AE 429 - Aircraft Performance and Flight Mechanics

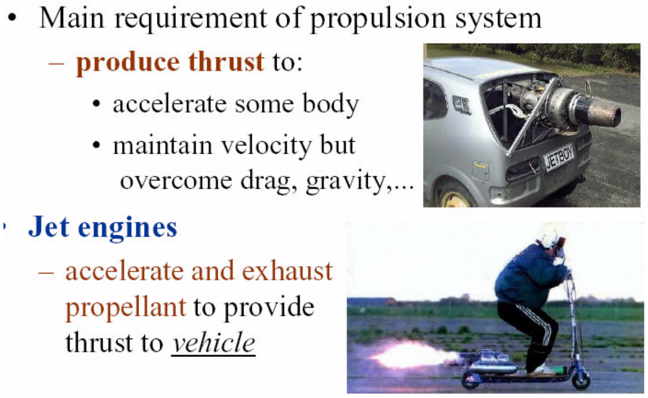
Propulsion
Characteristics

Types of Aircraft Propulsion Mechanics

- Reciprocating engine/propeller
- Turbojet
- Turbofan
- Turboprop

Important Characteristics:

•Thrust (or power)
•Fuel consumption



- Main requirement of propulsion system
  - **produce thrust** to:
    - accelerate some body
    - maintain velocity but overcome drag, gravity,...
- **Jet engines**
  - accelerate and exhaust propellant to provide thrust to *vehicle*

Engine Design - Goals

- Meet **required thrust** throughout flight envelope
  - aircraft: takeoff, climb, cruise, ...
  - spacecraft: launch, orbit transfer, planetary mission,...
- **High efficiency**
  - minimize amount of fuel (energy input) required to provide delivered thrust (energy output)
  - low weight (less thrust to accel. engine alone)
- Constraints
  - **materials limitations** (max. temperature, stress,...)
  - **low emissions**: NOx, soot, toxics, signature,....
  - other: size, lifetime, manufacturability, maintainability

Thrust and Efficiency tradeoff

- Propeller/reciprocating engine
  - (low trust, great efficiency)
- Turbojet (higher trust, less efficiency)
- Rocket (very high trust, poor efficiency)

Tradeoff: more power means less efficiency

Thrust (Power)- Propulsive force (“move as much air as fast as you can”)

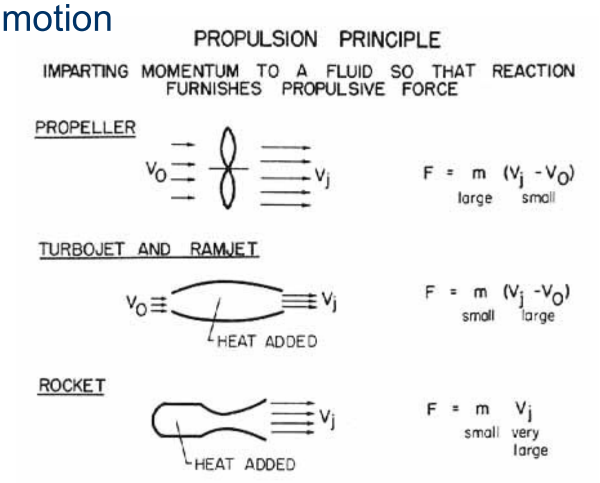
Fuel consumption- Efficiency in producing force

Thrust of all flight propulsion systems comes from the same principle reaction-as expressed by Newton's second law of motion

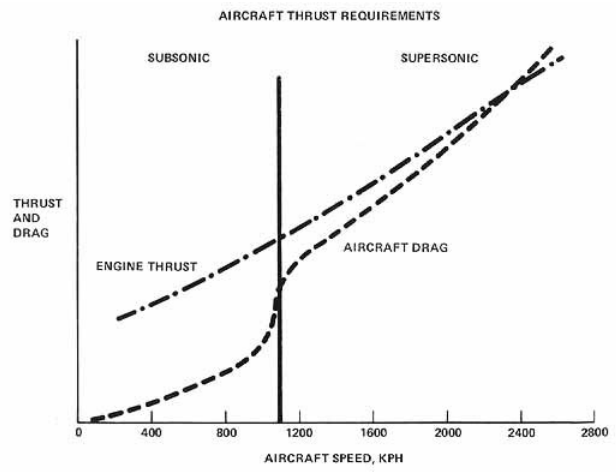
force = rate of change of momentum

or

force = mass flow rate times the change in fluid velocity

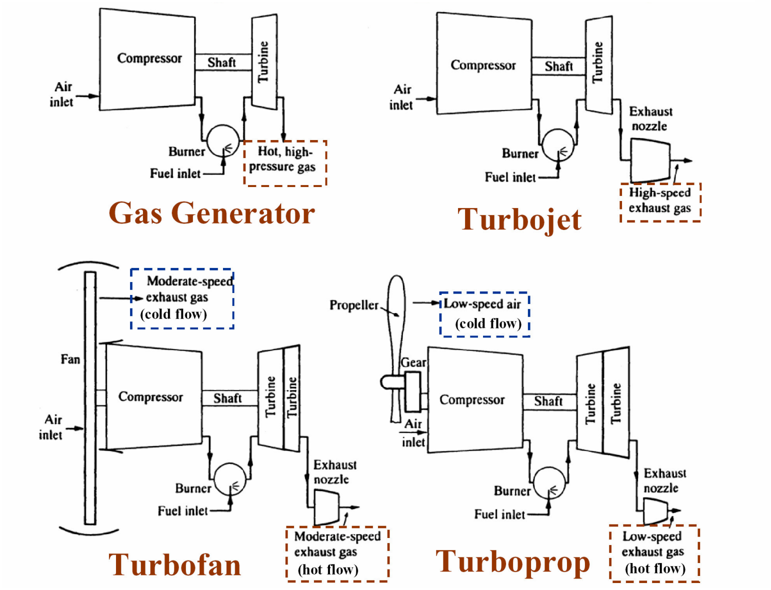


Propulsion principle is the same for propeller. turbojet. ramjet, and rocket. F = thrust (assumed same for all in comparison): m = mass flow of working fluid (air or exhaust gas) ; V_J = exhaust gas velocity; V_O= flight velocity. (NACA, 1953)

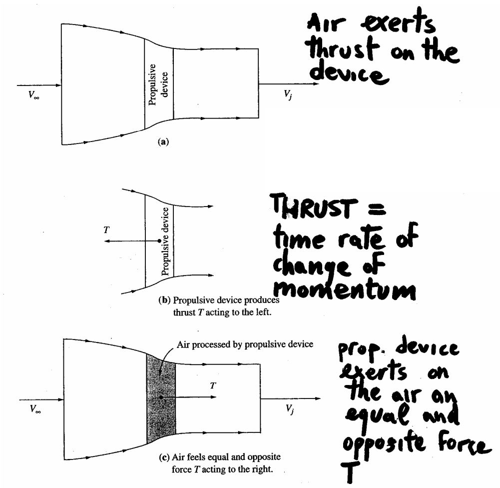


Aircraft thrust requirements increase with speed. (NACA, 1953.)

Turbine Engine Propulsion Systems



Thrust Fundamentals



(b) Propulsive device produces thrust T acting to the left.

(c) Air feels equal and opposite force T acting to the right.

Air exerts thrust on the device

THRUST = time rate of change of momentum

prop. device exerts on the air an equal and opposite force T

Figure 3.1 Reaction principle in propulsion.

Newton's 3rd Law- For every action, and equal and opposite reaction; Device exerts equal and opposite force T on air

Newton's 2nd Law- Force is equal to time rate of change of momentum
Momentum = Mass*Velocity (kg*m/s)

$$T = \dot{m}V_j - \dot{m}V_\infty = \dot{m}\left(V_j - V_\infty\right)$$

Thrust Eq. For Generic Propulsion Device

Thrust exerted on device via pressure and shear forces by air on exposed surfaces

Efficiency Fundamentals

Air stationary, device moving by……V=0

$$Power = Force \times Velocity$$

$$P_A = TV_\infty$$

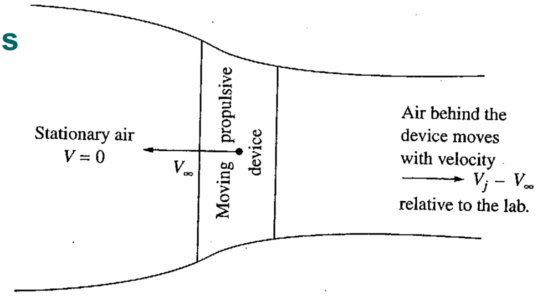


Figure 3.2 Sketch of the propulsive device moving into stationary air with velocity V_∞.

$$P_{Total} = TV_\infty + \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2$$

Wasted kinetic energy causes the sub-optimal efficiency $\frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2$

$$\eta_p = \frac{\text{useful power avaliable}}{\text{total power genrated}} = \frac{P_A}{P_{Total}}$$

Plug in thrust equation, total and available power

$$\eta_p = \frac{\dot{m}\left(V_j - V_\infty\right)V_\infty}{\dot{m}\left(V_j - V_\infty\right)V_\infty + \frac{1}{2}\dot{m}\left(V_j - V_\infty\right)^2}$$

$$\eta_p = \frac{1}{1 + \frac{1}{2}\left(V_j - V_\infty\right)/V_\infty} = \frac{1}{\frac{1}{2}\left(1 + V_j / V_\infty\right)}$$

$$\eta_p = \frac{2}{1 + V_j / V_\infty}$$

Observations:

- Max efficiency for $V_\infty = V_j$, but Thrust = 0 !
- Propeller: Thrust through large $\dot{m}$, small $V_j - V_\infty$
  so η_p is high
- Caveat: Thrust via Propellers is limited by tip speed, due to shock formation and resultant power loss; thus, propellers become ineffective at high speeds

- Jet engine: thrust through smaller $\dot{m}$ and higher $V_j - V_\infty$
  higher thrust but lower η_p (wasted kinetic energy)

Reciprocating Engine + Propeller

Use energy of combustion to expand products, move piston, turn crankshaft

Power Production

- Engine Size- Displacement (*d*)
  - Volume swept out by piston; total displacement is this volume multiplied by # of cylinders
- Speed- Revolutions per Minute (*rpm*)
  - Number of power strokes per minute
- Pressure- Mean effective pressure (p_e)
  - Higher the pressure on piston head, larger the power output $P \propto (d)(p_e)(rpm)$

Efficiency- Specific Fuel Consumption

$$c = \frac{\text{weight of fuel consumed per unit time}}{(\text{power})(\text{time})}$$

Want lots of power for little fuel . . . So minimize *c !!*

$$[c] = \frac{lb}{(ft \cdot lb/s)s} = \frac{1}{ft}$$ units

Same idea, different units

$$[SFC] = \frac{lb}{hp \cdot h}$$

Propeller

The propeller (as a collection of twisted wings) is subject to same drag sources as main wing, which results in losses

$$P_A = \eta_{pr} P, \qquad \eta_{pr} < 1$$

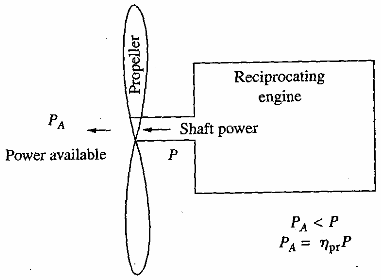


Figure 3.5 Schematic illustrating shaft power P and power available P_A from a propeller/reciprocating engine combustion.

Propeller efficiency is a function of the *advance ratio*, J

$$J = \frac{V_\infty}{ND}$$

N = # propeller revolutions per second
D = propeller diameter
β = pitch angle (between chord line and plane of rotation

V_∞ is small, α is positive, “lift” is in thrust direction….good

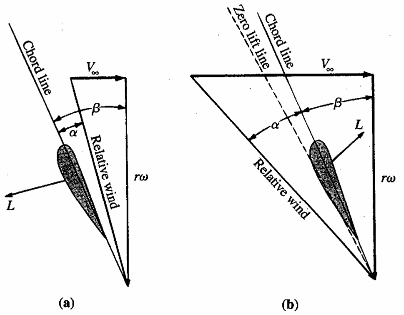
V_∞ is large, α is negative, “lift” is opposite thrust ….bad

r = radial distance of airfoil section to hub
ω = angular velocity of propeller

$$(r\omega)_{tip} = (D/2)(2\pi N) = \pi ND$$

$$\frac{V_\infty}{r\omega} = \frac{V_\infty}{r(2\pi N)}$$

$$\left(\frac{V_\infty}{r\omega}\right)_{tip} = \frac{V_\infty}{(D/2)(2\pi N)} = \frac{V_\infty}{\pi ND} = \frac{J}{\pi}$$



(a) (b)

Figure 3.6 Velocity and relative wind diagrams for a section of a revolving propeller: **(a)** Case for low V_∞ and **(b)** case for high V_∞.

Advance ratio J captures the critical efficiency metric of the propeller, the ratio of free-stream velocity to rotational translation

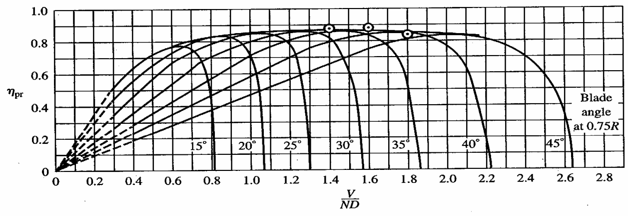
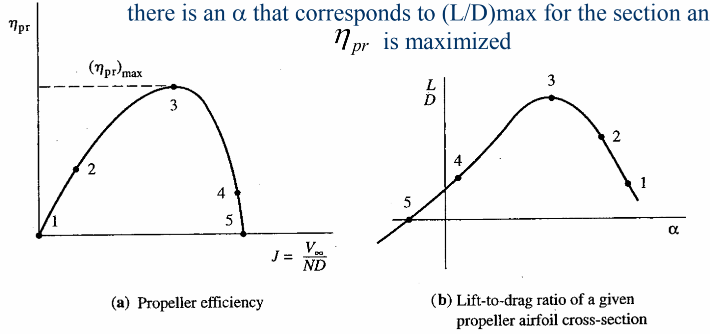


Figure 3.7 Propeller efficiency as a function of advance ratio for various pitch angles. Three-bladed propeller with Clark Y sections. (*After McCormick, Ref. 50.*)

Increasing V_∞ produces an "alpha sweep" from high + to high -; there is an α that corresponds to (L/D)max for the section and thus η_{pr} is maximized



(**a**) Propeller efficiency

(**b**) Lift-to-drag ratio of a given propeller airfoil cross-section

Figure 3.8 Effect of section lift-to-drag ratio on propeller efficiency.

Note: Pitched-fixed, N fixed

Max efficiency occurs at specific J, and thus specific V_∞

This is the design point, but what happens at different velocities drastic decrease in efficiency !

Solution: Adjust β to select proper J to traverse locus of maximum efficiency . . . . → the ***variable-pitch propeller***

However, variable pitch propeller created more aerodynamic torque, tending to retard rotation of propeller

So η_{pr} was increasing, but P was decreasing somewhat some loss in available power P_A

Solution: Adjust β to select maximize $\eta_{pr} P$, the power available P_A

. . . . → the ***constant-speed propeller (constant rpm)***

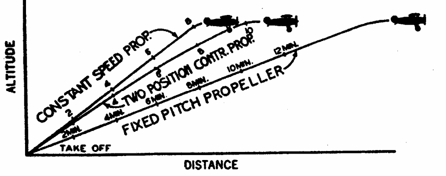
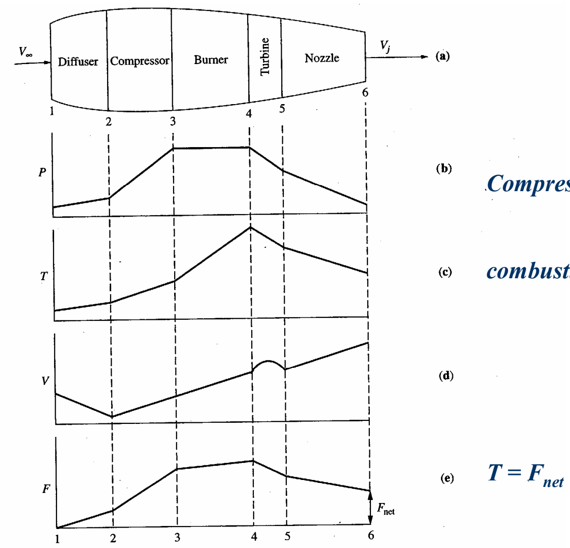


Figure 3.9 Comparison of airplane climb performance for three types of propellers: fixed-pitch, two-position (controllable), and constant-speed. Historic diagram by Carter (Ref. 38).

Turbojet

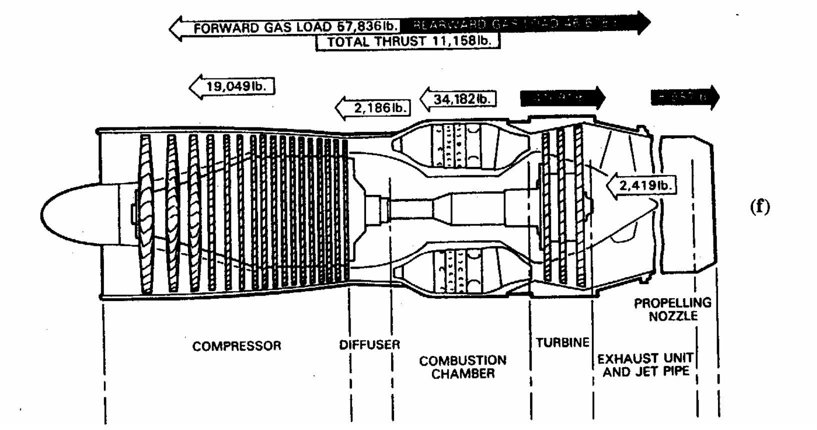
- Concentrates more on $\left(V_j - V_\infty\right)$ to generate high T
- Net thrust is resultant of pressure and shear forces on engine surfaces



Compression & expansion

combustion adds energy

$T = F_{net} > 0$



integrated thrust through a generic turbojet engine.

Thrust of Turbojet

Recall, $T = \dot{m}V_j - \dot{m}V_\infty = \dot{m}\left(V_j - V_\infty\right)$

$$T = \left(\dot{m}_{air} + \dot{m}_{fuel}\right)V_j - \dot{m}_{air}V_\infty + \left(p_e - p_\infty\right)A_e$$

$p_e =$ Gas pressure at nozzle exit
$p_\infty =$ ambient pressure
$A_e =$ nozzle exit area

Pressure term usually small

Thrust specific fuel consumption

$$c_t = \frac{\text{weight of fuel consumed per unit time}}{(\text{thrust})(\text{time})}$$

$$\left[c_t\right] = \frac{lb}{(lb)s} = \frac{1}{s}$$

Conventionally used thrust specific fuel consumption (TSFC) is slightly different,

$$\left[TSFC\right] = \frac{lb}{(lb)h} = \frac{1}{h}$$

Sensitivity of *T* and *TSFC* with Velocity and Altitude

Thrust- Subsonic Mach numbers

- Similar to Drag, Thrust and engine efficiency depends on “flight condition”, i.e. *velocity* and *altitude*

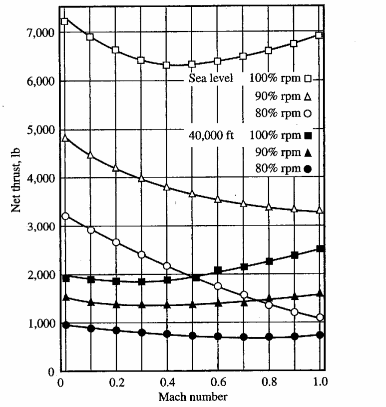


Figure 3.13 Typical results for the variation of thrust with subsonic Mach number for a turbojet.

$\dot{m}_{air} = \rho_\infty A_1 V_\infty$

$$T = \left(\dot{m}_{air} + \dot{m}_{fuel}\right) V_j - \dot{m}_{air} V_\infty + \left(p_e - p_\infty\right) A_e$$

Increase in $\dot{m}_{air}$ tends to cancel decrease in $\left(V_j - V_\infty\right)$

T is ***approximately*** constant with V_∞

$\frac{T}{T_0} = \frac{\rho}{\rho_0}$ Thrust proportional to density as altitude changes

$sub_0 \Rightarrow$ sea-level value

Sensitivity of *T* and *TSFC* with Velocity and Altitude

TSFC can be optimized via “cycle” parameters (items such as pressure ratios, temperatures, etc.).

This is achieved through proper design of the components (compressor, combustor, turbine, etc.)

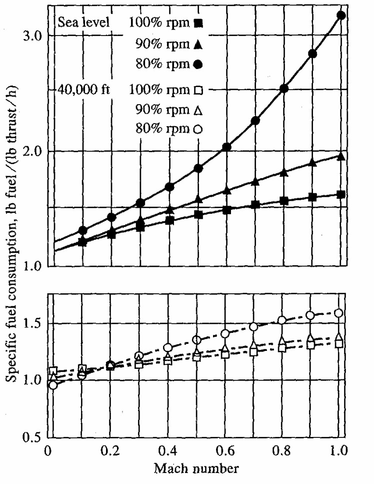


Figure 3.14 Typical results for the variation of thrust specific fuel consumption with subsonic Mach number for a turbojet.

$TSFC$ is ***approximately*** constant with altitude

$$TSFC = 1.0 + kM_\infty$$

k is a function of altitude and throttle (rpm)

Supersonic conditions

$$\frac{p_{total}}{p_{static}} = \left(1 + \frac{\gamma - 1}{2} M^2\right)^{(\gamma/(\gamma-1))}$$

$T \propto M_\infty$ supersonic conditions $T / T_{M=1} = 1.0 + 1.18(M_\infty - 1)$

Large total pressure recovered at diffuser inlet; thus, as speed increases, more pressure recovered and delivered to compressor, thus increasing V_j and thrust

$\delta = p / p_0$ Ratio of pressures at altitude and sea level

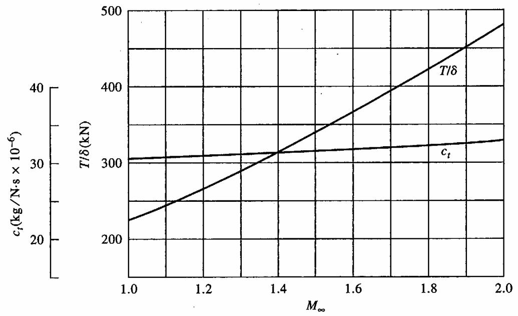


Figure 3.15 Typical results for the variation of thrust and thrust specific fuel consumption with supersonic Mach number for a turbojet.

$TSFC$ is ***approximately*** constant with speed

Turbofan

- 2 airflows, one through core (turbojet) and one "by-passed"
- Thrust obtained from by-passed flow approaches efficiency of propeller
- COMBINATION of improved efficiency and high thrust has made the Turbofan the choice for modern transport airplanes

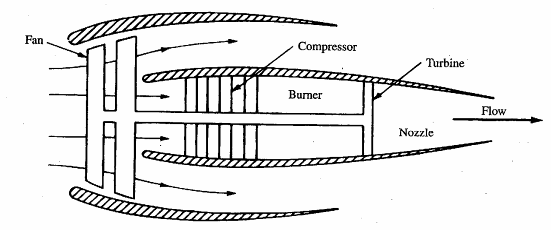


Figure 3.16 Schematic of a turbofan engine.

$$\text{By-Pass ratio} = \frac{\text{mass bypassed air}}{\text{mass core air}}$$

By-Pass ratio ↑ means TSFC ↓

Turbofan Performance Variations (high BPR)

Thrust variations depend on flight condition

In general, T decreases with V_∞ but to a lesser extent at high altitude

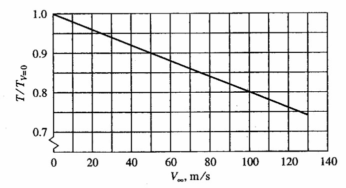


Figure 3.19 Maximum takeoff thrust as a function of velocity at sea level for the Rolls-Royce RB211-535E4 turbofan.

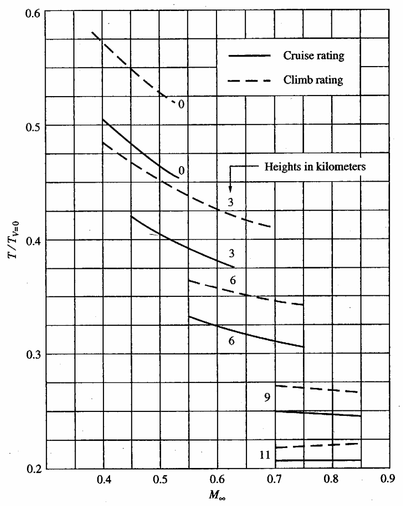


Figure 3.20 Variation of maximum thrust with Mach number and altitude for the Rolls-Royce RB211-535E4 turbofan. Note that $T_{V=0}$ is the thrust at zero velocity at sea level.

Turbofan Performance Variations (High BPR)

Turbofan **thrust specific fuel consumption** variations:

- c_T increases with increasing V_∞

$c_T = B(1 + kM_\infty)$ Only valid for $0.7 < M_\infty < 0.85$

Recall c_T ~ constant above M_∞ for turbojet

- c_T about constant with altitude

$T/T_{V=0} = AM_\infty^{-n}$ A and n are function of the altitude

At 3 Km:

$$T/T_{V=0} = 0.369M_\infty^{-0.305}$$

$$\frac{T}{T_0} = \left(\frac{\rho}{\rho_0}\right)^m$$ *m* about 1

$sub_0 \Rightarrow$ sea-level value

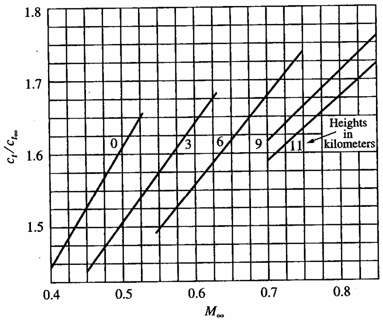


Figure 3.21 Variation of thrust specific fuel consumption with subsonic Mach number and altitude for the Rolls-Royce RB211-535E4 turbofan. Note that c_{t_∞} is the thrust specific fuel consumption at zero velocity at sea level.

Low BPR Designs

Primarily used on military fighters:

- Need thrust at high Mach, not efficiency !
- More like a turbojet !
- BPR between 0 and 1

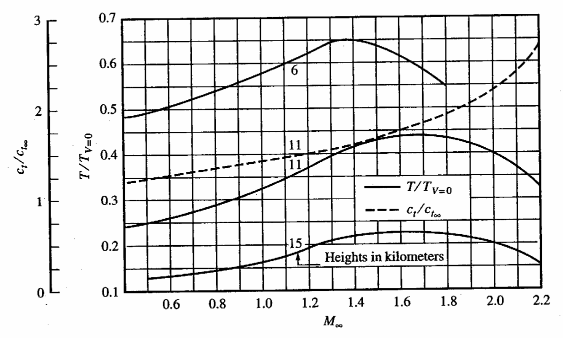


Figure 3.22 Variation of thrust and thrust specific fuel consumption with subsonic and supersonic Mach number and altitude for a generic military turbofan.

Turboprops

- Propeller driven by gas turbine engine
- Its **"niche"-**
  - More thrust than reciprocating engine, but less than turbojet/fan
  - Better specific fuel consumption than turbojet/fan, but less than reciprocating

Turboprop Power available:

$$P_A = (T_p + T_j)V_\infty$$

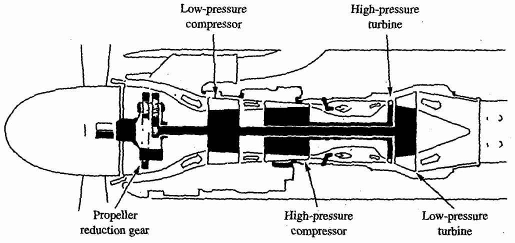


Figure 3.23 Schematic of a turboprop engine.

Shaft Power is most important (95%): $P_A = \eta_{pr} P_s + T_j V_\infty$

Equivalent Shaft Power is often used: $P_A = \eta_{pr} P_{es}$

Equivalent Shaft Power defined: $P_{es} = P_s + \dfrac{T_j V_\infty}{\eta_{pr}}$

Turboprops

$c_t = \dot{w}_{fuel}/T$ Thrust fuel consumption

$c_A = \dot{w}_{fuel}/P_A$ $c_S = \dot{w}_{fuel}/P_S$ $c_{es} = \dot{w}_{fuel}/P_{es}$

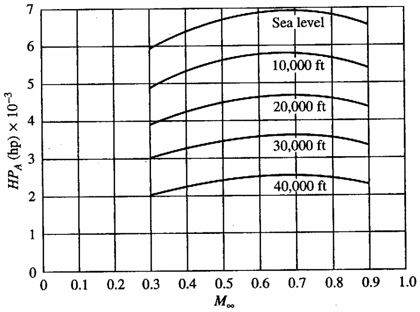


Figure 3.25 Variation of maximum horsepower available HP_A as a function of Mach number and altitude for a typical turboprop engine.

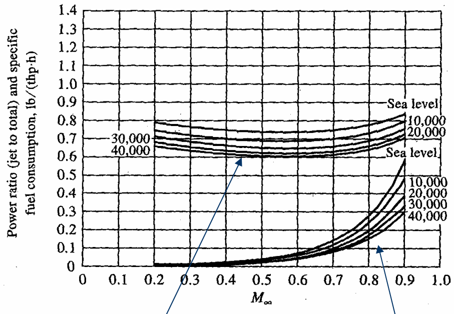


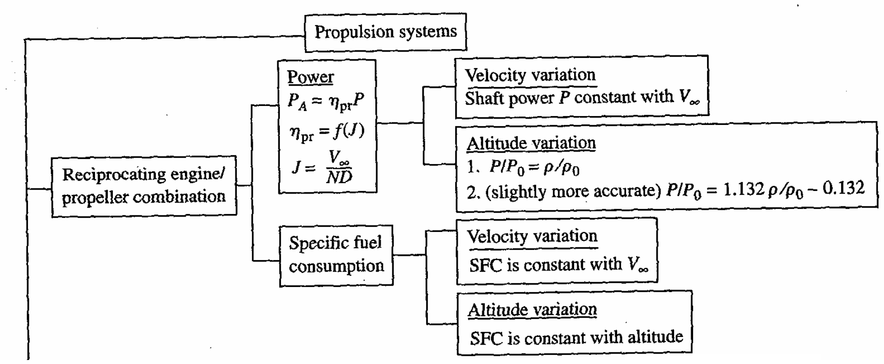
Figure 3.26 Variation of specific fuel consumption and ratio of jet to the total thrust horsepower with Mach number and altitude for a typical turboprop engine. Altitude is given in feet.

$P_A = T_A V_\infty$ is constant with speed

$P_A / P_{A0} = \left(\frac{\rho}{\rho_0}\right)^n$ variation with altitude

$n = 0.7$

Reciprocating Engine/Propeller Combination



Propulsion systems

Reciprocating engine/ propeller combination

Power
$P_A = \eta_{pr} P$
$\eta_{pr} = f(J)$
$J = \frac{V_\infty}{ND}$

Velocity variation
Shaft power P constant with V_∞

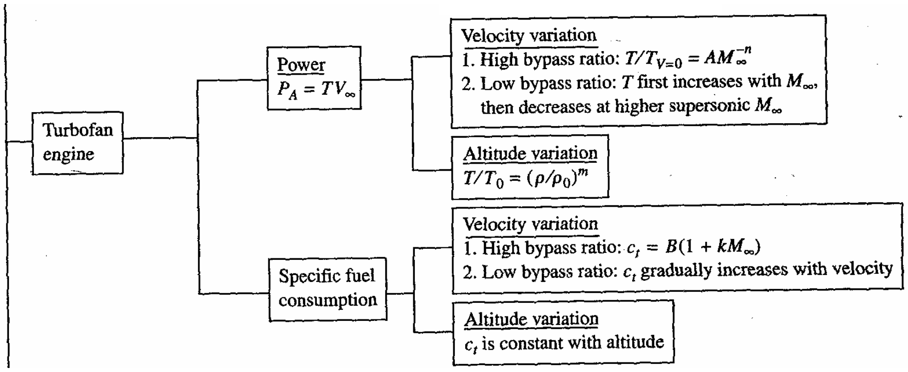
Altitude variation
1. $P/P_0 = \rho/\rho_0$
2. (slightly more accurate) $P/P_0 = 1.132\,\rho/\rho_0 - 0.132$

Specific fuel consumption

Velocity variation
SFC is constant with V_∞

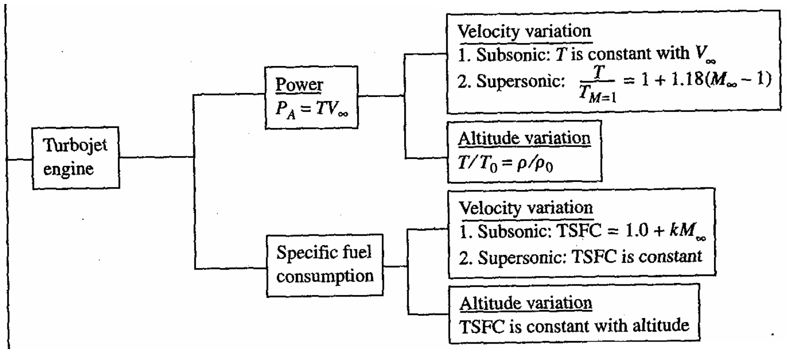
Altitude variation
SFC is constant with altitude

Turbofan Engine



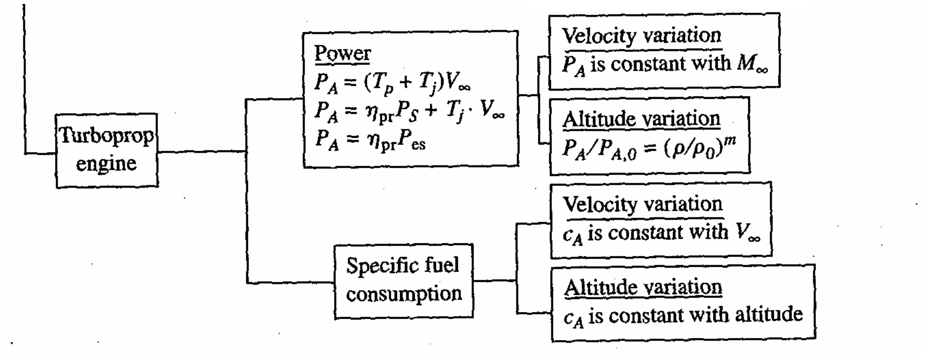
- Turbofan engine
  - Power $P_A = TV_\infty$
    - Velocity variation
      1. High bypass ratio: $T/T_{V=0} = AM_\infty^{-n}$
      2. Low bypass ratio: T first increases with M_∞, then decreases at higher supersonic M_∞
    - Altitude variation
      $T/T_0 = (\rho/\rho_0)^m$
  - Specific fuel consumption
    - Velocity variation
      1. High bypass ratio: $c_t = B(1 + kM_\infty)$
      2. Low bypass ratio: c_t gradually increases with velocity
    - Altitude variation
      c_t is constant with altitude

Turbojet Engine



- Turbojet engine
  - Power $P_A = TV_\infty$
    - Velocity variation
      1. Subsonic: T is constant with V_∞
      2. Supersonic: $\frac{T}{T_{M=1}} = 1 + 1.18(M_\infty - 1)$
    - Altitude variation
      $T/T_0 = \rho/\rho_0$
  - Specific fuel consumption
    - Velocity variation
      1. Subsonic: TSFC = $1.0 + kM_\infty$
      2. Supersonic: TSFC is constant
    - Altitude variation
      TSFC is constant with altitude

Turboprop Engine



Turboprop engine

Power

$P_A = (T_p + T_j)V_\infty$

$P_A = \eta_{\text{pr}} P_S + T_j \cdot V_\infty$

$P_A = \eta_{\text{pr}} P_{\text{es}}$

Velocity variation

P_A is constant with M_∞

Altitude variation

$P_A/P_{A,0} = (\rho/\rho_0)^m$

Specific fuel consumption

Velocity variation

c_A is constant with V_∞

Altitude variation

c_A is constant with altitude

The basic components of an air-breathing (jet) engine are the inlet, a compressor or fan, the combustor (burner), a turbine, and an exit nozzle. Different engines will use these components in various combinations. Some engine designs even leave out one or more of these components. But these are the basic building blocks of an engine. The figure below shows a typical jet engine design and its components.

Inlet:

The design of the inlet, or air intake, helps determine the amount of air flow into an engine. After deciding the cruise speed of the aircraft, engineers design the inlet to suck in as much of the air coming toward it as needed. Subsonic, supersonic and hypersonic cruise speeds each require a different inlet design. Inside the engine the next component, the compressor, works much, much better when the air enters fairly slowly, (usually much slower than cruise velocity), so the inner walls of the inlet are designed to slow the velocity of the air stream as it comes to the compressor.

Compressor:

The compressor is used to squeeze the air, or to increase the pressure of the air flow. This is vital to creating thrust. Using a balloon, as an example: as more air is blown into the balloon the pressure increases. Increased pressure will produce increased thrust. To increase the pressure you must use power (your lungs). The purpose of the compressor is to increase the pressure of the incoming air (power). Typical compressors increase the pressure of the air by 15 to 30 times the original pressure. Usually, an engine designer will choose among different compressors to find the compression ratio that fits the specifications of the airplane being built.

Combustor:

The slow moving, high pressure air from the compressor is fed into the combustor or burner where it is mixed with a highly flammable fuel and ignited. The very hot, high pressure air leaving the burner will be used to generate the thrust. These gases are very, very hot, and the engineer must be careful designing the components that come after the burner so they are not melted or destroyed. The combustion engineer works with the mixture of fuel and air to get just the right combination for a good, hot burn. Too little fuel and the mixture doesn't burn hot enough and the resulting thrust is lower. Too much fuel and the mixture doesn't burn completely; you may be getting enough thrust, but the engine is wasting fuel. Sometimes a second burner is used after the turbine. The second burner reheats the gases to a higher temperature just as they exit the engine into the much cooler outside air, the velocity of the gases increase, generating more thrust.

Turbine:

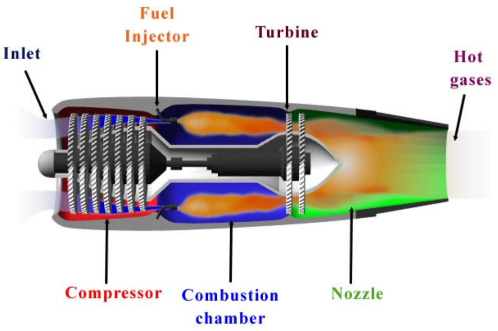
The very high temperature, high pressure gases are released from the burner and passed into the turbine (engine) where the local pressures are much lower. The high pressure gases begin to drop in pressure. As the pressure drops, the velocity of the flow, of exhaust gases, increases. As these gases leave the engine (turbine) they generate thrust. Part of this flow may also be used to power (run) the compressor. Although this decreases overall thrust, it is more efficient than having a separate power source for the compressor.

An engineer must be very careful in the design of a turbine because of the high temperature of the gases coming from the burner. If the materials in the turbine blades are not chosen well, the blades can melt and deform and be less efficient, or even break off and destroy the rest of the turbine.

Some engines use an afterburner. Remember, the afterburner does a second burn on the lower pressure gases coming from the turbine. Some of the gas flow is used to run the compressor, the afterburner reheats the gases which increases their velocity, thereby increasing thrust. Without the afterburner the additional thrust would not be there.

Nozzle:

The inside walls of the exit nozzle are shaped so that the exhaust gases continue to increase their velocity as they travel out of the engine. The higher the exit velocity of the gases, the more thrust that can be generated. Some fighter aircraft have adjustable nozzles, allowing the pilot to adjust thrust as needed. Other nozzles are of a fixed design because conditions do not change enough to need an adjustable nozzle. Again, the engineer must be concerned with the temperatures of the exhaust gases in the exit nozzle, expecially if there is an afterburner. If the walls on the inside of the nozzle melt and change, then the exhaust velocities and thrust may not be correct.



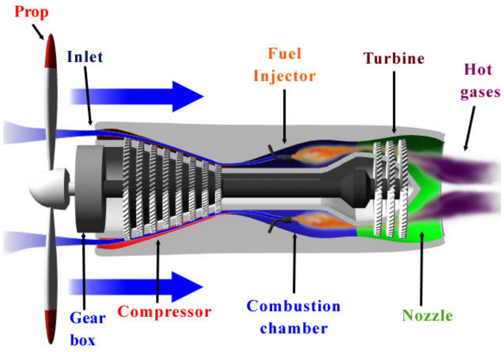
Turbojet:

This engine completely changed air transportation. It greatly reduced the expense of air travel and improved aircraft safety. The turbojet also allowed faster speeds, even supersonic speeds. It had a much higher thrust per unit weight ratio than the piston-driven engines, which led directly to longer ranges (flight distances) and higher payloads (more passengers and baggage). As it happened, it also has lower maintenance costs.

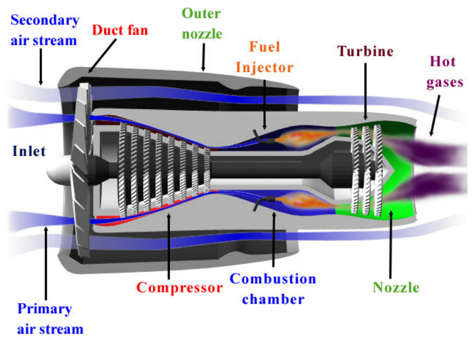
The typical turbojet engine has all 5 of the components described in the previous section: an inlet, a compressor, a combustor, a turbine, and a nozzle. The figure below shows a basic turbojet schematic with the 5 components clearly identified. To get an increased thrust, an afterburner can be added to the turbojet. The figure below is the turbojet with an afterburner. Most aircraft do not use an afterburner, because they use so much fuel. Fighter aircraft with afterburners only use them when absolutely necessary. If a pilot runs too long with the afterburner on, he or she risks running low on fuel before the mission is completed.

Remember, from the components section, that temperature is a very important factor when designing the turbine. The exhaust cannot be too hot or it will melt parts (such as the blades) in the turbine. However, the hotter the exhaust the more thrust there will be. The engineers use a technique called "turbine blade cooling". This allows hotter than normal exhaust from the combustor to enter the turbine engine. Cool air from the compressor is fed into hollow turbine blades, so they won't become overheated and warp or break. The cooling must be controlled very carefully to get maximum thrust.

The turbojet engine is the most popular engine for most high-speed aircraft, in spite of the higher fuel consumption. When high speed and performance are important, the cost of fuel is less important. Military fighters and fast business jets use turbojet engines.



Turboprop:
Soon after the first turbojets were in the air the turboprop engine was developed. This engine design produces two thrusts, one with the propeller and the other through exhaust. A large gear box makes it possible for the turbine to turn a large propeller at high speed, producing the first thrust. The large gear box has many moving parts (that could break) and can get in the way of the air stream going into the engine.
As the propeller speed increases, the tips of the blades may approach supersonic speeds. If this happens, the flow may separate and shocks may form, decreasing the air flow into the engine. For these reasons this type of engine is still restricted to slower speeds because of the large propeller and the gear box.
The sketch below shows the basic components of a turboprop engine. The propeller precedes the inlet and the compressor, but it serves the same purpose. It provides a large volume of high pressure air to the engine exhaust streams. An inlet and a compressor are used to send a part of the air flow to the burner. A turbine is used to power the propeller and the compressor, and the hot exhaust gases are accelerated out through the nozzle. (This is the second thrust, after the propeller) Because only a small part of the air flow is actually burned inside the engine, the turboprop engine can generate a lot of thrust with a low fuel consumption compared to a turbojet engine. When an airplane is designed to fly at lower speeds, the turboprop is usually the engine chosen.

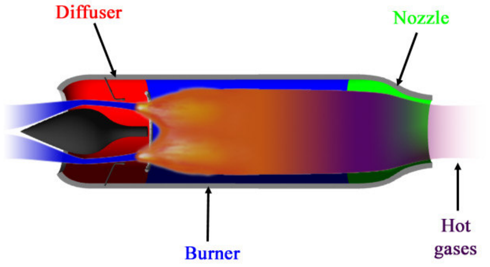


Turbofan:

As engineers struggled to overcome the limitations of the turboprop engine for airplanes at higher speeds, a new design emerged: the turbofan. It can be described as a compromise between the turboprop and the turbojet engines. It includes a large, internal propeller (sometimes called a ducted fan) and 2 streams of air flowing through the engine. The primary stream travels through all of the components like a turbojet engine, while the secondary stream is usually accelerated through a nozzle to mix with the primary exhaust stream. The figure below illustrates the design of a turbofan engine.

There are several advantages to the turbofan over the other 2 engines. The fan is not as large as a propeller, so the increase of speeds along the blades is less. Also, by enclosing the fan inside a duct or cowling, the aerodynamics are better controlled. There is less flow separation at the higher speeds and less trouble with shocks developing.

A turbofan engine can fly at transonic speeds up to Mach 0.9. While the fan is smaller than the propeller, it does suck in much more air flow than the turbojet engine, so it gets more thrust. Like the turboprop engine, the turbofan has low fuel consumption compared to a turbojet. The turbofan engine is the engine of choice for high-speed, subsonic commercial airplanes. While it is possible to put afterburners into one or both streams, the slight additional thrust gained is at the expense of a large increase in fuel consumption. The cost is so high, in fact, that they are rarely ever built into turbofan engines



Ramjets:

Below Mach 1.0 a compressor is very much needed as a component of an air-breathing engine. As an airplane increases its speed past Mach 1.0 the air pressure created from the speed of the air flow decreases the need for a compressor. As speeds approach Mach 3.5 - 4.0, a compressor isn't even needed. The ramjet is the most efficient engine because it has less components. The ramjet doesn't have a compressor or a turbine, and it has a much higher tolerance to high temperatures. A schematic of a ramjet engine is shown below. It has an inlet, a burner, and a nozzle.

A ramjet does have limitations. The first is that it will not work at less than supersonic speeds; another engine must first power the aircraft to supersonic speeds. Another limitation is the burning of the fuel and air mixture in the combustor. The ramjet inlet must slow the air flow from the supersonic speeds to subsonic speed for ignition in the burner. As the ramjet approaches Mach 6.0 the air coming into the burner is too hot to burn! This is due to the friction created as the supersonic air is slowed at the inlet to subsonic speed. At this speed not enough thrust is being generated to continue performance.

There is a proposed solution to the ramjet's speed limitation (Mach 6.0). It is called supersonic combustion ramjet (SCRAMJET). Instead of slowing the air flow down to subsonic speeds for combustion, the SCRAMJET will ignite the air while still supersonic (thus avoiding the friction at the inlet). Fuel must still be injected into the airstream to be ignited. Unfortunately, today's fuels do not ignite quickly enough. The development of a workable fuel injection system for the SCRAMJET is still in its early stages.