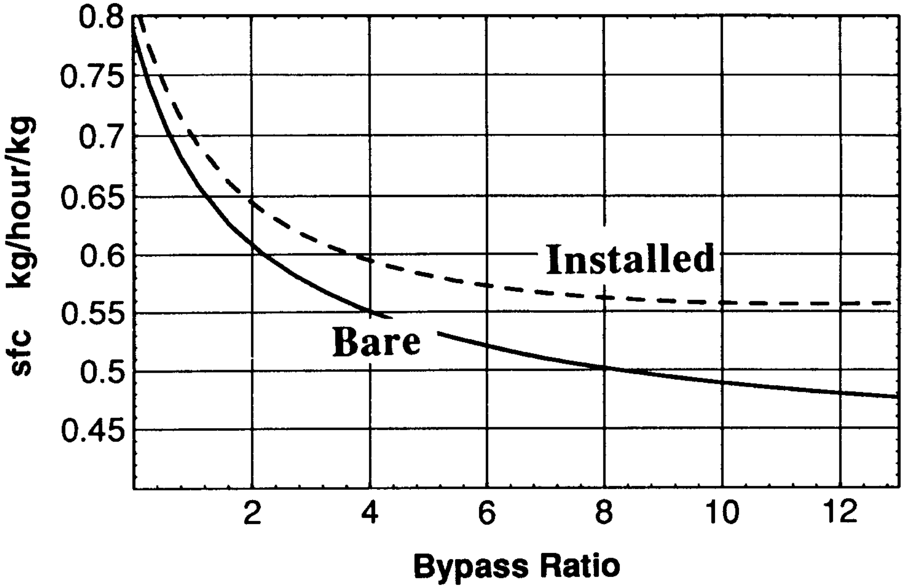
Correspondingly, there is a diminishing reduction in the sfc.



As expected, as the bypass ratio is increased the sfc decreases (page 76):

However, as the bypass ratio is increased the engine becomes larger and the drag on the nacelle increases.

The increased drag causes the sfc to be higher than anticipated.



Fan Diameter and Number of Engines (Extended material):

Using the earlier ideas it is possible to “optimise” the number of engines and the diameter of the fan for a given cruising condition.

$$\text{Drag} = \text{Net Thrust} = F_N$$

$$\text{Drag}_{\text{airframe}} + \text{Drag}_{\text{engines}} = \dot{m}_a (V_j - V)$$

For podded (mounted in a nacelle) engines, drag scales according to:

$$\text{Drag}_{\text{engines}} \propto \pi D_{\text{fan}} \times l_{\text{engine}} \times n_{\text{engine}} = \pi \left(D_{\text{fan}} \sqrt{n_{\text{engine}}} \right)^2 \times \left(l_{\text{engine}} \big/ D_{\text{fan}} \right)$$

Hence for a given fan diameter (D_{fan}), the required jet velocity can be estimated.

(Actually more convenient to use “effective fan diameter” = $D_{\text{fan}} \sqrt{n_{\text{engine}}}$)

Fuel burn estimation (Extended material):

Propulsive efficiency: $\eta_p = \dfrac{2V}{V_j + V}$

Overall efficiency:

$$\eta_p \times \eta_{th} = \frac{\text{power to aircraft}}{\Delta KE} \times \frac{\Delta KE}{\text{fuel heat release}} = \frac{\text{power to aircraft}}{\text{fuel heat release}} = \eta_o$$

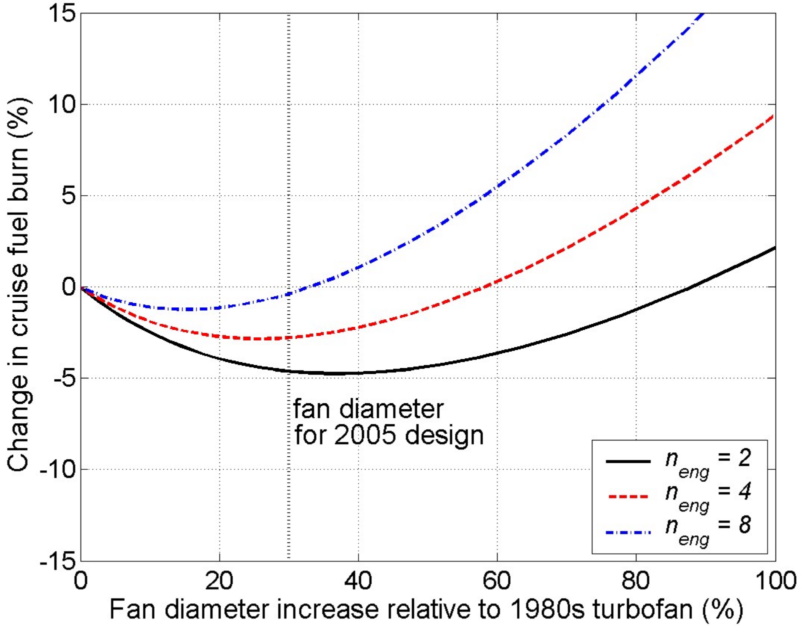
This can be expanded into:

$$\eta_p \times \eta_{th} = \frac{\text{Thrust} \times \text{speed}}{\dot{m}_f \, LCV} = \frac{F_N \, V}{\dot{m}_f \, LCV}$$

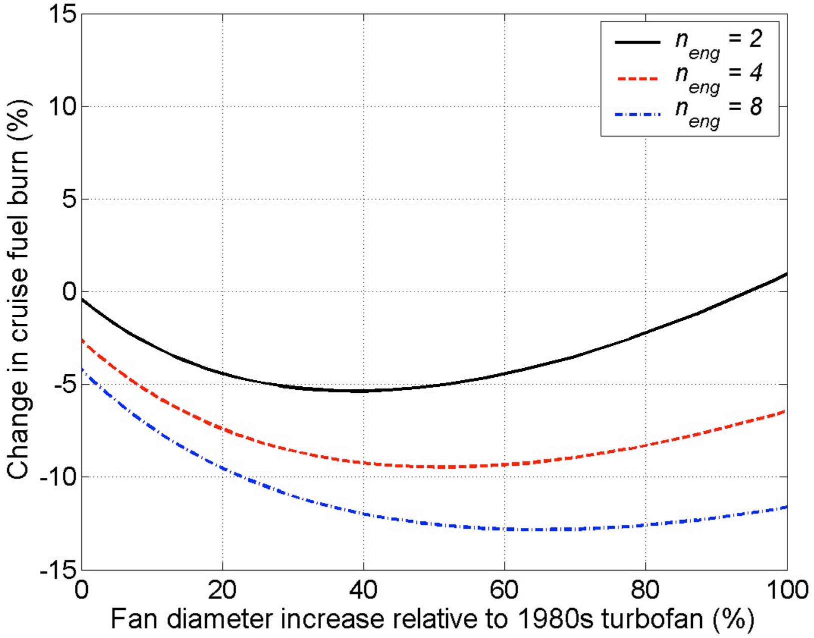
Rearranging yields:

Fuel burn: $\dot{m}_f = \dfrac{F_N \, V}{\eta_p \, \eta_{th} \, LCV}$

Fuel burn study (Extended material):



Podded (engine in nacelle).



Embedded (engines in aircraft body).

Small number of podded engines or large number of engines within the airframe.

(Information from Silent Aircraft Initiative, Cambridge-MIT research project.)