# Turbojet

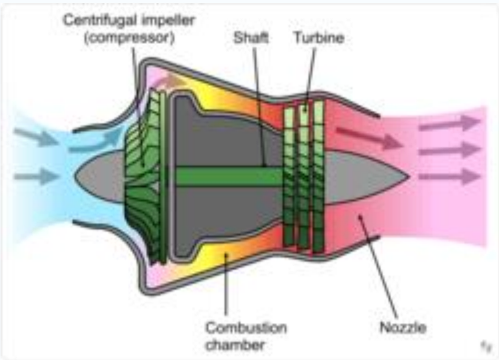
**Turbojets** are the simplest and oldest kind of general purpose jet engine. Two different engineers, Frank Whittle in Britain and Hans von Ohain in Germany, developed the concept during the late 1930s. Fighter aircraft, fitted with turbojet engines, first entered service in 1944, towards the end of World War II.

A turbojet engine is used primarily to propel aircraft. Air is drawn into the rotating compressor via the intake and is compressed to a higher pressure before entering the combustion chamber. Fuel is mixed with the compressed air and ignited by flame in the eddy of a flame holder. This combustion process significantly raises the temperature of the gas. Hot combustion products leaving the combustor expand through the turbine, where power is extracted to drive the compressor. Although this expansion process reduces the turbine exit gas temperature and pressure, both parameters are usually still well above ambient conditions. The gas stream exiting the turbine expands to ambient pressure via the propelling nozzle, producing a high velocity jet in the exhaust plume. If the jet velocity exceeds the aircraft flight velocity, there is a net forward thrust upon the airframe.

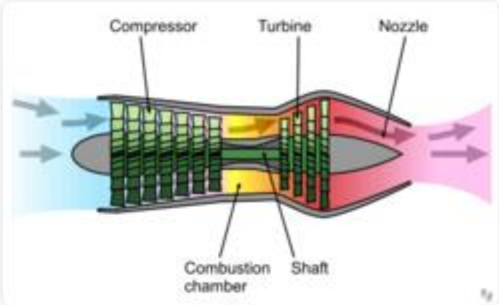
Modern jet engines are mainly turbofans, where some (if not most) of the air entering the intake bypasses the combustor.

Although ramjet engines are simpler in design (virtually no moving parts) they are incapable of operating at low flight speeds.

### Air intake



Schematic diagram showing the operation of a centrifugal flow turbojet engine. The compressor is driven via the turbine stage and throws the air outwards, requiring it to be redirected parallel to the axis of thrust.



Schematic diagram showing the operation of an axial flow turbojet engine. Here, the compressor is again driven by the turbine, but the air flow remains parallel to the axis of thrust.

Preceding the compressor is the air intake (or inlet), which is designed to recover, as efficiently as possible, the ram pressure of the streamtube approaching the intake. Downstream of the intake, air enters the compression system.

**Compressor**

The compressor, which rotates at very high speed, adds energy to the airflow, at the same time squeezing it into a smaller space, thereby increasing its pressure and temperature.

In most turbojet-powered aircraft, bleed air is extracted from the compressor section at various stages to perform a variety of jobs including air conditioning/pressurization, engine inlet anti-icing, and many others.

Several types of compressor are used in turbojets and gas turbines in general: axial, centrifugal, axial-centrifugal, double-centrifugal, etc.

Early turbojet compressors had overall pressure ratios as low as 5:1 (as do a lot of simple auxiliary power units and small propulsion turbojets today). Aerodynamic improvements, plus splitting the compression system into two separate units and/or fitting anti-stall systems, enabled later turbojets to have overall pressure ratios of 15:1 or more. In comparison, modern civil turbofan engines have overall pressure ratios as high as 44:1 or more.

After leaving the compressor section, the compressed air enters the combustor.

**Combustor**

The burning process in the combustor is significantly different from that in a piston engine. In a piston engine the burning gases are confined to a small volume and, as the fuel burns, the pressure increases dramatically. In a turbojet the air and fuel mixture passes, unconfined, through the combustion chamber. As the mixture burns its temperature increases dramatically, the pressure actually decreasing a few percent.

In detail, the fuel-air mixture must be brought almost to a stop so that a stable flame can be maintained, this occurs just after the beginning of the combustion chamber. The aft part of this flame front is allowed to progress rearward in the engine. This ensures that the rest of the fuel is burned as the flame becomes hotter when it leans out, and because of the shape of the combustion chamber the flow is accelerated rearwards. Some pressure drop is unavoidable, as it is the reason why the expanding gases travel out the rear of the engine rather than out the front. Less than 25% of the air is involved in combustion, in some engines as little as 12%, the rest acting as a reservoir to soak up the heating effect of the fuel burning.

Another difference between piston engines and jet engines is that the peak flame temperature in a piston engine is experienced only momentarily, and for a small portion of the entire cycle. The combustor in a jet engine is exposed to the peak flame temperature continuously and operates at a pressure high enough that a stoichiometric fuel-air ratio would melt the can and everything downstream. Instead, jet engines run a very lean mixture, so lean that it would not normally support combustion. A central core of the flow (primary airflow) is mixed with enough fuel to burn readily. The cans are carefully shaped to maintain a layer of fresh unburned air between the metal surfaces and the central core. This unburned air (secondary airflow) mixes into the burned gases to bring the temperature down to something the turbine can tolerate.

**Turbine**

Hot gases leaving the combustor are allowed to expand through the turbine. In the first stage the turbine is largely a reaction turbine (similar to a pelton wheel) and rotates because of the impact of the hot gas stream. Later stages are convergent ducts that accelerate the gas rearward and gain energy from that process. Pressure drops, and energy is transferred into the shaft. The turbine's rotational energy is used primarily to drive the compressor. Some shaft power is extracted to drive accessories, like fuel, oil, and hydraulic pumps. Because of its significantly higher entry temperature, the turbine pressure ratio is much lower than that of the compressor. In a turbojet almost two thirds of all the power generated by burning fuel is used by the compressor to compress the air for the engine.

**Nozzle**

After the turbine, the gases are allowed to expand through the exhaust nozzle to atmospheric pressure, producing a high velocity jet in the exhaust plume. In a convergent nozzle, the ducting narrows progressively to a throat. The nozzle pressure ratio on a turbojet is usually high enough for the expanding gases to reach Mach 1.0 and choke the throat. Normally the flow will go supersonic in the exhaust plume, external to the engine.

If, however, a convergent-divergent "de Laval" nozzle is fitted, the divergent (increasing flow area) section allows the gases to reach supersonic velocity within the nozzle itself. This is slightly more efficient on thrust, than using a convergent nozzle. There is, however, the added weight and complexity, since the con-di nozzle must be fully variable, to cope basically with engine throttling.

**Net thrust**

Below is an approximate equation for calculating the net thrust of a turbojet:

$$F_n = m \cdot (V_{jfe} - V_a)$$

where:

$m =$ intake mass flow

$V_{jfe} =$ fully expanded jet velocity (in the exhaust plume)

$V_a =$ aircraft flight velocity

Whilst the $m.V_{jfe}$ term represents the nozzle gross thrust, the $m.V_a$ term represents the ram drag of the intake. Obviously, the jet velocity must exceed that of the flight velocity if there is to be a net forward thrust on the airframe.

**Thrust to power ratio**

A simple turbojet engine will produce thrust of approximately: 2.5 pounds force per horsepower (15 mN/W).

**Cycle improvements**

Increasing the overall pressure ratio of the compression system raises the combustor entry temperature. Therefore, at a fixed fuel flow and airflow, there is an increase in turbine inlet temperature. Although the higher temperature rise across the compression system, implies a larger temperature drop over the turbine system, the nozzle temperature is unaffected, because the same amount of heat is being added to the system. There is, however, a rise in nozzle pressure, because overall pressure ratio increases faster than the turbine expansion ratio. Consequently, net thrust increases, whilst specific fuel consumption (fuel flow/net thrust) decreases.

So turbojets can be made more fuel efficient by raising overall pressure ratio and turbine inlet temperature in unison. However, better turbine materials and/or improved vane/blade cooling are required to cope with increases in both turbine inlet temperature and compressor delivery temperature. Increasing the latter requires better compressor materials..

**Early designs**

Early German engines had serious problems controlling the turbine inlet temperature. Their early engines averaged only ten hours of operation before failing—often with chunks of metal flying out the back of the engine when the turbine overheated. British engines tended to fare better due to better metals. The Americans had the best materials because of their reliance on turbosupercharging in high altitude bombers of World War II. For a time some US jet engines included the ability to inject water into the engine to cool the compressed flow before combustion, usually during takeoff. The water would tend to prevent complete combustion and as a result the engine ran cooler again, but the planes would takeoff leaving a huge plume of smoke.

Today these problems are much better handled, but temperature still limits airspeeds in supersonic flight. At the very highest speeds, the compression of the intake air raises the temperature to the point that the compressor blades will melt. At lower speeds, better materials have increased the critical temperature, and automatic fuel management controls have made it nearly impossible to overheat the engine.

**Sources**

Constructing A Turbocharger Turbojet Engine. Edwin H. Springer. Turbojet Technologies 2001.

**See also**

- turbofan
- turboprop
- jet engine
- ramjet
- propfan

## Auxiliary power unit

**APIC Honeywell APU for a small Airbus**

An **Auxiliary Power Unit** (**APU**) is a relatively small self-contained generator used in aircraft to start the main engines, usually with compressed air, and to provide electrical power and air conditioning while the aircraft is on the ground. In many aircraft, the APU can also provide electrical power in the air.

APU's are also fitted to some tanks to provide electrical power when stationary, without the high fuel consumption caused by running the main engine.

A gasoline piston engine APU was first used on the Pemberton-Billing P.B.31 Night Hawk Scout aircraft in 1916. The Boeing 727 in 1963 was the first jetliner to feature a gas turbine APU, allowing it to operate at smaller, regional airports, independent from ground facilities.

Although APUs have been installed in many locations on various military and commercial aircraft, they are usually mounted at the rear of modern jet airliners. The APU exhaust can be seen on most modern airliners as a small pipe exiting at the aircraft tail.

In most cases the APU is powered by a small gas turbine engine that provides compressed air from within or drives an air compressor (load compressor). Recent designs have started to explore the use of the Wankel engine in this role. The Wankel offers power-to-weight ratios better than normal piston engines and better fuel economy than a turbine.

APUs fitted to ETOPS airplanes are more critical than others, as they supply backup electrical and compressed air in place of the dead engine during emergencies. While most APUs may or may not be startable while the aircraft is in flight, ETOPS compliant APUs must be flight-startable at all altitudes. If such APUs malfunction, the airplane cannot be released for ETOPS flight and is forced to take a longer route.

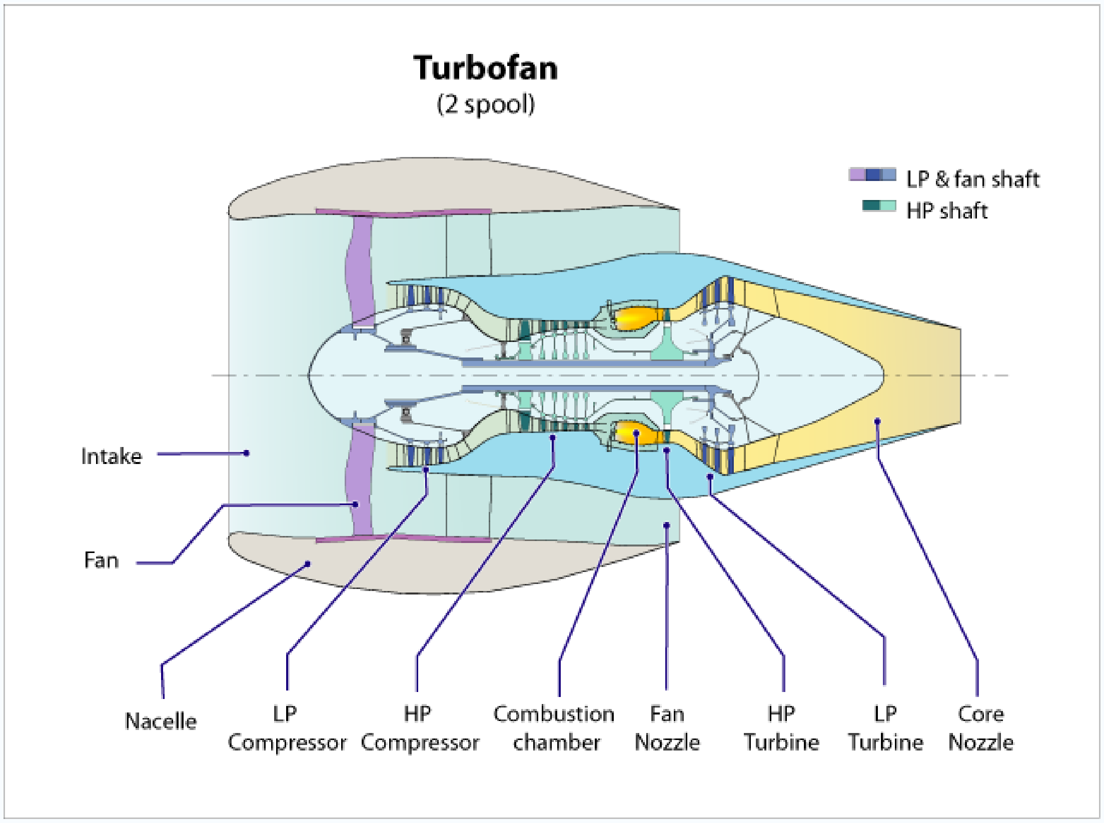
APUs are even more critical for space shuttle flight operations. Unlike aircraft APU's, they provide hydraulic pressure, not electrical power. The space shuttle has three redundant APUs, powered by hydrazine fuel. They only function during powered ascent and during re-entry and landing. During powered ascent, the APUs provides hydraulic power for gimballing of shuttle's engines and control surfaces. During landing, they power the control surfaces and brakes. Landing can be accomplished with only one APU working.

A typical gas turbine APU for commercial transport aircraft comprises three main sections:

- Power section
- Load compressor
- Gearbox

The power section is the gas generator portion of the engine and produces all the power for the APU. The load compressor is generally a shaft- mounted compressor that provides all pneumatic power for the aircraft. There are two actuated devices, the inlet guide vanes that regulate airflow to the load compressor and the surge control valve that maintains stable or surge- free operation of the turbo machine. The third section of the engine is the gearbox. The gearbox transfers power from the main shaft of the engine to an oil- cooled generator for electrical power. Within the gearbox, power is also transferred to engine accessories such as the fuel control unit, the lube module, and cooling fan. In addition, there is also a starter motor connected through the gear train to perform the starting function of the APU.

# Jet Propulsion




Cross section of a high bypass two spool turbofan engine

## Introduction

This book intends to provide an introduction to jet propulsion at the undergraduate level. A jet engine is a type of air-breathing internal combustion engine often used on aircraft. The principle of all jet engines is essentially the same; they accelerate a mass (air and combustion products) in one direction and, from Newton's third law of motion, the engine experiences thrust in the opposite direction.

## Sister books

- Rocket Propulsion
- Aerodynamics
- Computational Fluid Mechanics
- Aero Engines - Aircraft Gas Turbine Engine Technology

## Components

- Propellants
- Static components
    - Intakes
        - Air enters a jet engine via the intake or inlet, which is a carefully shaped duct connecting the streamtube (approaching the inlet) to the compressor face. A major objective is lose as little total (or stagnation) pressure as possible in the

process, whilst minimizing any distortion to the flow entering the compressor. Supersonic intakes often employ cones or ramps to create conical/oblique shock waves to help improve pressure recovery at supersonic flight speeds.

- Combustors
    - Fuel is injected in the combustor and is ignited to heat the compressed air.
    - An afterburner (or reheat) is a combustor located immediately upstream of the engine final nozzle, where fuel is burnt to raise the nozzle entry gas temperature, thereby increasing the net thrust of the engine. Because of the relatively high fuel consumption associated with afterburning, the system has to be used sparingly. A variable area nozzle is normally fitted to accommodate the increased gas volume flow when the afterburner is alight. Increasing the nozzle area enables a satisfactory compression match to be maintained, as nozzle temperature is increased. Afterburning is used mainly on military aircraft to reduce take-off roll and to overcome the additional drag encountered when the aircraft is flying at transonic and supersonic conditions. Concorde, the supersonic airliner, also incorporated engine afterburning, but the system was unlit at supersonic cruise, which considerably enhanced the aircraft's range.

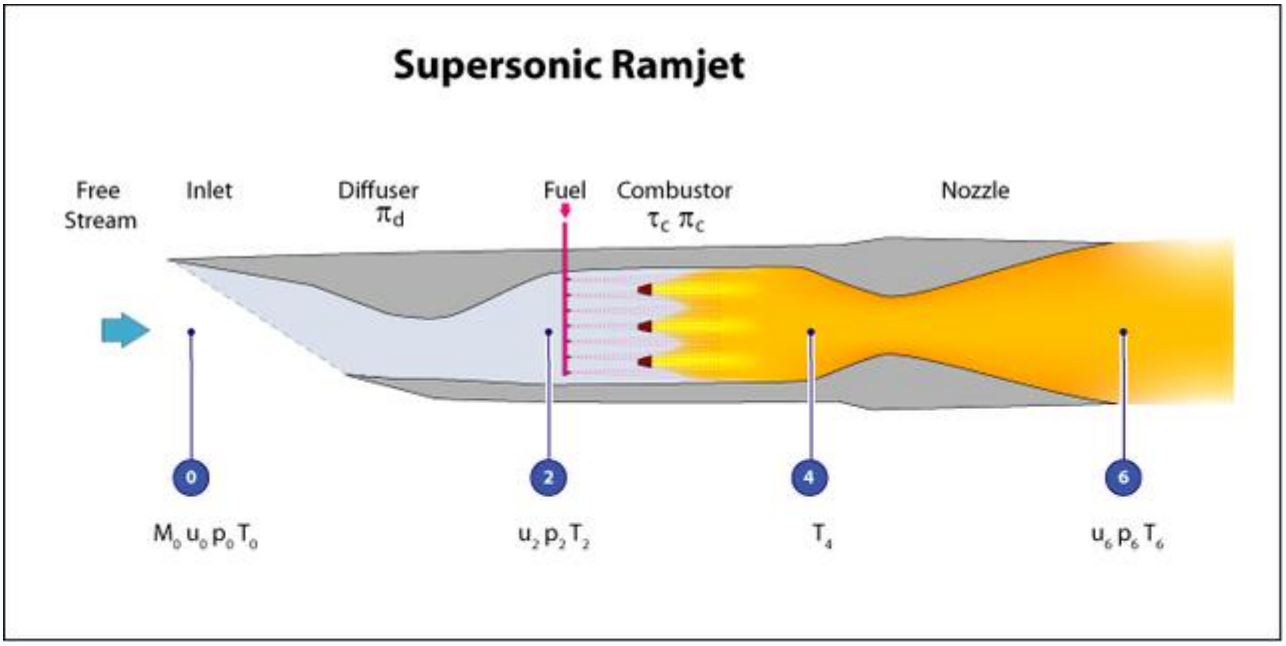
- Nozzles
    - The exhaust gases (and the bypass air on a turbofan) usually expand through a nozzle to ambient pressure, the purpose being to accelerate the flow to a high velocity, by reducing the static pressure of the stream. Normally convergent nozzles, which have a progressive reduction in flow area, are fitted. However, where the nozzle presure ratio is sufficiently high, such as on advanced military engines and supersonic transport engines (e.g.Concorde), a convergent-divergent nozzle may be fitted, to enable the jet accelerate to a supersonic velocity to obtain close to full expansion to ambient pressure. The extra thust obtained is usually sufficient to offset the extra weight of the divergent section. Thrust vectoring nozzles and thrust reversers redirect the jet from the norm of pointing aft.

## Jet Propulsion/Jet engine types

A ramjet uses the open Brayton cycle. No rotating machinery is used and compression is achieved by the intake and diffuser. As such they require speed to compress air enough that good efficiency can be achieved. Ramjets are inefficient at subsonic speeds and their efficiency improves at supersonic speeds.

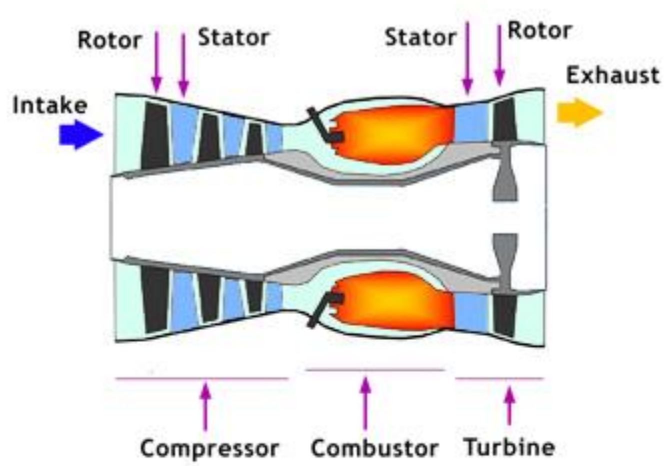
Fuel is injected into the compressed air and burnt using flameholders to stabilize the turbulent flame as in afterburners.

At hypersonic speeds the compression and dissociation processes make full diffusion unattractive and supersonic combustion is being researched. Scramjet slow the air down to low supersonic speeds and then burn high flame velocity fuels such as hydrogen or methane to try to get net thrust.




## Turbojet

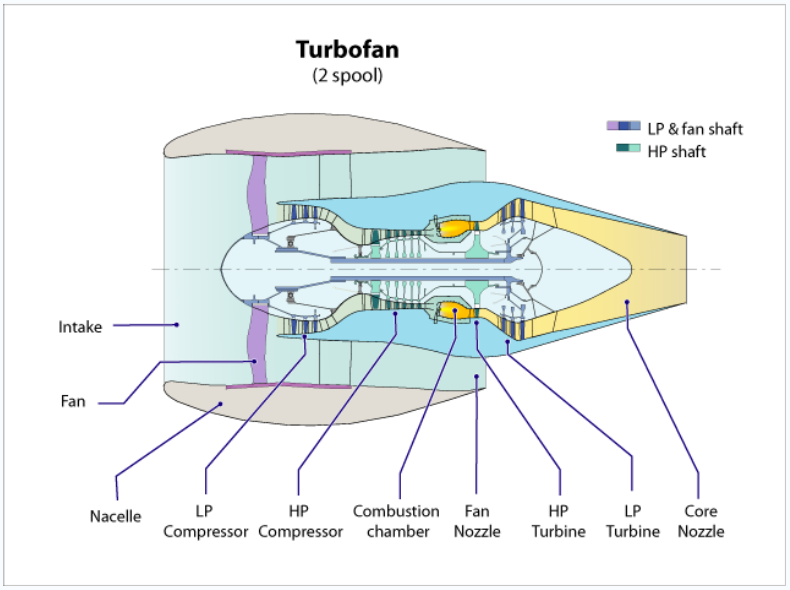
A turbojet adds a rotating compressor powered by a turbine. This allows increased compression beyond the stagnation pressure of the intake and improves the efficiency over a ramjet at lower speeds. The hot air after it leaves the turbine is accelerated by the nozzle and ejected. An afterburner can be used to augment the thrust.




## Turbofan

A shrouded fan allows a larger mass of air to be moved by a shrouded fan whose flow bypasses the core. The relative size of the fan compared to the core is identified by the bypass ratio.

The figure below shows the typical layout of a two shaft high bypass turbofan.




## Propfan

Increasing the size of the fan and the bypass ratio causes a weight penalty. Unducted fans or Propfans have reduced weight penalty. However the increased noise has not been acceptable and they have never been used in production aircraft.

## Turboprop

Turboshaft with a gearbox and a propeller.

## Turboshaft

Intake, Compressor, Combustor, and Turbine powering a shaft. Used in helicopters, APUs, as well as surface applications like tanks, ships, electricity generation.

## Pulse Jet

Uses pulse detonation to close off the intake without primary compression. Intake closure may be dynamic or with mechanical valves such as reed valves.