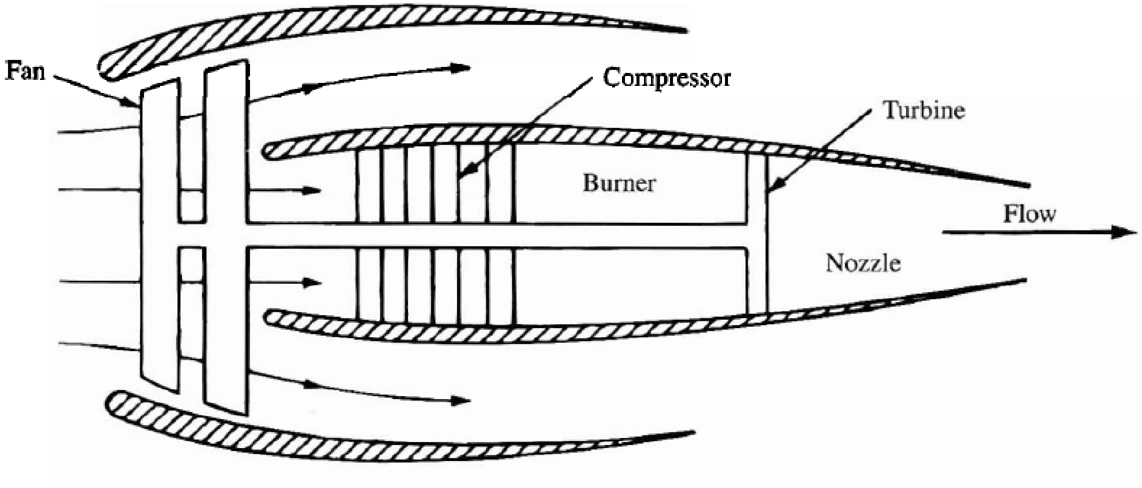
THE TURBOFAN ENGINE

The ***turbofan*** engine is a propulsive mechanism to combine the high thrust of a turbojet with the high efficiency of a propeller. Basically, a turbojet engine forms the ***core*** of the turbofan; the core contains the diffuser, compressor, burner, turbine, and nozzle. However, in the turbofan engine, the turbine drives not only the compressor, but also a large fan ***external*** to the core. The fan itself is contained in a shroud that is wrapped around the core. The flow through a turbofan engine is split into two paths. One passes through the fan and flows externally over the core; this air is processed only by the fan, which is acting in the manner of a sophisticated, shrouded propeller. The propulsive thrust obtained from this flow through the fan is generated with an efficiency approaching that of a propeller. The second air path is through the core itself. The propulsive thrust is obtained from the flow through the core is generated with an efficiency associated with a turbojet. The overall propulsive efficiency of a turbofan is therefore a compromise between that of a propeller and that of a turbojet.



This compromise has been found to be quite successful-the vast majority of jet-propelled airplanes today are powered by turbofan engines.

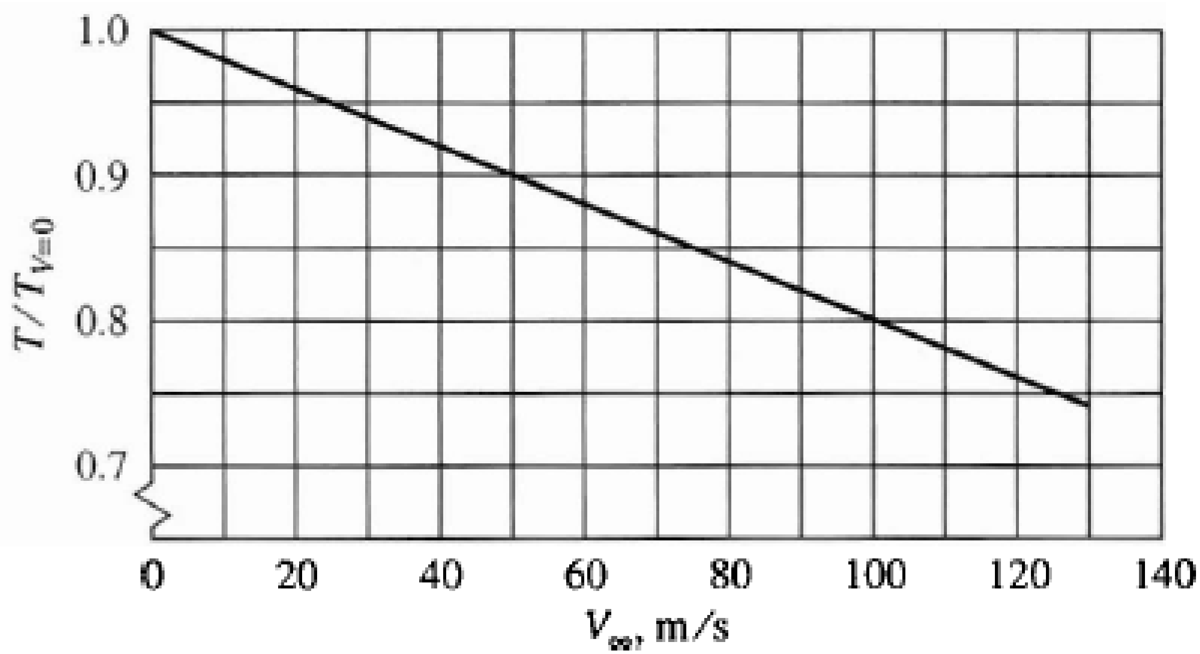
An important parameter of a turbofan engine is the bypass ***ratio,*** defined as the mass flow passing through the fan, externally to the core divided by the mass flow through the core itself. Everything else being equal, the higher the bypass ratio, the higher the propulsive efficiency. For the large turbofan engines that power airplanes such as the Boeing 747, for example, the Rolls-Royce RB211 and the Pratt & Whitney JTBD, the bypass ratios are on the order of 5. Typical values of the thrust specific fuel consumption for these turbofan engines are 0.6 lb/(lb h) almost half that of a conventional turbojet engine.

Variations of Thrust and Specific Fuel Consumption with Velocity and Altitude

For high-bypass-ratio turbofans-those with bypass ratios on the order of 5 (these are the class of turbofans that power civil transports) the performance seems to be closer to that of a propeller than that of a turbojet in some respects. The thrust of a civil turbofan engine has a strong variation with velocity; thrust decreases as V_∞ increases:

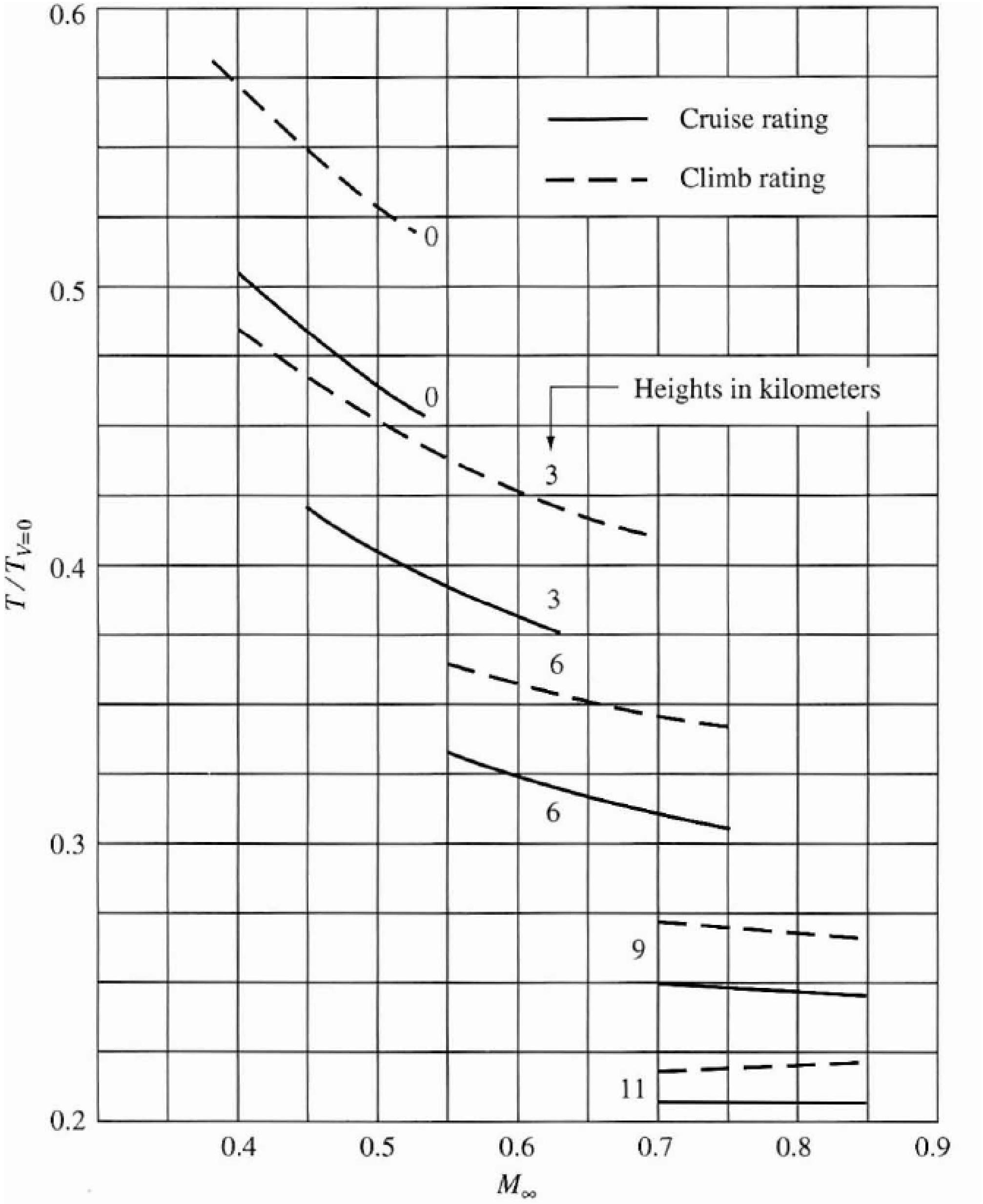
$$\frac{T}{T_{V=0}} = 1 - 2.52 \times 10^{-3} V_\infty + 4.34 \times 10^{-6} V_\infty^2$$

The equation holds for $V_\infty < 130$ m/s.



At higher subsonic velocities for a given, constant altitude, the decrease in thrust with Mach number can be correlated by

$$\boxed{\frac{T}{T_{V=0}} = A M_\infty^{-n}}$$



Although the variation of T for a civil turbofan is a strong function of V, (or Ma) at lower altitudes, at the relatively high altitude of 11 **km,** T is relatively constant for the narrow Mach number range from 0.7 to 0.85. This corresponds to normal cruise Mach numbers for civil transports such as the Boeing 747. Hence, for the analysis of airplane performance in the cruise range, it appears reasonable to assume T= constant.

The variation of T with altitude is approximated by

$$\boxed{\frac{T}{T_0} = \left(\frac{\rho}{\rho_0}\right)^m}$$

The variation of thrust specific fuel consumption with both altitude and Mach number is shown in Fig. The ratio of the thrust specific fuel consumption at the specified altitude and Mach number, to the value at zero velocity and at sea level, is shown**.** The variation with velocity at a given altitude follows the relation:

$$c_t = B(1 + kM_\infty)$$

where B and k are empirical constants

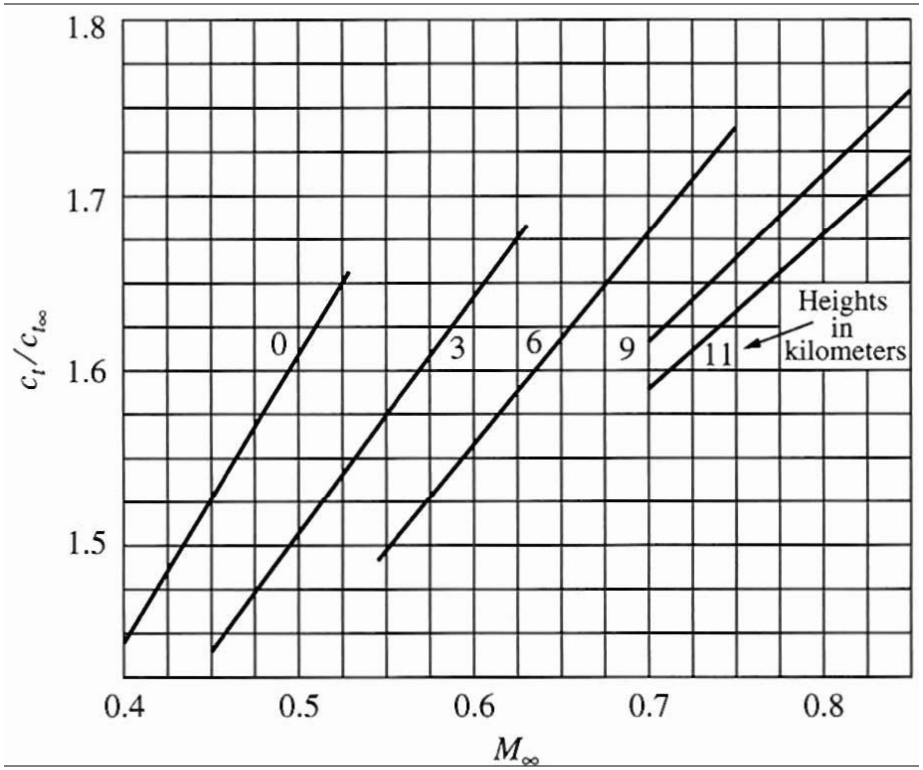
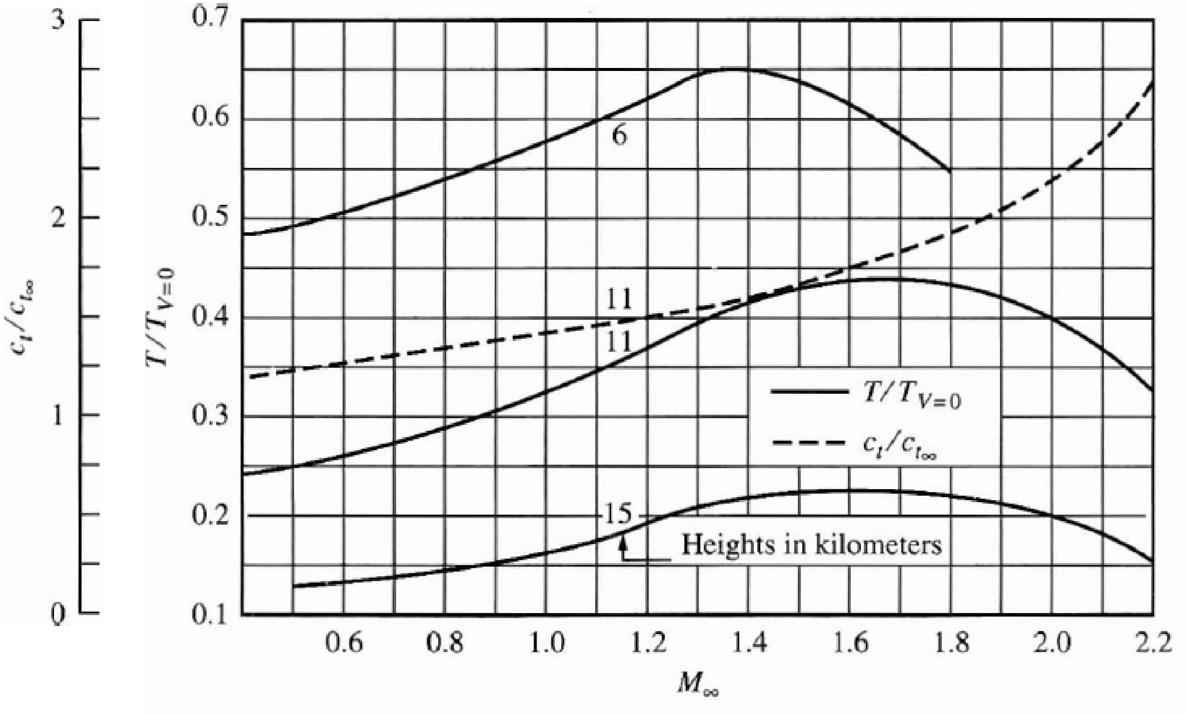


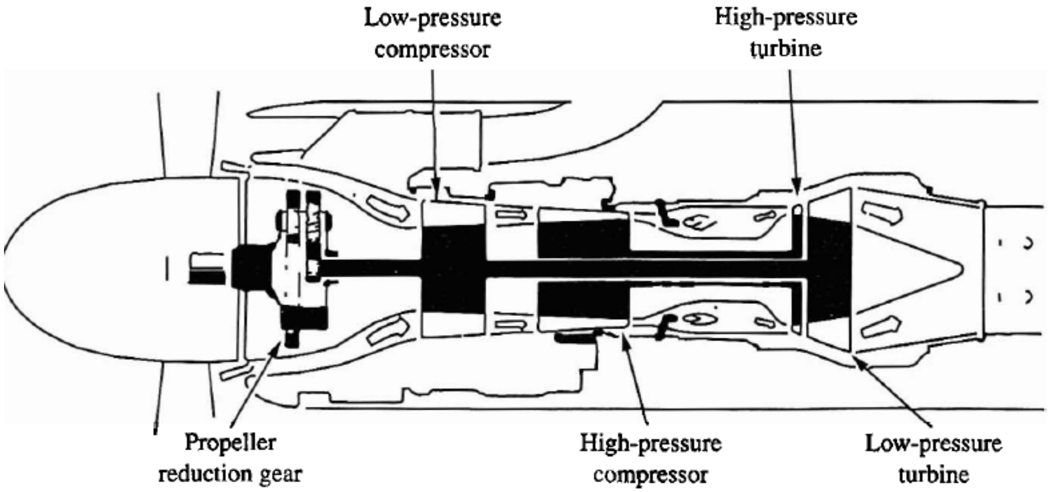
Figure shows why turbofans were not used on the Concorde supersonic transport, with its cruising Mach number of 2.2. The thrust specific fuel consumption of a turbojet engine is almost constant with speed **in** the supersonic regime. However, for a turbofan, ***ct*** increases markedly with an increase in Ma. For this reason, a turbojet is more fuel-efficient than a turbofan if the design Mach number is 2.2. The ordinate in Figure is expanded. Hence, the altitude effect on ***ct,*** looks larger than it really is. To first order, is constant with altitude.

For low-bypass-ratio turbofans-those with bypass ratios between 0 and 1-the performance is somewhat different from that for the high-bypass-ratio case discussed above. The performance of low-bypass-ratio turbofans is much closer to that of a turbojet than that of a propeller. Typical generic variations of $T/T_{v=0}$ and $c_t/c_{t\infty}$ versus Ma, for a military, low-bypass-ratio turbofan are



after a small initial decrease at low subsonic Mach numbers, the thrust increases for increasing Mach number well above Mach 1. The dashed line gives the variation of thrust specific fuel consumption versus Mach number for a military turbofan. Note that **ct,** for the low-bypass-ratio turbofan gradually increases as M, increases for subsonic and transonic speeds, and begins to rapidly increase at Mach **2** and beyond. This is unlike the variation of **ct,** for a pure turbojet engine, which is relatively constant in the low supersonic regime.

THE TURBOPROP



The turboprop is essentially a propeller driven by a gas-turbine engine, it is the closest to the reciprocating engine/propeller combination**. T**he inlet air is compressed by an axial-flow compressor, mixed with fuel and burned in the combustor, expanded through a turbine, and then exhausted through a nozzle. Unlike the turbojet, the turbine powers not only the compressor but also the propeller. By design, most of the available work in the flow is extracted by the turbines, leaving little available for jet thrust. For most turboprops, only about 5% of the total thrust is associated with the jet exhaust, and remaining 95% comes from the propeller.

the turboprop falls in between the reciprocating engine/propeller combination and the turbofan or turbojet. The turboprop generates more thrust than a reciprocating engine/propeller device, but less than a turbofan or turbojet. On the other hand, the turboprop has a specific fuel consumption higher than that of the reciprocating engine/propeller combination, but lower than that of **a** turbofan or turbojet. Also, the maximum speed of a turboprop-powered airplane is limited to that at which the propeller efficiency becomes seriously degraded by shock wave formation on the propeller usually around Ma=0.6 to 0.7.

the thrust generated by the turboprop is the sum of the propeller thrust *Tp,* and the jet thrust *Tj.* For the engine in flight at velocity V, the power available from the turboprop is

$$\boxed{P_A = \left(T_p + T_j\right) V_\infty}$$

The main business end of a turboprop is the shaft coming from the engine to which the propeller is attached via some type of gearbox mechanism. Hence the *shaft power Ps,* coming from the engine is a meaningful quantity. Because of losses associated with the propeller the power obtained from the propeller/shaft combination is η_{pr} *Ps.* Hence, the net power available, which includes the jet thrust, is

$$\boxed{P_A = \eta_{\mathrm{pr}} P_s + T_j V_\infty}$$

Sometimes manufacturers rate their turboprops in terms of the *equivalent shaftpower Pes* which is an overall power rating that *includes* the effect of the jet thrust:

$$\boxed{P_A = \eta_{\mathrm{pr}} P_{\mathrm{es}}}$$

Combining the two:

$$\eta_{\mathrm{pr}} P_{\mathrm{es}} = \eta_{\mathrm{pr}} P_s + T_j V_\infty$$

$$\boxed{P_{\mathrm{es}} = P_s + \frac{T_j V_\infty}{\eta_{\mathrm{pr}}}}$$