8 DESIGN OF TURBOFAN ENGINES (WEEK 8)

8.1 OBJECTIVES

After studying this Section you will be able to:

- explain how high-bypass ratio and high turbine entry temperature technologies contribute to increasing overall efficiency.
- optimise the specification of a turbofan engine on the basis of the fan pressure ratio.
- explain the ways in which fan pressure ratio affects the effective net thrust of an engine.

8.2 ENGINE ARCHITECTURE

8.2.1 Turbojet Engine

Figure 1 shows the Rolls-Royce Viper engine, which is a pure turbo-jet engine. The turbo-jet structure is relatively lightweight and low-cost, and this Viper was used as an expendable power source for target drones, among other applications.

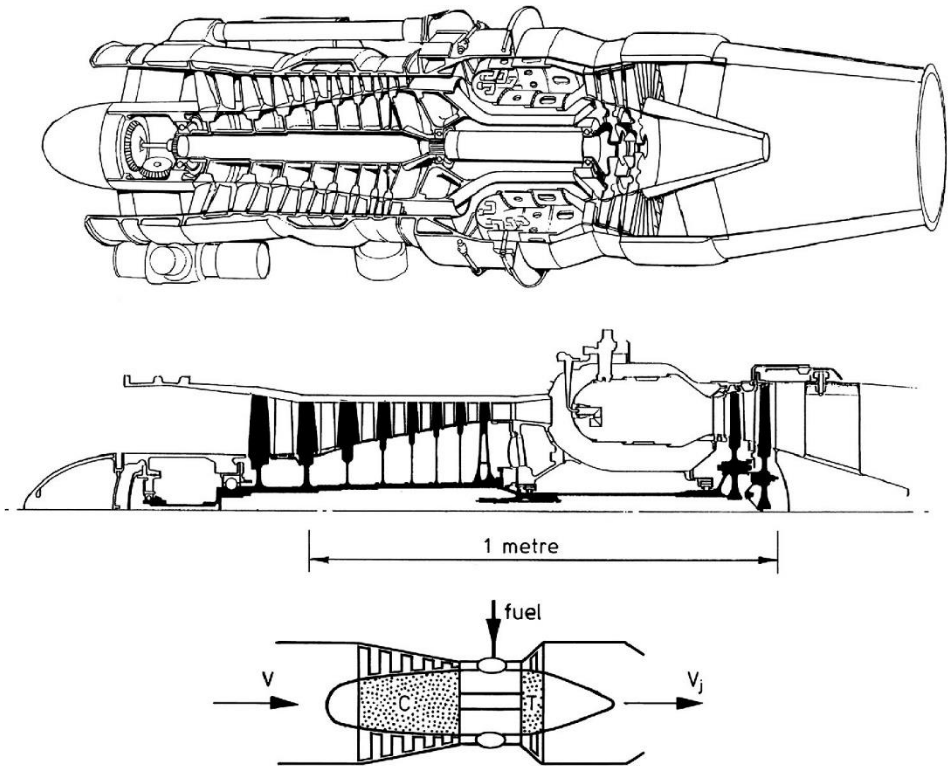


Figure 1. The Rolls-Royce Viper Mark 601 single-shaft turbojet shown as a cut-away, in simplified cross-section and as a schematic.

The turbojet configuration yields a high jet velocity, making it suitable for propulsion of supersonic craft. Four Rolls-Royce Olympus 593 turbojet engines, shown in Figure 2were used to power Concorde at around twice the speed of sound. The Olympus is a two-spool engine, with the shaft bearing the high-pressure compressor and turbine rotating more rapidly than the inner concentric shaft bearing the low-pressure compressor and turbine. The two-spool design facilitates operation at speeds below the design speed, including starting.

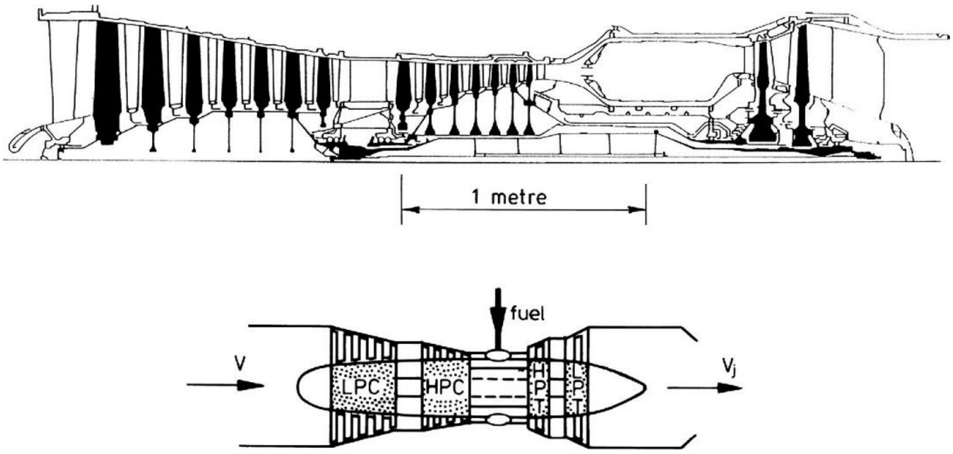


Figure 2. The Rolls-Royce Olympus 593 shown as a simplified cross-section and as a schematic.

8.2.2 The Turbofan Engine

The turbofan engine has been developed in order to improve the propulsive efficiency by increasing the mass flow rate of air through the engine. Figure 3 shows the Pratt & Whitney JT8D-1 turbofan engine that powered the Boeing 727 and 737 aircraft, with bypass ratios between 0.3 and 1.5.

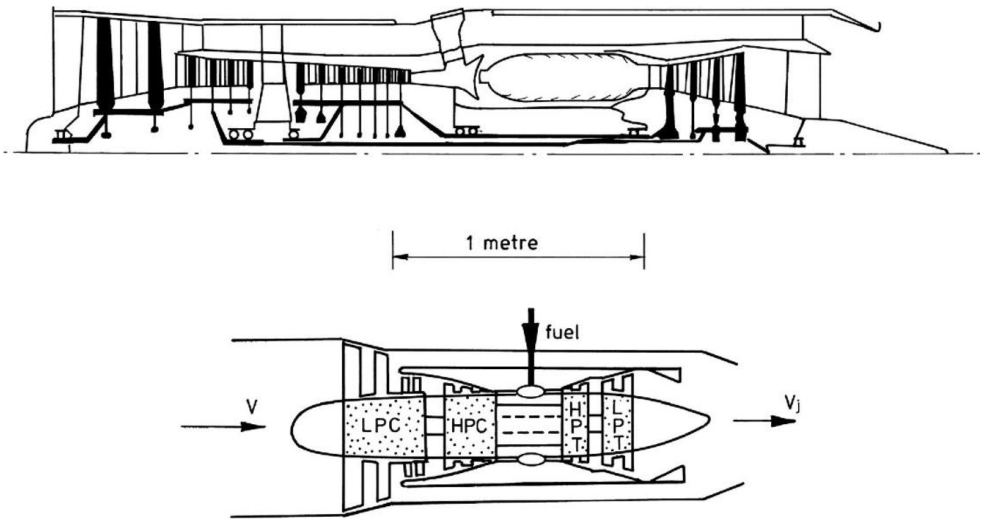
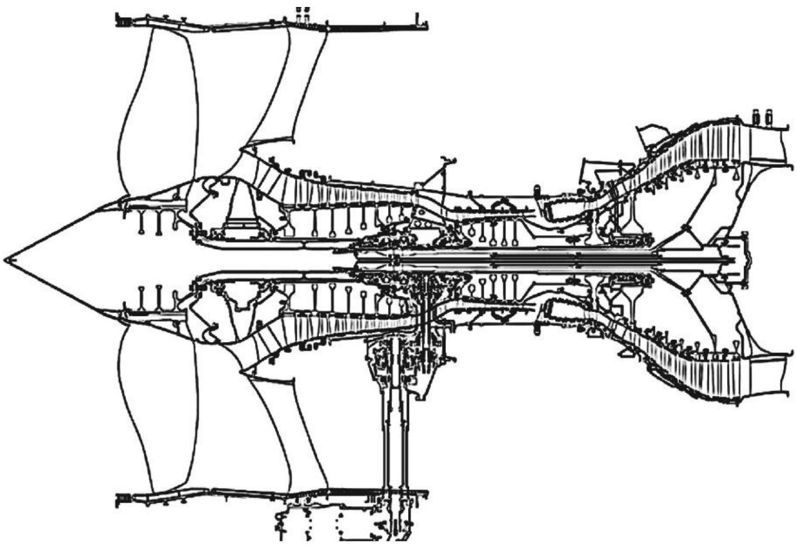


Figure 3. The Pratt & Whitney JT8D-1 shown as a simplified cross-section and as a schematic

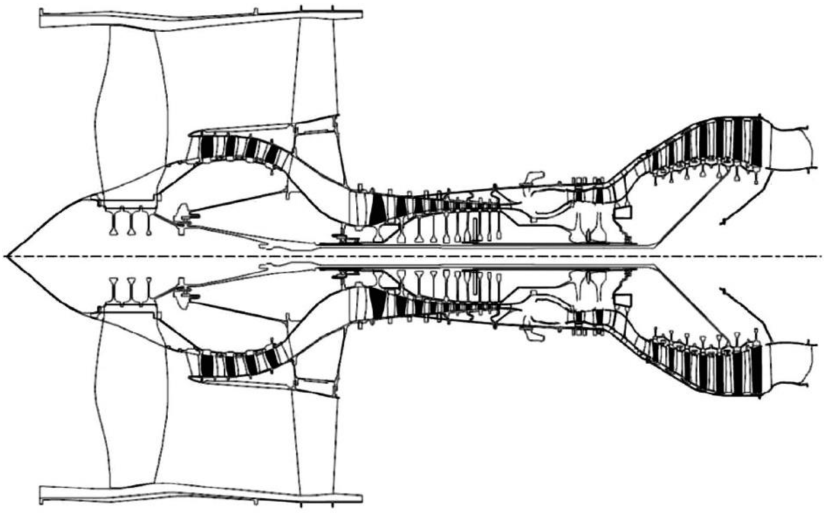
8.2.3 The High-Bypass Ratio Engine

The bypass ratio for modern airliners usually exceeds five. Three examples of high bypass ratio engines are shown in Figure 4. The Rolls-Royce Trent 1000 and GEnx engines each have a bypass ratio of around 9.5, giving both high propulsive efficiency, and relatively low jet noise (since jet noise scales with jet velocity to the power of eight). The smaller Pratt & Whitney GT1524 in Figure 4c is used on the Bombardier C-series, and achieves a bypass ratio of 12. The GT1524 employs a gearbox between the low pressure (LP) turbine and the fan, allowing a smaller and higher-speed LP turbine to be adopted. Due to the high power transmitted through the LP shaft and the difficulty removing heat generated by the friction in the gears, the transmission efficiency is critical.

The GEnx and GT1524 engines each employ two spools with a *booster*, which is a number of compressor stages on the LP shaft after the fan. Rolls-Royce is the only western engine manufacturer marketing three-spool engines, with the objective of achieving better off-design performance (including starting) and a better optimised engine structure, but at the substantial cost of added mechanical complexity. The overall pressure ratio in all three engines is approximately 45. The GEnx and GT1524 achieve this with a pressure ratio of around 2.5 across the fan and booster, and around 20 across the HP compressor. The Trent 1000 employs a pressure ratio of around 1.5 across the fan near the hub, around 7 in the intermediate pressure (IP) compressor, and a little over 4 in the HP compressor.



(a)



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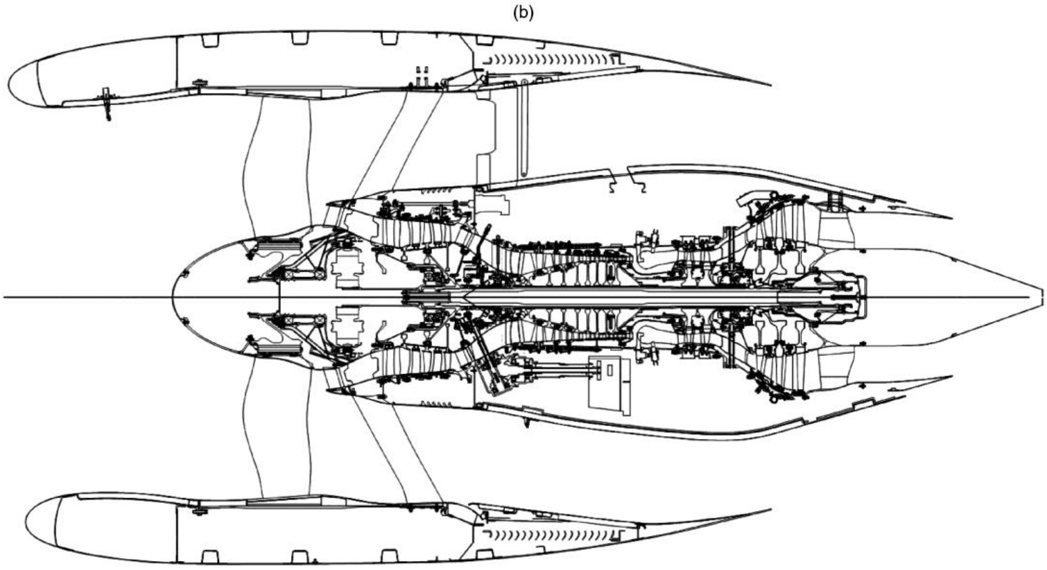


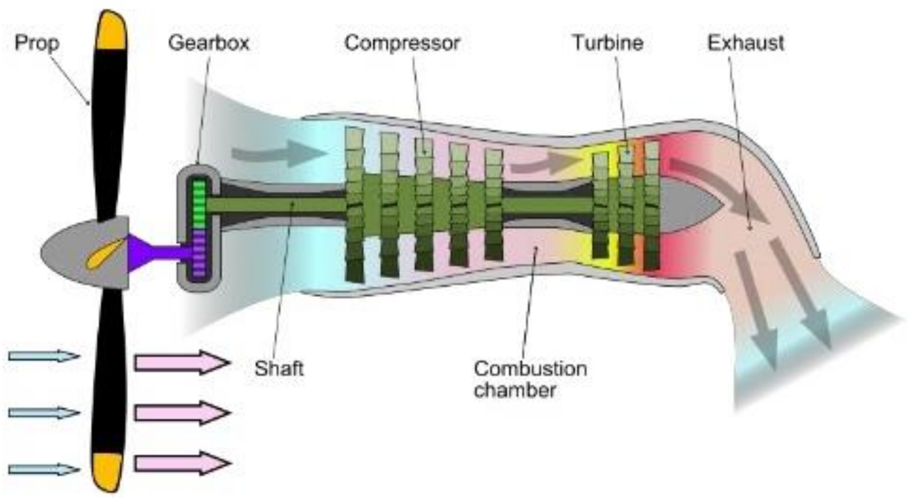
(c)

Figure 4. (a) Rolls-Royce Trent 1000 (fan tip diameter 2.84 m). (b) The General Electric GEnx (fan tip diameter 2.82 m). (c) The Pratt \& Whitney GT 1524 with gear box between LP turbine and fan. This engine shown with nacelle.

8.2.4 The Turboprop engine

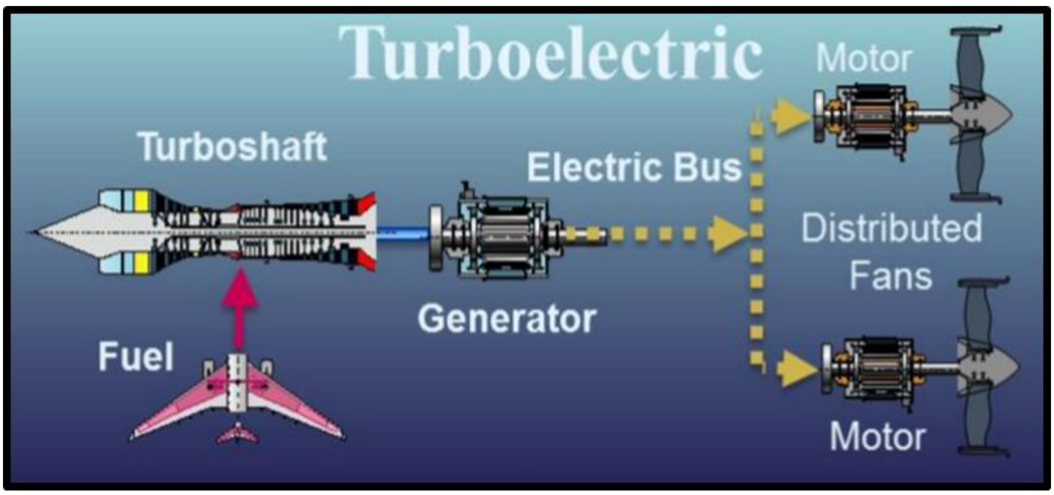
A turboprop consists of a propeller powered by a gas turbine core. The majority of the thrust is produced by the propeller, with a small contribution from the gas turbine exhaust. The propeller may be driven by the shaft from the low-pressure spool or by a separate free-power turbine shaft. In either case a gearbox is used to allow the turbine to turn faster than the propeller. The effective bypass ratio can be extremely large, giving very high propulsive efficiency in low Mach flight.

External propellers are limited to moderate Mach number flight by wave drag and noise generated by excessive propeller tip speeds.



8.2.5 Turboelectric propulsion

The turboelectric concept uses gas turbines to drive electric generators, transmits the electricity to separate electric motors, and the electric motors drive propulsion fans. The use of electric transmission allows the turbine and fan speeds to vary independently, and allows a free choice of the number, size, rotational speed and location of propulsion fans.



A particular advantage of electric fans is that they may be located where they ingest and then accelerate the slow-moving fluid from the fuselage or wing boundary layers, reducing the ram drag on the fans, and further increasing propulsive efficiency. This *boundary layer-ingestion concept is illustrated in*

Figure 5. A turboelectric propulsion concept that uses an electric fan at the tail that ingests the boundary layer from the fuselage. The electric fan is powered by generators driven by two under-wing turbofan engines (credit NASA).

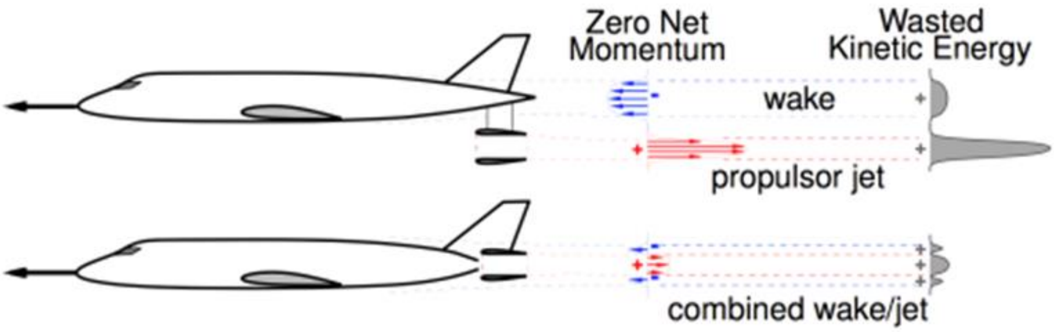


Figure 6. Wasted kinetic energy (top) is reduced by the *boundary layer-ingestion* concept (bottom), which accelerates the slow-moving boundary layer fluid to provide he required net thrust[1].

However there is a trade-off between the improved propulsive efficiency and increased fuel consumption due to additional weight of the electric generators, transmission and motors. The potential benefits of distributed turboelectric propulsion and boundary layer ingestion are a strong motivation for development of light-weight superconducting electric motors and generators.

[1] http://arrow.utias.utoronto.ca/crsa/iwacc/2016/mit-hall.david-boundarylayeringestionpropulsion.pdf

8.3 SELECTION OF FAN PRESSURE RATIO

8.3.1 Introduction

In this section we set about selection of the fan pressure ratio, *fpr* for a civil turbofan engine. The *fpr* sets the bypass jet velocity, and therefore the engine diameter and bypass ratio that is required in order to achieve a specified thrust. A high overall pressure ratio gives good thermal efficiency for the engine core, while a low fan pressure ratio reduces the jet velocity, giving better propulsive efficiency. The high-bypass ratio engine configuration is a means to achieve a high overall efficiency, by combining high propulsive and thermal efficiencies,

N

typically $V_{jc} \approx V_{jb}$ by design

$$\eta_o = \eta_p \times \eta_{th}$$

The designer is free to vary the ratio of core and bypass jet velocities, however near-equal velocity magnitudes are used in order to minimise noise and to maximise propulsive efficiency. Once the fan pressure ratio and the ratio of core and bypass jet velocities is specified, and the power output from the core has been fixed by specifying the overall pressure ratio and the turbine entry temperature, the bypass ratio of the engine can be determined.

8.3.2 Fan Pressure Ratio and Bypass Ratio

The bypass ratio is used commonly as a descriptor of the engine type. The first generation of big commercial engines (Pratt & Whitney JT9D, General Electric CF6, Rolls-Royce RB211) had bypass ratios around 5. More recent large engines (GEnx and Trent 1000 and Trent XWB) have bypass ratios near to 10. We may assume that a bypass ratio at least as great will be used for the next generation of civil aircraft engines.

The fan pressure ratio provides the force to accelerate the bypass jet. Increasing the fan pressure ratio increases the jet velocity, even while keeping the bypass ratio fixed. The fan pressure ratio therefore characterises the engine design better than the bypass ratio. A further alternative descriptor for the engine type is the specific thrust, defined by the net thrust divided by overall mass flow:

$$\text{specific thrust} = \frac{F_N}{\dot{m}_{air}} = V_j - V.$$

8.3.3 Engine Layout and Station Numbering

The standard numbering scheme for stations in a turbojet engine and in a two-shaft turbofan engine are shown in Figure 7.

$$\eta_p \approx \frac{2V}{V_j+V} \rightarrow (V_{jb} \approx V_{jc})$$

T_{19} = temp of bypass exhaust

$$h_0 = h + \frac{1}{2}V^2 \quad \text{\} stagnation enthalpy}$$

$$c_p(T_{019} - T_{19}) = \frac{1}{2}V_{jb}^2$$

$$V_{jb} = \sqrt{2c_p T_{019}\left(1-\frac{T_{19}}{T_{019}}\right)}$$

if fully expanded then $P_{19} = P_A$ → isentropic relations

$$V_{jb} = \sqrt{2c_p T_{019}\left(1-\left(\frac{P_A}{P_{019}}\right)^{\frac{\gamma-1}{\gamma}}\right)}$$

efficiency

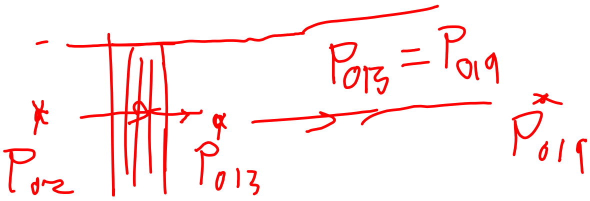
intake's pres

$$\frac{P_A}{P_{019}} = \underbrace{\frac{P_A}{P_{02}}}_{\text{BPR}} \times \underbrace{\frac{P_{02}}{P_{013}}}_{\frac{1}{\text{FPR}}}$$

fan output's pres

BPR bypass pressure ratio

$\frac{1}{\text{FPR}}$ fan pressure ratio



upstream of intake

changes required but some attempt to keep similar convention

additions

note the turbine and compressor work must be equal on individual spools!

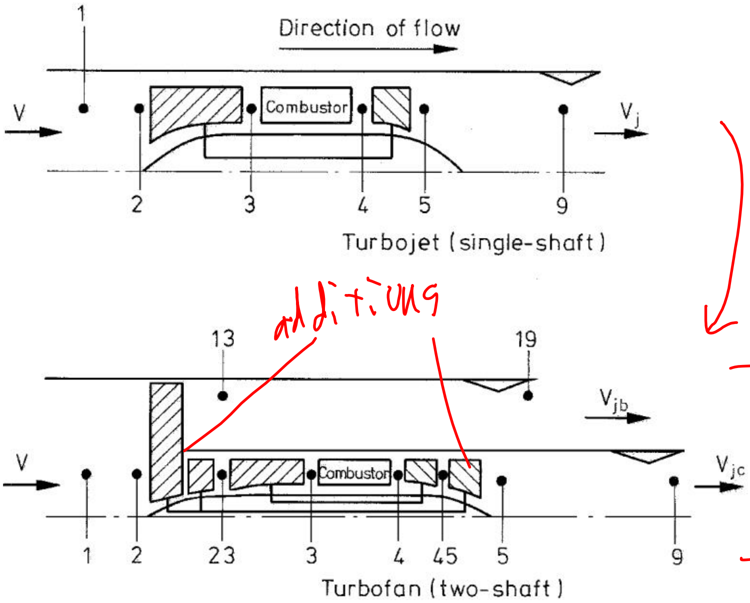


Figure 7. Standard numbering schemes for stations in jet engines.

The temperature-entropy plots for flow through the core and bypass of the turbofan engine, based on core engine calculations in Exercise 8.1, are illustrated in Figure 8. The static pressure in the jet is assumed equal to the ambient pressure p=9=p_a=p_1. In Figure 8 it is assumed that the flow velocity at station 2 is still equal to V, and therefore that the static pressure at station 2 is equal to the static pressure in the environment.

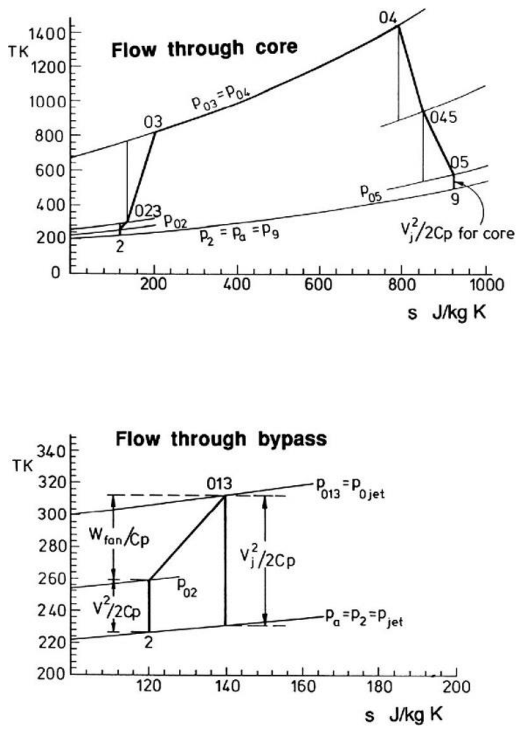


Figure 8. Temperature-entropy diagrams for the high bypass ratio engine. Core and bypass jet velocities set equal. Cruise at M=0.85 at 31,000 *fpr* ~ 1.8, core pressure ratio =32, turbine entry temperature = 1407 K, fan, compressor and turbine efficiencies = 90 %.

8.3.4 The Specification of the Fan Pressure Ratio

Neglecting pressure drop between the fan and the bypass duct nozzle, the pressure ratio across the bypass nozzle is given by,

$$\frac{\mathrm{p}_{013}}{\mathrm{p}_{\mathrm{a}}}=\frac{\mathrm{p}_{013}}{\mathrm{p}_{02}}\frac{\mathrm{p}_{02}}{\mathrm{p}_{\mathrm{a}}}=\mathrm{fpr}\frac{p_{02}}{p_a}$$

noting that *fpr* is a stagnation pressure ratio. The temperature into the nozzle can be written

$$\mathrm{T}_{013}=\mathrm{T}_{02}\left(1+\frac{\mathrm{fpr}^{\frac{(\gamma-1)}{\gamma}}-1}{\eta_f}\right),$$

where η_f is the isentropic efficiency of the fan, $T_{02}=T_a(1+0.5(\gamma-1)M^2)$ and, assuming any deceleration up to station 2 is isentropic, $p_{02}/p_a=(T_{02}/T_a)^{(\gamma/(\gamma-1))}$.

For nozzle pressure ratios less than around three, it is a good approximation to assume that irreversibilities are small and to treat the flow as isentropic, giving the bypass jet velocity as

$$V_{jb}=\sqrt{2c_p(T_{013}-T_{19})}=\sqrt{2c_pT_{013}\left(1-(p_a/p_{013})^{\frac{\gamma-1}{\gamma}}\right)}$$

This equation implies that for a given ambient condition and flight Mach number, and a fixed fan isentropic efficiency, the jet velocity depends only on the fan pressure ratio.

The jet velocity depends on the stagnation temperature T_{09} and pressure p_{09} at entry into the core nozzle. Assuming there is no loss of heat or stagnation pressure in the flow between the LP turbine exit and the nozzle entry, $T_{09}=T_{05}$ and $p_{09}=p_{05}$. The exit pressure is well approximated by $p_9=p_a$. The core jet velocity is then equal to,

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

The bypass jet velocity has been fixed by the *fpr*. The core jet velocity can now be chosen by varying the pressure ratio across the LP turbine, p_{045}/p_{05}. The core and bypass jet velocities are always similar in magnitude, but here we make them equal

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

which is simple and corresponds to maximum propulsive efficiency. The effect of varying this ratio is assessed later. At this stage we have developed equations for the pressure ratios and the jet velocities, but not for the bypass ratio.

The power required to drive the booster and the fan is provided by the power extracted by the LP turbine,

$$\dot{m}_c c_p(T_{045}-T_{05})=\dot{m}_c c_p(T_{023}-T\_02)+bpr\,\dot{m}_c c_p(T_{013}-T_{02}).$$

The temperature T_{05} can be determined using the isentropic relation (and isentropic efficiency if less than unity) based on the LPT inlet temperature T_{045} and the pressure ratio p_{045}/p_{05}, so that the only remaining unknown is the bypass ratio.

Assuming that the core engine exit conditions p_{045} and T_{045} are given, the procedure for calculation can be summarised as:

1. Choose the fan pressure ratio, which determines the bypass jet velocity.
2. Choose the ratio of core jet velocity to bypass jet velocity (here made equal).
3. Guess a value for LP turbine pressure ratio, p_{045}/p_{05}.
4. From p_{045}/p_{05} find T_{05} and p_{05}/p_a.
5. Compute core jet velocity V_{jc} and compare it to the bypass jet velocity V_{jb}. If V_{jc} is too large increase p_{045}/p_{05} (i.e. lower p_{05}) and return to (iv).
6. From p_{045}/p_{05} and T_{045} find LP shaft power and then compute bypass ratio.
7. Compute gross thrust and net thrust per unit mass flow through the core.

The analysis in this Section considers flight at M=0.78 and 35,000 ft. The pressure ratio for the core flow through the fan and booster is assumed to be 2.5 and the high pressure compressor ratio equal to 18. Exercise 8.1 shows that the temperature rise up to the booster exit $T_{023} - T_{02} = 81.6\ K$. The conditions at entry to the LP turbine are $T_{045} = 1033.5\ K$ and $p_{045} = 363.5\ kPa$ in the following analysis.

8.3.5 The Impact of Fan Pressure Ratio

The calculation procedure above has been applied across a range of fan pressure ratios to produce Figure 9-Figure 13. For each *fpr* the LP turbine pressure ratio is varied (by changing p_{05} and therefore the core nozzle pressure ratio p_{09}/p_{05}) until the core and bypass velocities are equal. T_{045}, p_{045}, M=0.78 and altitude of 35,000 ft are kept constant. The analysis shows:

- reducing fpr corresponds to an increased bpr for a fixed engine core (Figure 9).
- increasing bpr requires more work to be extracted from the LPT (Figure 9).
- increasing bpr increases gross thrust since the jet has more momentum for a fixed kinetic energy (Figure 10).
- increasing bpr has limited impact on net thrust, since the increase in gross thrust is offset by the increase of ram drag (Figure 10).
- reducing fpr from 1.8 to 1.5 improves sfc by 6 % (Figure 11).
- Reducing fpr from 1.8 to 1.5 reduces specific thrust, meaning that the air mass flow rate needs to increase by 36 % to retain the same thrust (Figure 11).

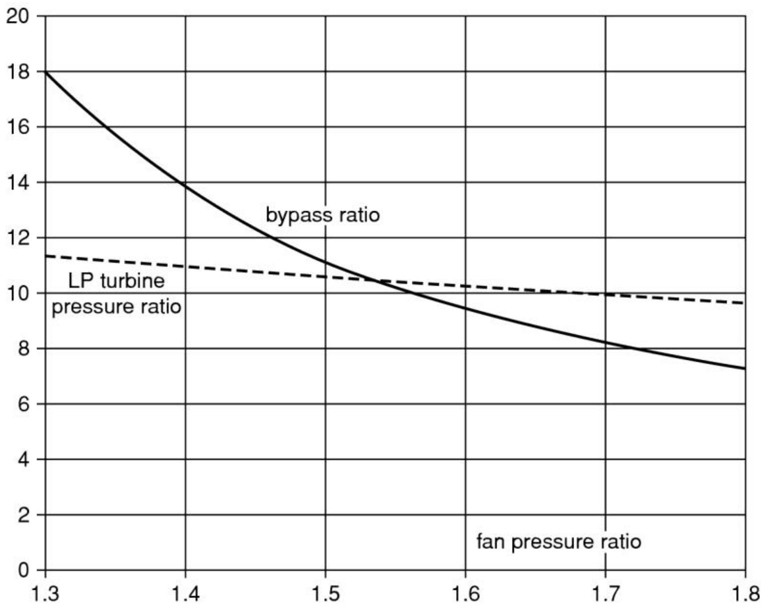
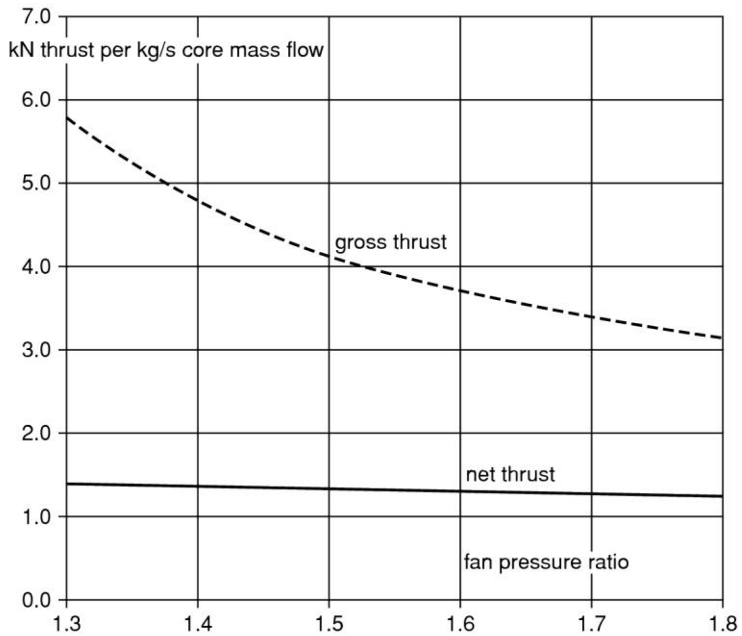


Figure 9. Predicted variation in LP turbine pressure ratio and bypass ratio with fan pressure ratio for a constant core overall pressure ratio (opr) = 45, T_{04} = 1500 K. M=0.78 at 35,000 ft. Bare engine. Core and bypass jet velocities equal.



$F_G = \dot{m} V_j$

$F_N = \dot{m}(V_j - V_a)$

Figure 10. Predicted variation in gross and net thrust with fan pressure ratio for a constant core opr=45, T_{04} = 1500 K. M=0.78 at 35,000 ft. Bare engine. Core and bypass jet velocities equal.

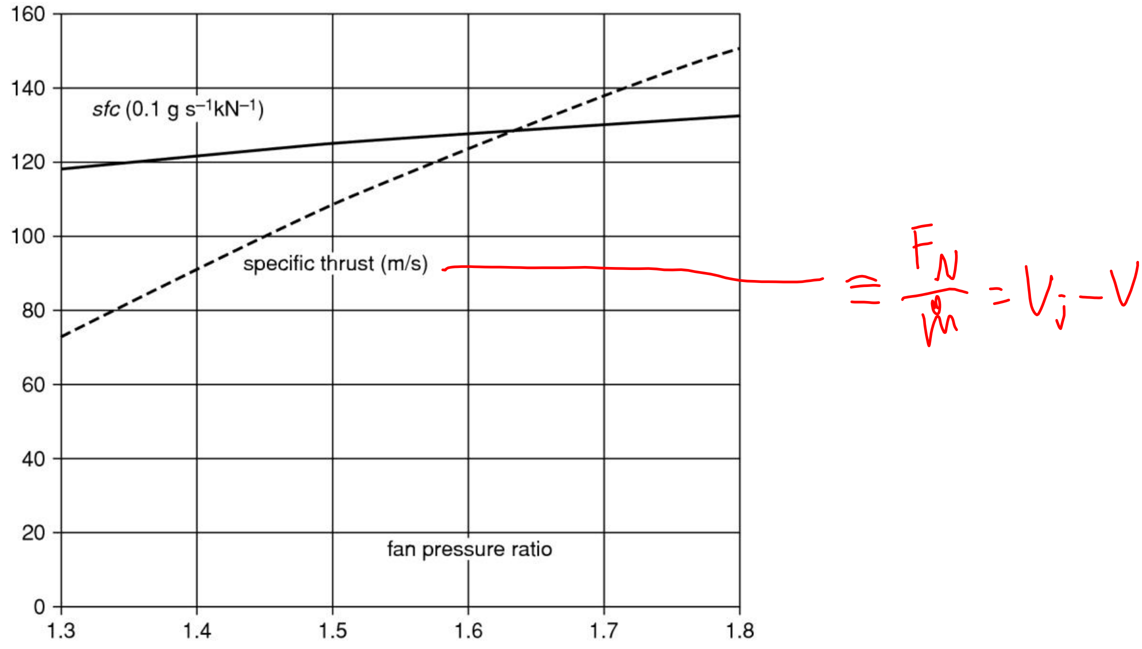


Figure 11. Predicted variation in specific thrust and \textit{sfc} with fan pressure ratio for a constant core opr=45, T_{04} = 1500 K. M=0.78 at 35,000 ft. Bare engine. Core and bypass jet velocities equal.

8.3.6 The Bare Engine and the Effect of the Nacelle

So far we have considered the net thrust of the *bare* engine by considering the momentum change of the flow along the stream tube entering the engine. Engines are surrounded by a nacelle, and the combination of the engine and nacelle is called the *power plant*. There is a drag on the outside of the nacelle and also on the inside of the fan duct, and these losses, as well as the engine weight added by increasing the bypass ratio need to be considered when determining the optimum fan pressure ratio.

We lump together the drag on the nacelle and the losses in the bypass duct, and model them as being proportional to the square of flight velocity,

$$D_{nac} \propto A_w \rho V^2$$

For a given style of engine, the wetted area A_w will be proportional to the fan's frontal area $\pi d^2/4$. For a fixed fan style, flight speed and altitude, the mass flow is related to the fan frontal area by $\dot{m}/\rho V = \pi d^2/4$, and therefore the wetted area is $A_w \propto \dot{m}/\rho V$. The mass flow rate through the engine is given by $\dot{m} = F_N/X$, where F_N is the net thrust and X is the engine specific thrust. The engine specific thrust $X = V_j - V$ is determined by fan pressure ratio. The nacelle drag can then be written

$$D_{nac} = kV(F_N/X)$$

where *k* is an empirical constant depending on the style of the fan and nacelle. *k* needs to be determined from experiment or detailed calculation, but *k* = 0.04 gives plausible predictions. The effective net thrust from the power plant is then

$$F_{N,effective} = F_{N,bar}(1 - kV/x)$$

For the New Efficient Aircraft cruising at M=0.78, 35,000 ft and V=231 m/s,

$$F_{N,effective} = F_{N,bare}(1 - 9.25/X)$$

The net thrust is reduced by on the order of 10 % and, since the engine core is fixed, the sfc is increased by the same proportion. The variation of the bare and effective sfc with fpr is shown in Figure 12, revealing that reducing fpr leads to nacelle drag having an increased impact on sfc. However it is only when the engine weight is considered that a true minimum in sfc emerges.

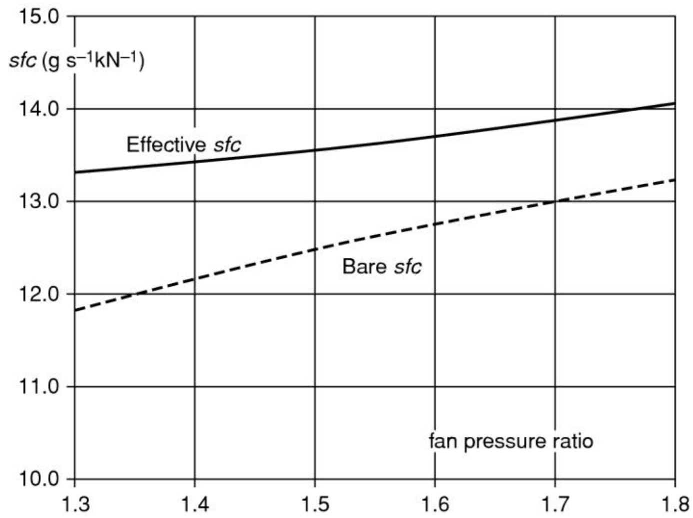


Figure 12. Predicted variation in sfc with fan pressure ratio for a constant core, opr=45, $T_{04}=1500$ K. M=0.78 at 35,000 ft. Core and bypass jet velocities equal. Assumed $sfc_{effective}=sfc_{bare}/\{1.00-9.25/X\}$ where X=*specific thrust*.

8.3.7 Effect of Engine Weight and Selection of Fan Pressure Ratio

It is easy to forget that the objective of the engine maker is *not* to produce the engine with the best sfc but the engine that gives the airline the best yield. A key influence on the yield is the weight of fuel at take-off and the mass of the power plant, since reducing these allows an increase in the mass of payload that can be carried on each flight. Reductions in the fuel bill may in fact be a secondary consideration. The weight of two engines, nacelles and their pylons is about 10 % of the maximum take-off weight of the aircraft. The weight of the bare engine is around half of this, with the large low-pressure spool contributing most of the mass.

Reducing fpr means that a higher fan area is needed in order to achieve the required thrust. A simple geometric scaling of the engine would suggest that the engine weight would scale with the cube of the fan diameter. In practice, a smaller exponent provides a better fit to the weights of previous engines,

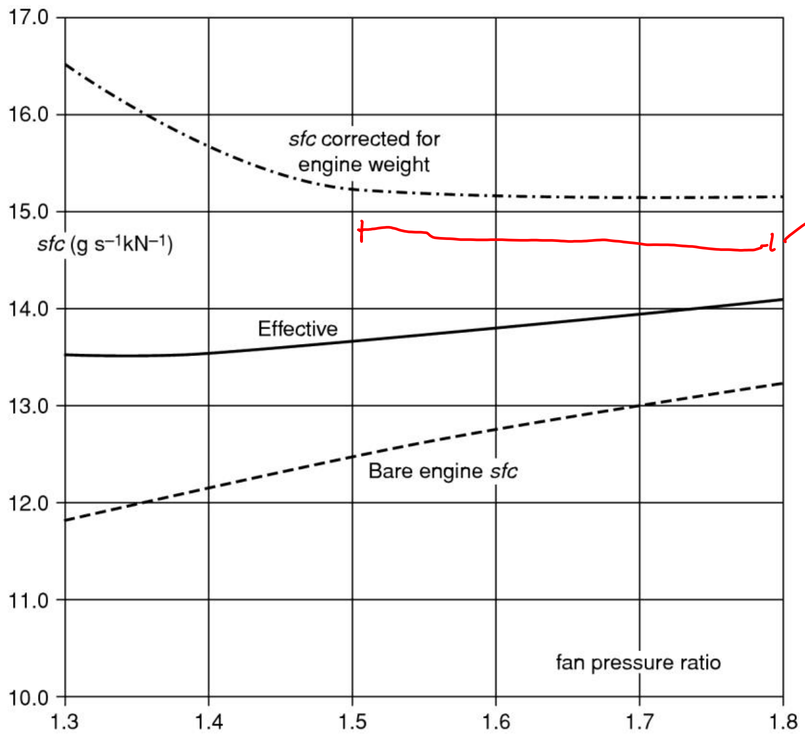
$$W_{engine} \propto d^{2.4}$$

Neglecting the effect of the power plant weight on the weight of the rest of the aircraft structure, we account for the influence of the power plant weight by considering the additional lift required to counter it, and then subtract the corresponding drag to obtain a corrected value of the net thrust,

$$F_{N,corrected} = F_{N,effective} - \frac{W_{engine}}{(L/D)}$$

where L/D is the lift-to drag ratio of the aircraft.

A plausible estimate for the mass of a modern 3 m diameter turbofan engine, including nacelle and pylon is around 12 tonne. Using this value and L/D=21.6, the variation of the corrected net thrust is shown in Figure 13. Although the analysis is approximate, Figure 13 shows that there is a substantial penalty for fan pressure ratios less than 1.5 in terms of fuel consumption. Furthermore, extremely large diameter engines may not fit under the wing of the typical aircraft, nor fit in aircraft used for airfreight of engine components. On the other hand, reducing fpr tends to reduce jet noise. The choice of fpr therefore requires somewhat more detailed analysis than presented here, especially concerning the noise produced around airports, and the value fpr=1.5 is in line with the recent values adopted by aero-engine manufacturers on the basis of their more detailed analysis.



fan pressure ratio has a large optimal region

Figure 13. Predicted variation in sfc with fan pressure ratio with allowance for drag due to engine weight. Engine weight assumed to be given by 12 $(d/3)^{2.4}$ tonne, where d is fan diameter. For a constant core, opr = 45, T_{04} = 1500 K. M = 0.78 at 35,000ft. Core and bypass jet velocities equal.

8.4 Summary

The drive to increase propulsive efficiency motivates development of engine architectures that act on a large mass flow rate of air, but accelerate its velocity by a small amount. The turbofan, turboprop, and turboelectric architectures offer improved propulsive efficiencies compared to the turbojet engine for most flight conditions. In addition to propulsive efficiency, the choice of engine architecture and choice of fan pressure ratio or bypass ratio depends on a trade-off between noise emission, weight, drag, compatibility with the air frame, technological risk as well as operational requirements (e.g. handling of large components).