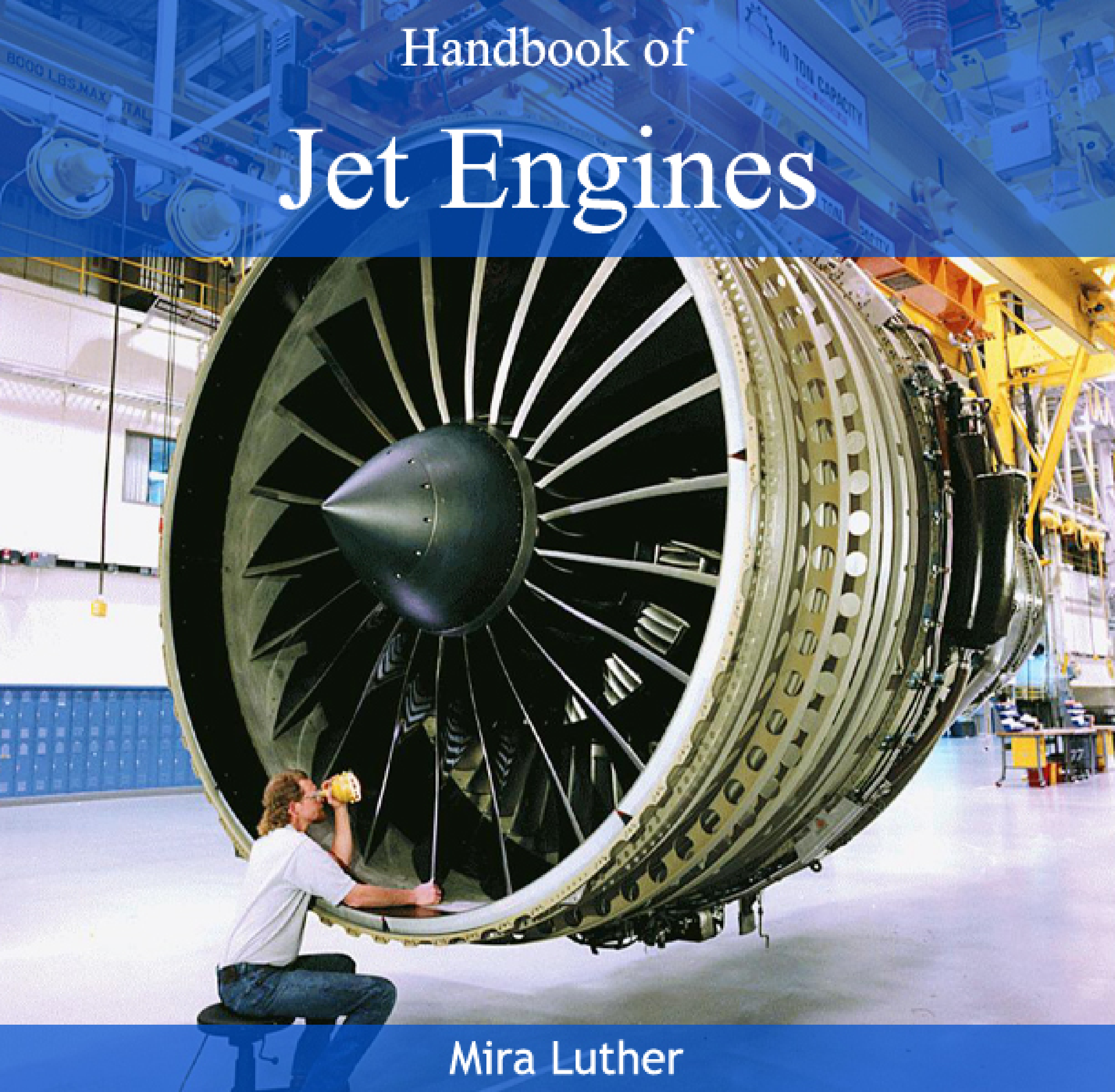
Handbook of Jet Engines



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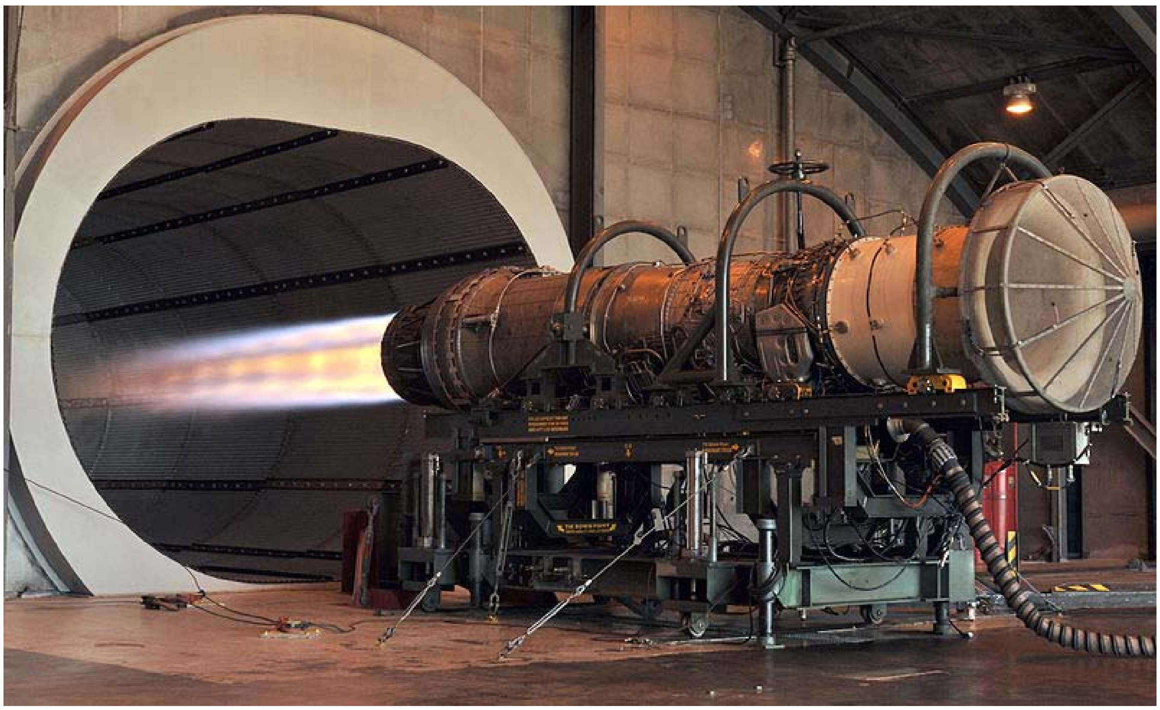
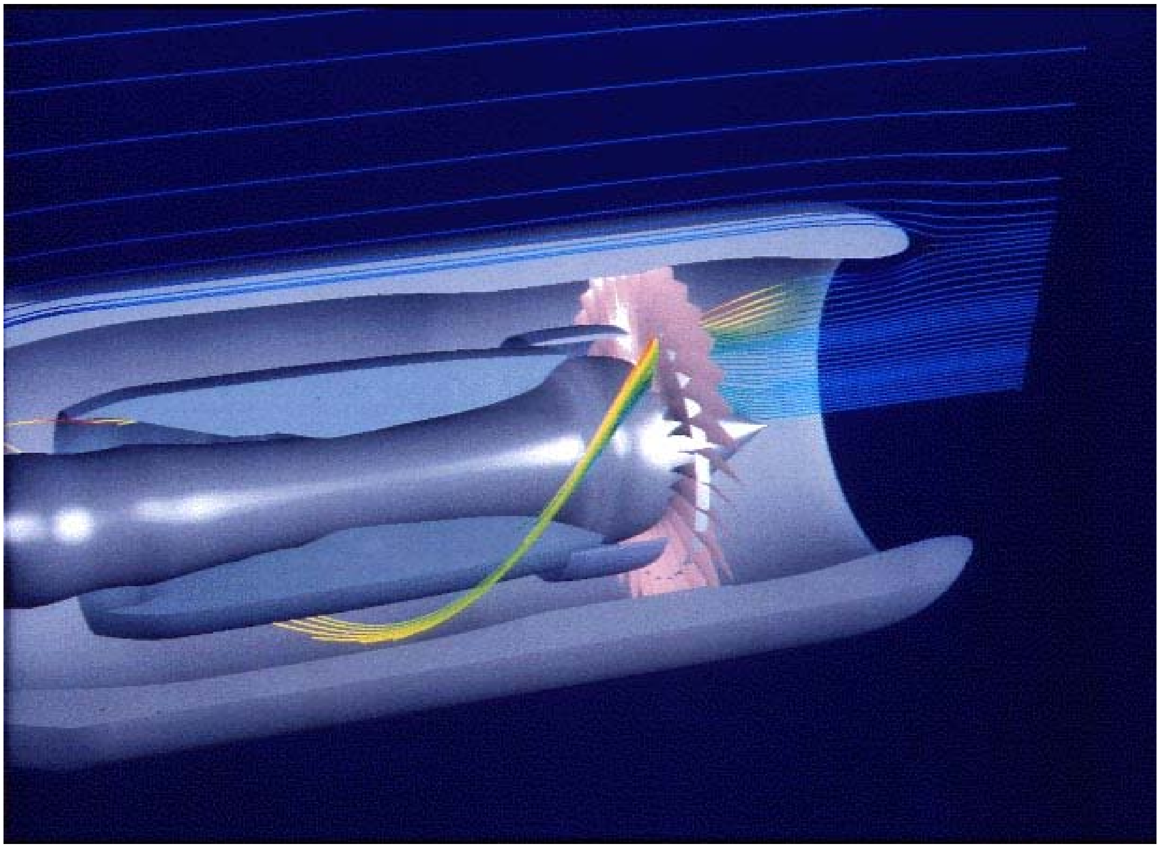
Chapter- 1

Introduction to Jet Engine



A Pratt & Whitney F100 turbofan engine for the F-15 Eagle being tested in the hush house at Florida Air National Guard base. The tunnel behind the engine muffles noise and allows exhaust to escape



Simulation of a low bypass turbofan's airflow

A **jet engine** is a reaction engine that discharges a fast moving jet of fluid to generate thrust by *jet propulsion* and in accordance with Newton's laws of motion. This broad definition of jet engines includes turbojets, turbofans, rockets, ramjets, pulse jets and pump-jets. In general, most jet engines are internal combustion engines but non-combusting forms also exist.

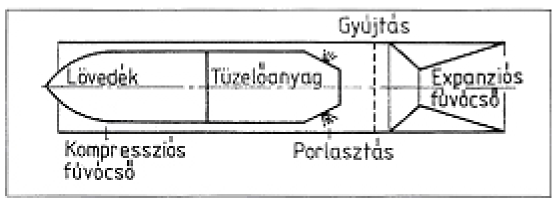
In common parlance, the term *jet engine* loosely refers to an internal combustion airbreathing jet engine (a *duct engine*). These typically consist of an engine with a rotary (rotating) air compressor powered by a turbine ("Brayton cycle"), with the leftover power providing thrust via a propelling nozzle. These types of jet engines are primarily used by jet aircraft for long distance travel. Early jet aircraft used turbojet engines which were relatively inefficient for subsonic flight. Modern subsonic jet aircraft usually use high-bypass turbofan engines which give high speeds, as well as (over long distances) better fuel efficiency than many other forms of transport.

History

Jet engines can be dated back to the invention of the aeolipile before the first century AD. This device used steam power directed through two nozzles to cause a sphere to spin rapidly on its axis. So far as is known, it was not used for supplying mechanical power, and the potential practical applications of this invention were not recognized. It was simply considered a curiosity.

Jet propulsion only took off, literally and figuratively, with the invention of the gunpowder-powered rocket by the Chinese in the 13th century as a type of fireworks, and gradually progressed to propel formidable weaponry. However, although very powerful, at reasonable flight speeds rockets are very inefficient and so jet propulsion technology stalled for hundreds of years.

The earliest attempts at airbreathing jet engines were hybrid designs in which an external power source first compressed air, which was then mixed with fuel and burned for jet thrust. In one such system, called a *thermojet* by Secondo Campini but more commonly, motorjet, the air was compressed by a fan driven by a conventional piston engine. Examples of this type of design were the Caproni Campini N.1, and the Japanese Tsu-11 engine intended to power Ohka kamikaze planes towards the end of World War II. None were entirely successful and the N.1 ended up being slower than the same design with a traditional engine and propeller combination.



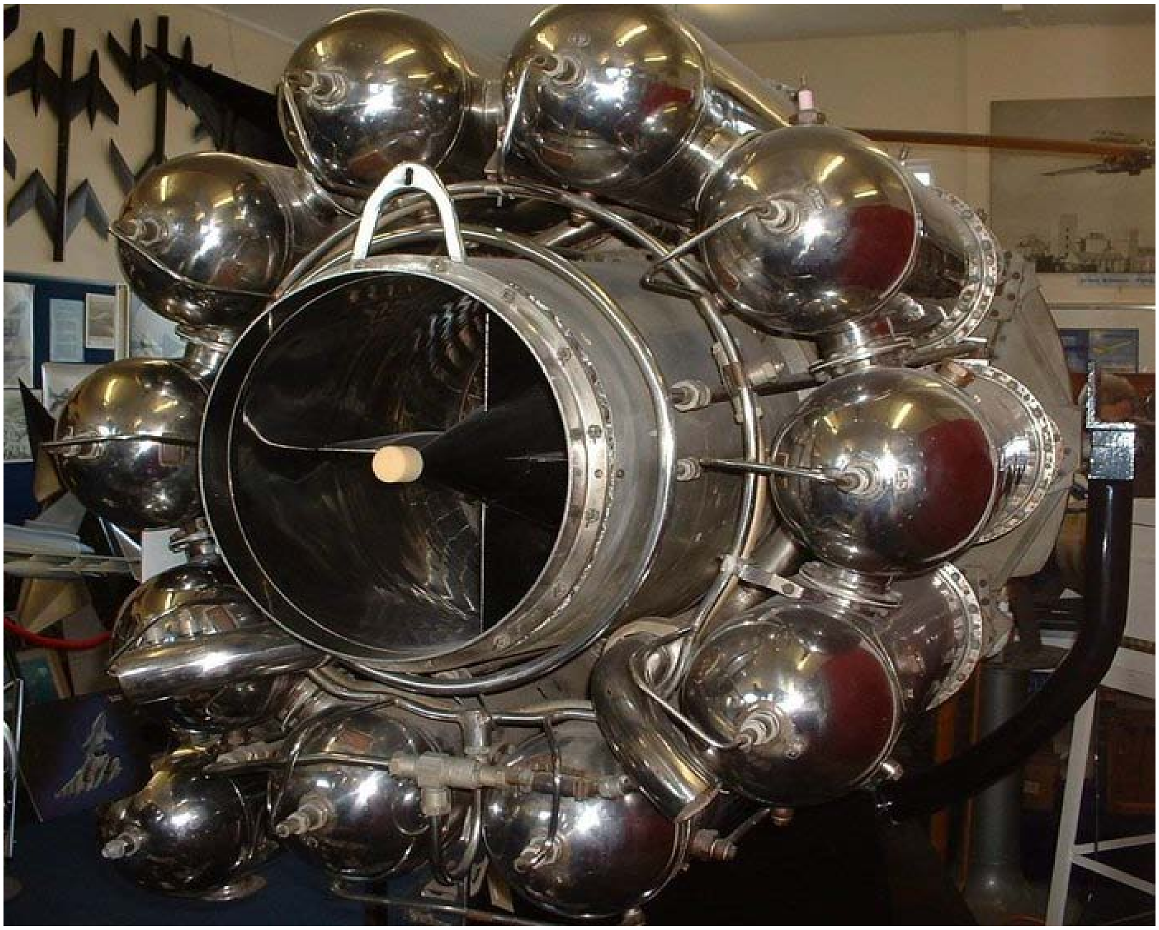
Albert Fonó's ramjet-cannonball from 1915

Even before the start of World War II, engineers were beginning to realize that the piston engine was self-limiting in terms of the maximum performance which could be attained; the limit was due to issues related to propeller efficiency, which declined as blade tips approached the speed of sound. If engine, and thus aircraft, performance were ever to increase beyond such a barrier, a way would have to be found to radically improve the design of the piston engine, or a wholly new type of powerplant would have to be developed. This was the motivation behind the development of the gas turbine engine, commonly called a "jet" engine, which would become almost as revolutionary to aviation as the Wright brothers' first flight.

The key to a practical jet engine was the gas turbine, used to extract energy from the engine itself to drive the compressor. The gas turbine was not an idea developed in the 1930s: the patent for a stationary turbine was granted to John Barber in England in 1791. The first gas turbine to successfully run self-sustaining was built in 1903 by Norwegian engineer Ægidius Elling. Limitations in design and practical engineering and metallurgy prevented such engines reaching manufacture. The main problems were safety, reliability, weight and, especially, sustained operation.

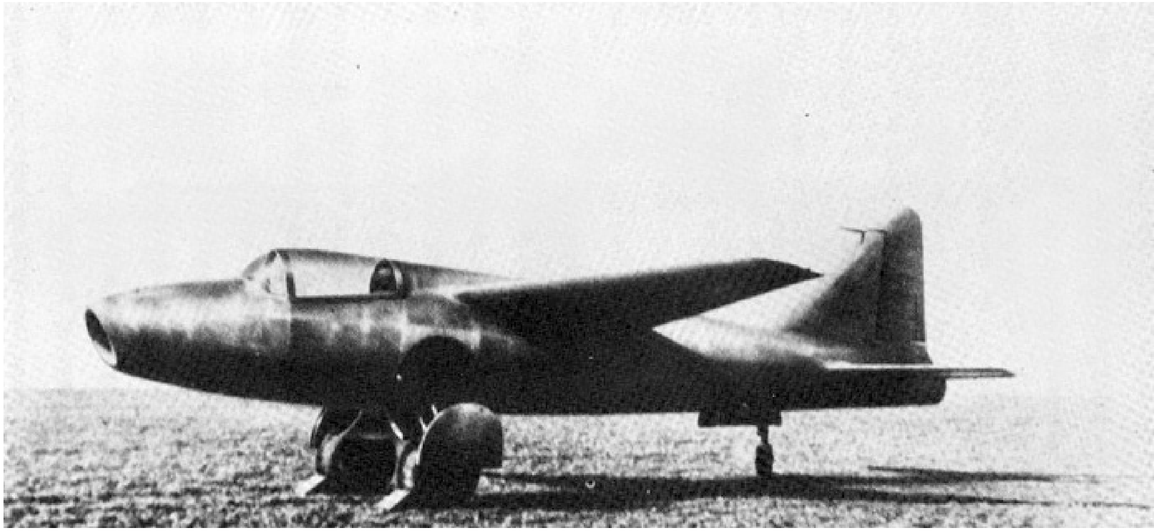
The first patent for using a gas turbine to power an aircraft was filed in 1921 by Frenchman Maxime Guillaume. His engine was an axial-flow turbojet. Alan Arnold

Griffith published *An Aerodynamic Theory of Turbine Design* in 1926 leading to experimental work at the RAE.



The Whittle W.2/700 engine flew in the Gloster E.28/39, the first British aircraft to fly with a turbojet engine, and the Gloster Meteor

In 1928, RAF College Cranwell cadet Frank Whittle formally submitted his ideas for a turbo-jet to his superiors. In October 1929 he developed his ideas further. On 16 January 1930 in England, Whittle submitted his first patent (granted in 1932). The patent showed a two-stage axial compressor feeding a single-sided centrifugal compressor. Practical axial compressors were made possible by ideas from A.A.Griffith in a seminal paper in 1926 ("An Aerodynamic Theory of Turbine Design"). Whittle would later concentrate on the simpler centrifugal compressor only, for a variety of practical reasons. Whittle had his first engine running in April 1937. It was liquid-fuelled, and included a self-contained fuel pump. Whittle's team experienced near-panic when the engine would not stop, accelerating even after the fuel was switched off. It turned out that fuel had leaked into the engine and accumulated in pools, so the engine would not stop until all the leaked fuel had burned off. Whittle was unable to interest the government in his invention, and development continued at a slow pace.



Heinkel He 178, the world's first aircraft to fly purely on turbojet power

In 1935 Hans von Ohain started work on a similar design in Germany, apparently unaware of Whittle's work. His first device was strictly experimental and could only run under external power, but he was able to demonstrate the basic concept. Ohain was then introduced to Ernst Heinkel, one of the larger aircraft industrialists of the day, who immediately saw the promise of the design. Heinkel had recently purchased the Hirth engine company, and Ohain and his master machinist Max Hahn were set up there as a new division of the Hirth company. They had their first HeS 1 centrifugal engine running by September 1937. Unlike Whittle's design, Ohain used hydrogen as fuel, supplied under external pressure. Their subsequent designs culminated in the gasoline-fuelled HeS 3 of 1,100 lbf (5 kN), which was fitted to Heinkel's simple and compact He 178 airframe and flown by Erich Warsitz in the early morning of August 27, 1939, from Rostock-Marienehe aerodrome, an impressively short time for development. The He 178 was the world's first jet plane.

A cutaway of the Junkers Jumo 004 engine

Austrian Anselm Franz of Junkers' engine division (*Junkers Motoren* or **Jumo**) introduced the axial-flow compressor in their jet engine. Jumo was assigned the next engine number in the RLM **109-0xx** numbering sequence for gas turbine aircraft powerplants, "004", and the result was the Jumo 004 engine. After many lesser technical difficulties were solved, mass production of this engine started in 1944 as a powerplant for the world's first jet-fighter aircraft, the Messerschmitt Me 262 (and later the world's first jet-bomber aircraft, the Arado Ar 234). A variety of reasons conspired to delay the engine's availability, causing the fighter to arrive too late to improve Germany's position in World War II. Nonetheless, it will be remembered as the first use of jet engines in service.

Meanwhile, in Britain the Gloster E28/39 had its maiden flight on 15 May 1941 and the Gloster Meteor finally entered service with the RAF in July 1944.

Following the end of the war the German jet aircraft and jet engines were extensively studied by the victorious allies and contributed to work on early Soviet and US jet fighters. The legacy of the axial-flow engine is seen in the fact that practically all jet engines on fixed wing aircraft have had some inspiration from this design.

By the 1950s the jet engine was almost universal in combat aircraft, with the exception of cargo, liaison and other specialty types. By this point some of the British designs were already cleared for civilian use, and had appeared on early models like the de Havilland Comet and Avro Canada Jetliner. By the 1960s all large civilian aircraft were also jet powered, leaving the piston engine in low-cost niche roles such as cargo flights.

The efficiency of turbojet engines was still rather worse than piston engines but by the 1970s, with the advent of high bypass turbofan jet engines, an innovation not foreseen by the early commentators such as Edgar Buckingham, at high speeds and high altitudes that seemed absurd to them, fuel efficiency was about the same as the best piston and propeller engines.

Uses

Jet engines are usually used as aircraft engines for jet aircraft. They are also used for cruise missiles and unmanned aerial vehicles.

In the form of rocket engines they are used for fireworks, model rocketry, spaceflight, and military missiles.

Jet engines have also been used to propel high speed cars, particularly drag racers, with the all-time record held by a rocket car. A turbofan powered car ThrustSSC currently holds the land speed record.

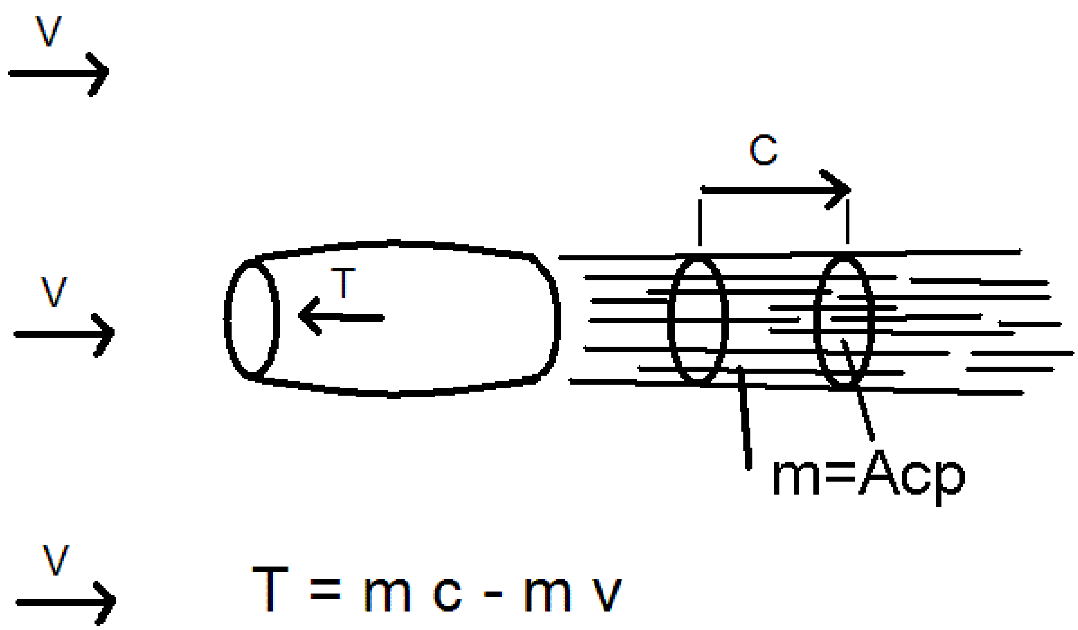
Jet engine designs are frequently modified for non-aircraft applications, as industrial gas turbines. These are used in electrical power generation, for powering water, natural gas, or oil pumps, and providing propulsion for ships and locomotives. Industrial gas turbines can create up to 50,000 shaft horsepower. Many of these engines are derived from older military turbojets such as the Pratt & Whitney J57 and J75 models. There is also a derivative of the P&W JT8D low-bypass turbofan that creates up to 35,000 HP.

General physical principles

All jet engines are reaction engines that generate thrust by emitting a jet of fluid rearwards at relatively high speed. The forces on the inside of the engine needed to create this jet give a strong thrust on the engine which pushes the craft forwards.

Jet engines make their jet from propellant from tankage that is attached to the engine (as in a 'rocket') as well as in **duct engines** (those commonly used on aircraft) by ingesting an external fluid (very typically air) and expelling it at higher speed.

Thrust



Thrust from airbreathing jet engines depends on the difference in speed of the air before and after it goes through the jet engine, the 'master cross-section' A, and the density of the air p

The motion impulse of the engine is equal to the fluid mass multiplied by the speed at which the engine emits this mass:

$$I = mc$$

where m is the fluid mass per second and c is the exhaust speed. In other words, a vehicle gets the same thrust if it outputs a lot of exhaust very slowly, or a little exhaust very quickly. (In practice parts of the exhaust may be faster than others, but it is the *average* momentum that matters, and thus the important quantity is called the **effective exhaust speed** - c here.)

However, when a vehicle moves with certain velocity v, the fluid moves towards it, creating an opposing ram drag at the intake:

$$mv$$

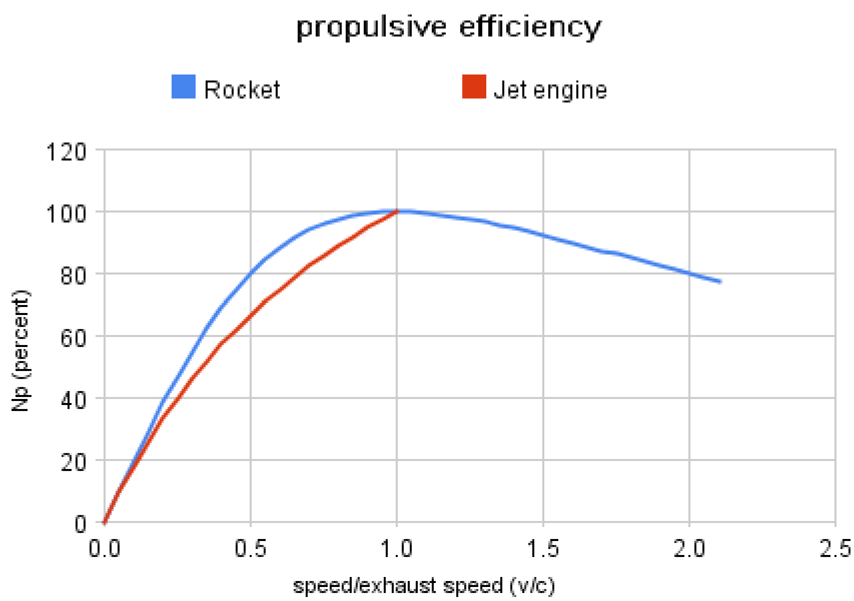
Most types of jet engine have an intake, which provides the bulk of the fluid exiting the exhaust. Conventional rocket motors, however, do not have an intake, the oxidizer and fuel both being carried within the vehicle. Therefore, rocket motors do not have ram drag; the gross thrust of the nozzle is the net thrust of the engine. Consequently, the thrust characteristics of a rocket motor are different from that of an air breathing jet engine, and thrust is independent of speed.

The jet engine with an intake duct is only useful if the velocity of the gas from the engine, c, is greater than the vehicle velocity, v, as the net engine thrust is the same as if the gas were emitted with the velocity $c - v$. So the thrust is actually equal to

$$S = m(c - v)$$

This equation shows that as v approaches c, a greater mass of fluid must go through the engine to continue to accelerate at the same rate, but all engines have a designed limit on this. Additionally, the equation implies that the vehicle can't accelerate past its exhaust velocity as it would have negative thrust.

Energy efficiency



Dependence of the energy efficiency (η) upon the vehicle speed/exhaust speed ratio (v/c) for air-breathing jet and rocket engines

Energy efficiency (η) of jet engines installed in vehicles has two main components, *cycle efficiency* (η_c)- how efficiently the engine can accelerate the jet, and *propulsive efficiency* (η_p)-how much of the energy of the jet ends up in the vehicle body rather than being carried away as kinetic energy of the jet.

Even though overall energy efficiency η is simply:

$$\eta = \eta_p \eta_c$$

Propulsive efficiency

For all jet engines the *propulsive efficiency* is highest when the engine emits an exhaust jet at a speed that is the same as, or nearly the same as, the vehicle velocity as this gives the smallest residual kinetic energy.(Note:) The exact formula for air-breathing engines moving at speed *v* with an exhaust velocity *c* is given in the literature as: is

$$\eta_p = \frac{2}{1 + \frac{c}{v}}$$

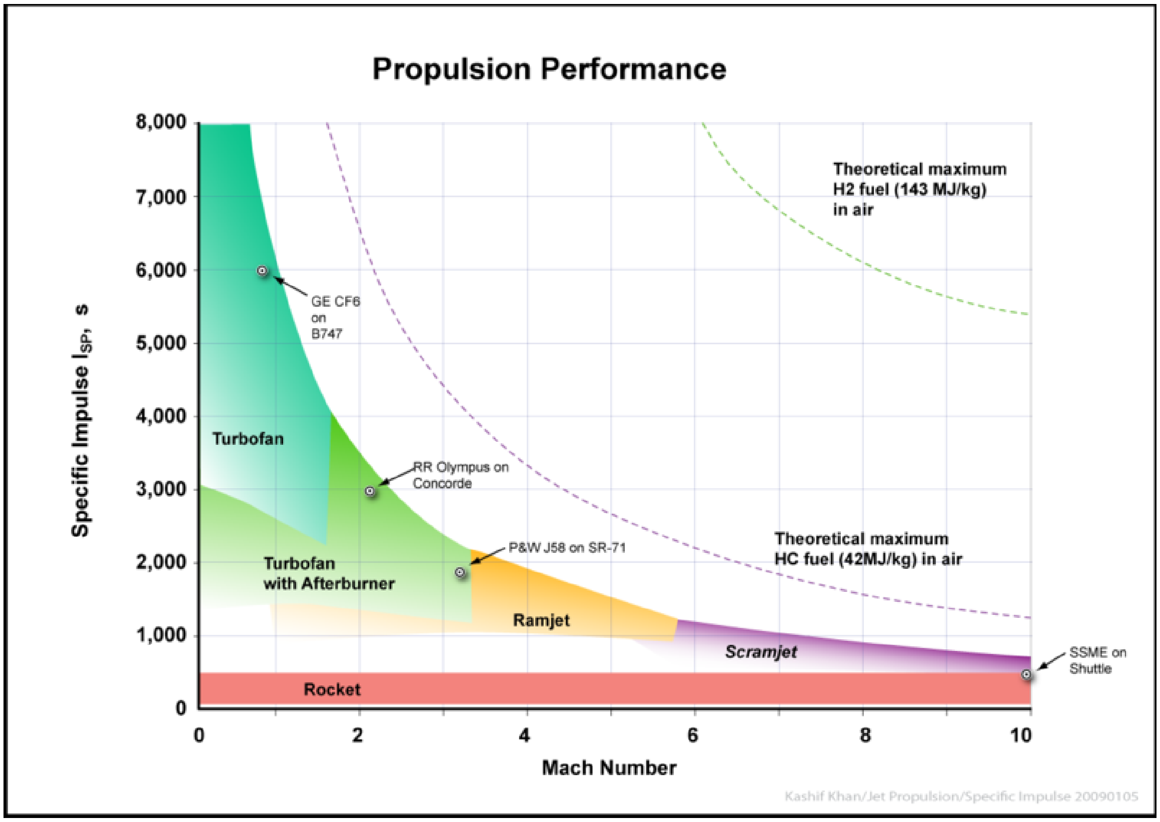
And for a rocket:

$$\eta_p = \frac{2\frac{v}{c}}{1 + (\frac{v}{c})^2}$$

Cycle efficiency

In addition to propulsive efficiency, another factor is cycle efficiency; essentially a jet engine is typically a form of heat engine. Heat engine efficiency is determined by the ratio of temperatures that are reached in the engine, in this case at the entry to the propulsive nozzle, to the temperature that they are exhausted at, which in turn is limited by the overall pressure ratio that can be achieved.

Cycle efficiency is highest in rocket engines (~60+%), as they can achieve extremely high combustion temperatures and can have very large, energy efficient nozzles. Cycle efficiency in turbojet and similar is nearer to 30%, the practical combustion temperatures and nozzle efficiencies are much lower.



Specific impulse as a function of speed for different jet types with kerosene fuel (hydrogen I_{sp} would be about twice as high). Although efficiency plummets with speed, greater distances are covered, it turns out that efficiency per unit distance (per km or mile) is roughly independent of speed for jet engines as a group; however airframes become inefficient at supersonic speeds

Fuel/propellant consumption

A closely related (but different) concept to energy efficiency is the rate of consumption of propellant mass. Propellant consumption in jet engines is measured by **Specific Fuel**

Consumption, **Specific impulse** or **Effective exhaust velocity**. They all measure the same thing. Specific impulse and effective exhaust velocity are strictly proportional, whereas specific fuel consumption is inversely proportional to the others.

For airbreathing engines such as turbojets energy efficiency and propellant (fuel) efficiency are much the same thing, since the propellant is a fuel and the source of energy. In rocketry, the propellant is also the exhaust, and this means that a high energy propellant gives better propellant efficiency but can in some cases actually can give *lower* energy efficiency.

Engine type	Scenario	SFC in lb/(lbf·h)	SFC in g/(kN·s)	Specific impulse (s)	Effective exhaust velocity (m/s)
NK-33 rocket engine	Vacuum	10.9	309	330	3,240
SSME rocket engine	Space shuttle vacuum	7.95	225	453	4,423
Ramjet	Mach 1	4.5	127	800	7,877
J-58 turbojet	SR-71 at Mach 3.2 (Wet)	1.9	53.8	1,900	18,587
Rolls-Royce/Snecma Olympus 593	Concorde Mach 2 cruise (Dry)	1.195	33.8	3,012	29,553
CF6-80C2B1F turbofan	Boeing 747-400 cruise	0.605	17.1	5,950	58,400
General Electric CF6 turbofan	Sea level	0.307	8.696	11,700	115,000

It can be seen that the subsonic turbofans such as General Electric's CF6 uses a lot less fuel to generate thrust for a second than Concorde's turbojet, the 593. However, since energy is force times distance and the distance per second is greater for Concorde, the actual power generated by the engine for the same amount of fuel is higher for Concorde at Mach 2 cruise than the CF6- Concorde's engines are more efficient for *thrust per mile*, indeed, the most efficient ever.

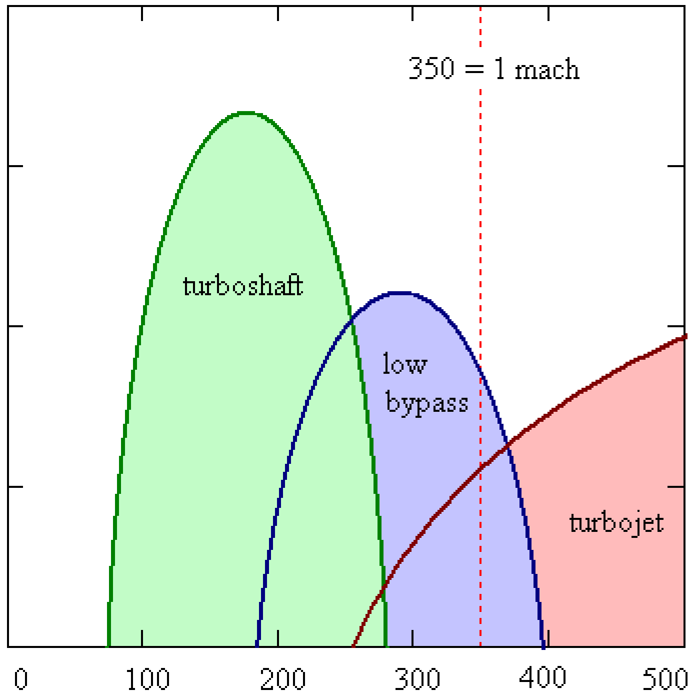
Thrust-to-weight ratio

The thrust to weight ratio of jet engines of similar principles varies somewhat with scale, but mostly is a function of engine construction technology. Clearly for a given engine, the lighter the engine, the better the thrust to weight is, the less fuel is used to compensate for drag due to the lift needed to carry the engine weight, or to accelerate the mass of the engine.

As can be seen in the following table, rocket engines generally achieve very much higher thrust to weight ratios than duct engines such as turbojet and turbofan engines. This is primarily because rockets almost universally use dense liquid or solid reaction mass which gives a much smaller volume and hence the pressurisation system that supplies the nozzle is much smaller and lighter for the same performance. Duct engines have to deal with air which is 2-3 orders of magnitude less dense and this gives pressures over much larger areas, and which in turn results in more engineering materials being needed to hold the engine together and for the air compressor.

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2
RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME rocket engine	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

Comparison of types



Comparative suitability for (left to right) turboshaft, low bypass and turbojet to fly at 10 km altitude in various speeds. Horizontal axis - speed, m/s. Vertical axis displays engine efficiency.

Propeller engines are useful for comparison. They accelerate a large mass of air but by a relatively small maximum change in speed. This low speed limits the maximum thrust of any propeller driven airplane. However, because they accelerate a large mass of air, propeller engines, such as turboprops, can be very efficient.

On the other hand, turbojets accelerate a much smaller mass of the air and burned fuel, but they emit it at the much higher speeds possible with a de Laval nozzle. This is why they are suitable for supersonic and higher speeds.

Low bypass turbofans have the mixed exhaust of the two air flows, running at different speeds (c1 and c2). The thrust of such engine is

$$S = m1\ (c1 - v) + m2\ (c2 - v)$$

where m1 and m2 are the air masses, being blown from the both exhausts. Such engines are effective at lower speeds, than the pure jets, but at higher speeds than the turboshafts and propellers in general. For instance, at the 10 km altitude, turboshafts are most effective at about Mach 0.4 (0.4 times the speed of sound), low bypass turbofans become more effective at about Mach 0.75 and turbojets become more effective than mixed exhaust engines when the speed approaches Mach 2-3.

Rocket engines have extremely high exhaust velocity and thus are best suited for high speeds (hypersonic) and great altitudes. At any given throttle, the thrust and efficiency of a rocket motor improves slightly with increasing altitude (because the back-pressure falls thus increasing net thrust at the nozzle exit plane), whereas with a turbojet (or turbofan) the falling density of the air entering the intake (and the hot gases leaving the nozzle) causes the net thrust to decrease with increasing altitude. Rocket engines are more efficient than even scramjets above roughly Mach 15.

Altitude and speed

With the exception of scramjets, jet engines, deprived of their inlet systems can only accept air at around half the speed of sound. The inlet system's job for transonic and supersonic aircraft is to slow the air and perform some of the compression.

The limit on maximum altitude for engines is set by flammability- at very high altitudes the air becomes too thin to burn, or after compression, too hot. For turbojet engines altitudes of about 40 km appear to be possible, whereas for ramjet engines 55 km may be achievable. Scramjets may theoretically manage 75 km. Rocket engines of course have no upper limit.

At more modest altitudes, flying faster compresses the air in at the front of the engine, and this greatly heats the air. The upper limit is usually thought to be about Mach 5-8, as above about Mach 5.5, the atmospheric nitrogen tends to react due to the high temperatures at the inlet and this consumes significant energy. The exception to this is scramjets which may be able to achieve about Mach 15 or more, as they avoid slowing the air, and rockets again have no particular speed limit.

Noise

Noise is due to shockwaves that form when the exhaust jet interacts with the external air. The intensity of the noise is proportional to the thrust as well as proportional to the fourth power of the jet velocity.Generally then, the lower speed exhaust jets emitted from engines such as high bypass turbofans are the quietest, whereas the fastest jets are the loudest.

Although some variation in jet speed can often be arranged from a jet engine (such as by throttling back and adjusting the nozzle) it is difficult to vary the jet speed from an engine over a very wide range. Engines for supersonic vehicles such as Concorde, military jets and rockets need to have supersonic exhaust to support their top speeds, making them especially noisy even at low speed.

Chapter- 2

Turbojet

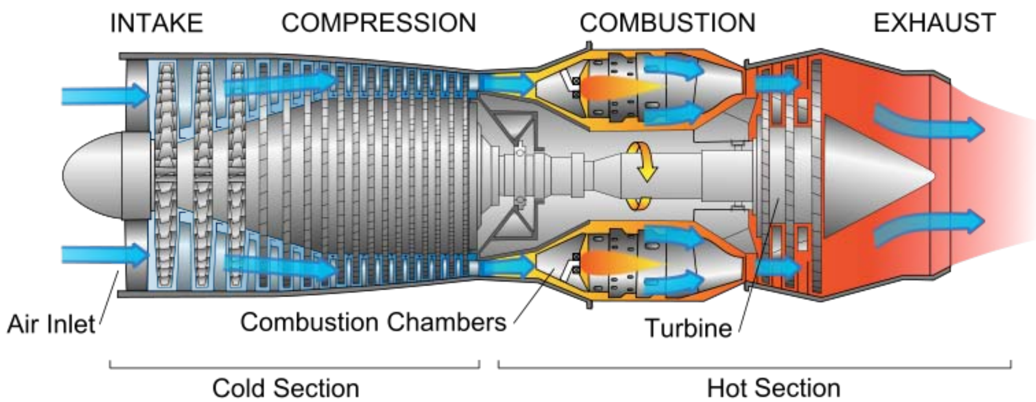


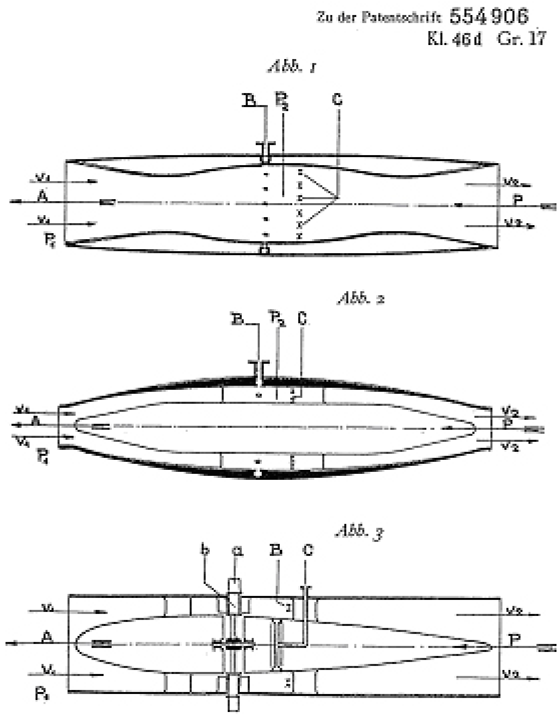
Diagram of a typical gas turbine jet engine

The **turbojet** is the oldest kind of general-purpose jet engine. Two engineers, Frank Whittle in the United Kingdom and Hans von Ohain in Germany, developed the concept independently into practical engines during the late 1930s.

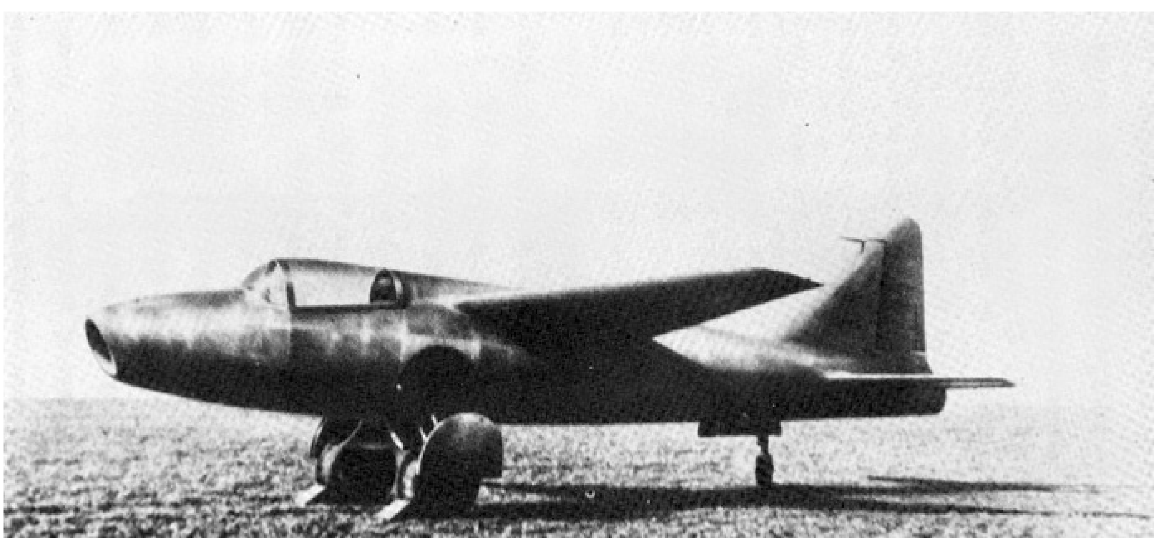
Turbojets consist of an air inlet, an air compressor, a combustion chamber, a gas turbine (that drives the air compressor) and a nozzle. The air is compressed into the chamber, heated and expanded by the fuel combustion and then allowed to expand out through the turbine into the nozzle where it is accelerated to high speed to provide propulsion.

Turbojets are quite inefficient if flown below about Mach 2. and very noisy. Most modern aircraft use turbofans instead for economic reasons. Turbojets are still very common in medium range cruise missiles, due to their high exhaust speed, low frontal area and relative simplicity.

History



Albert Fonó's German patent for jet Engines (January 1928). The third illustration is a turbojet



Heinkel He 178, the world's first aircraft to fly purely on turbojet power, using an HeS 3 engine

The first patent for using a gas turbine to power an aircraft was filed in 1921 by Frenchman Maxime Guillaume. His engine was to be an axial-flow turbojet, but was never constructed, as it would have required considerable advances over the state of the art in compressors.

Practical axial compressors were made possible by ideas from A.A.Griffith in a seminal paper in 1926 ("An Aerodynamic Theory of Turbine Design").

On 27 August 1939 the Heinkel He 178 became the world's first aircraft to fly under turbojet power with test-pilot Erich Warsitz at the controls, thus becoming the first practical jet plane. The first two operational turbojet aircraft, the Messerschmitt Me 262 and then the Gloster Meteor entered service towards the end of World War II in 1944.

A turbojet engine is used primarily to propel aircraft, but has been used for other vehicles, such as cars. 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 a 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 momentum of the exhaust stream exceeds the momentum of the intake stream, the impulse is positive, thus, there is a net forward thrust upon the airframe.

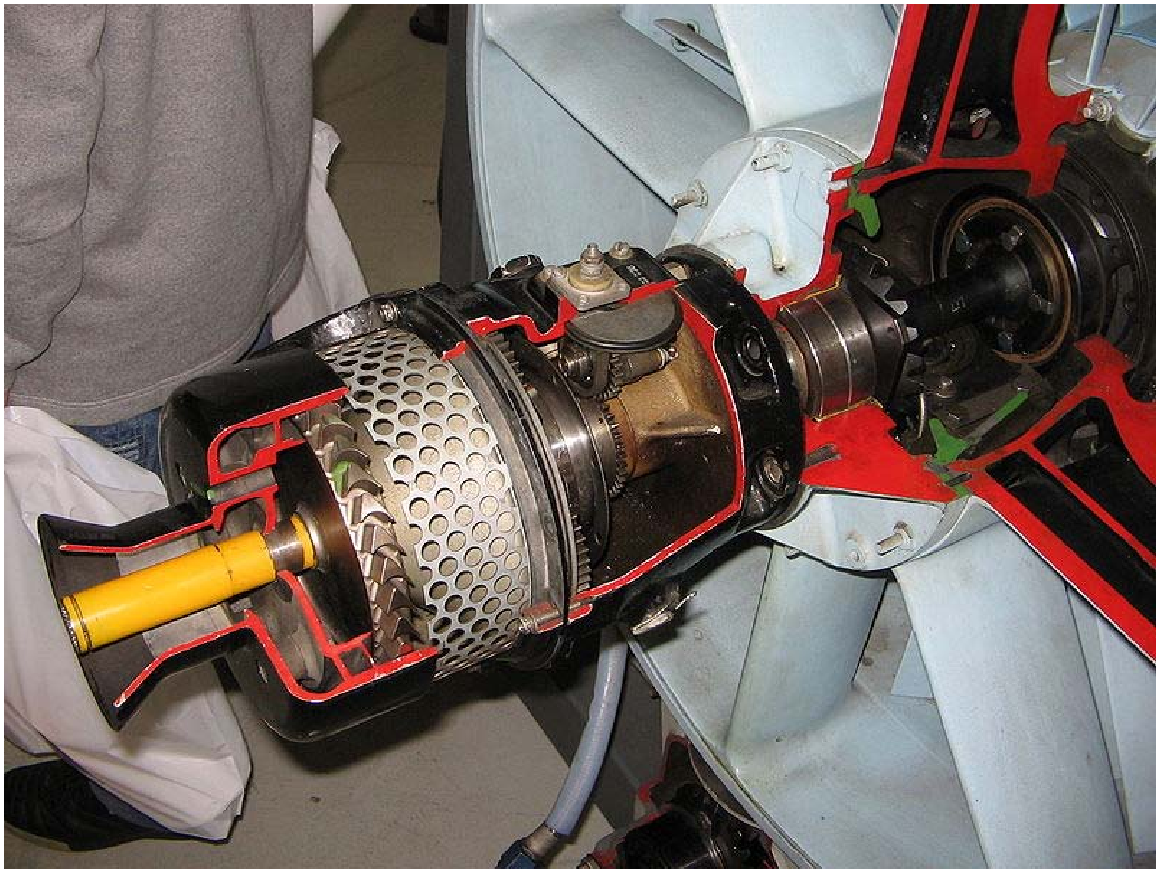
Early generation jet engines were pure turbojets, designed initially to use a centrifugal compressor (as in the Heinkel HeS 3), and very shortly afterwards began to use Axial compressors (as in the Junkers Jumo 004) for a smaller diameter to the overall engine housing. They were used because they were able to achieve very high altitudes and speeds, much higher than propeller engines, because of a better compression ratio and because of their high exhaust speed. However, they were not very fuel efficient. Modern jet engines are mainly turbofans, where a proportion of the air entering the intake bypasses the combustor; this proportion depends on the engine's bypass ratio. This makes turbofans much more efficient than turbojets at high subsonic/transonic and low supersonic speeds.

One of the most recent uses of turbojet engines was the Olympus 593 on Concorde. Concorde used turbojet engines because it turns out that the small cross-section and high exhaust speed is ideal for operation at Mach 2. Concorde's engine burnt less fuel to produce a given thrust for a mile at Mach 2.0 than a modern high-bypass turbofan such as General Electric CF6 at its Mach 0.86 optimum speed. Concorde's airframe, however, was far less efficient than that of any subsonic airliner.

Turbojet engines had a significant impact on commercial aviation. Aside from being faster than piston engines, turbojets had greater reliability, with some models demonstrating dispatch reliability rating in excess of 99.9%. Pre-jet commercial aircraft were designed with as many as 4 engines in part because of concerns over in-flight failures. Overseas flight paths were plotted to keep planes within an hour of a landing field, lengthening flights. Turbojets' reliability allowed for three and two-engine designs, and more direct long-distance flights.

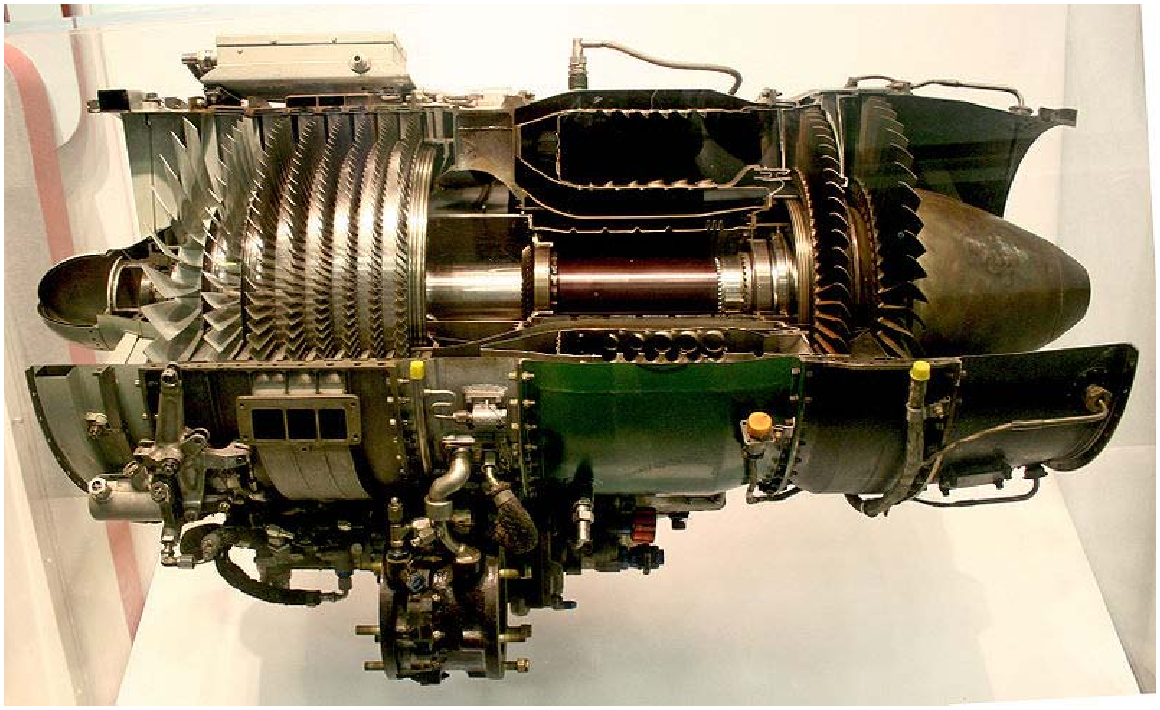
Although ramjet engines are simpler in design as they have virtually no moving parts, they are incapable of operating at low flight speeds.

Early designs



Cutaway of an air start system of a General Electric J79 turbojet. The small turbine and epicyclic gearing are clearly visible

Early German engines had serious problems controlling the turbine inlet temperature. A lack of suitable alloys due to war shortages meant the turbine rotor and stator blades would sometimes disintegrate on first operation and never lasted long. Their early engines averaged 10–25 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, running for 150 hours between overhauls. A few of the original fighters still exist with their original engines, but many have been re-engined with more modern engines with greater fuel efficiency and a longer TBO (such as the reproduction Me-262 powered by General Electric J85s).



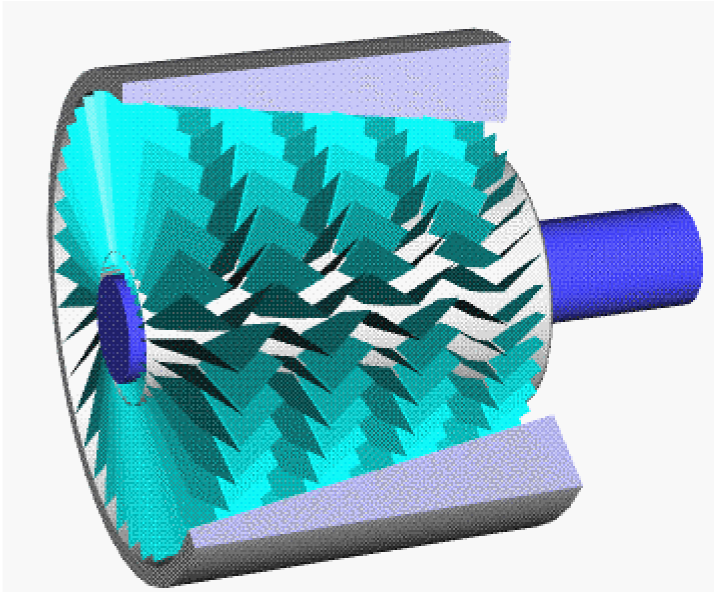
J85-GE-17A turbojet engine from General Electric (1970)

The United States had the best materials because of their reliance on turbo/supercharging 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 take off leaving a huge plume of smoke.

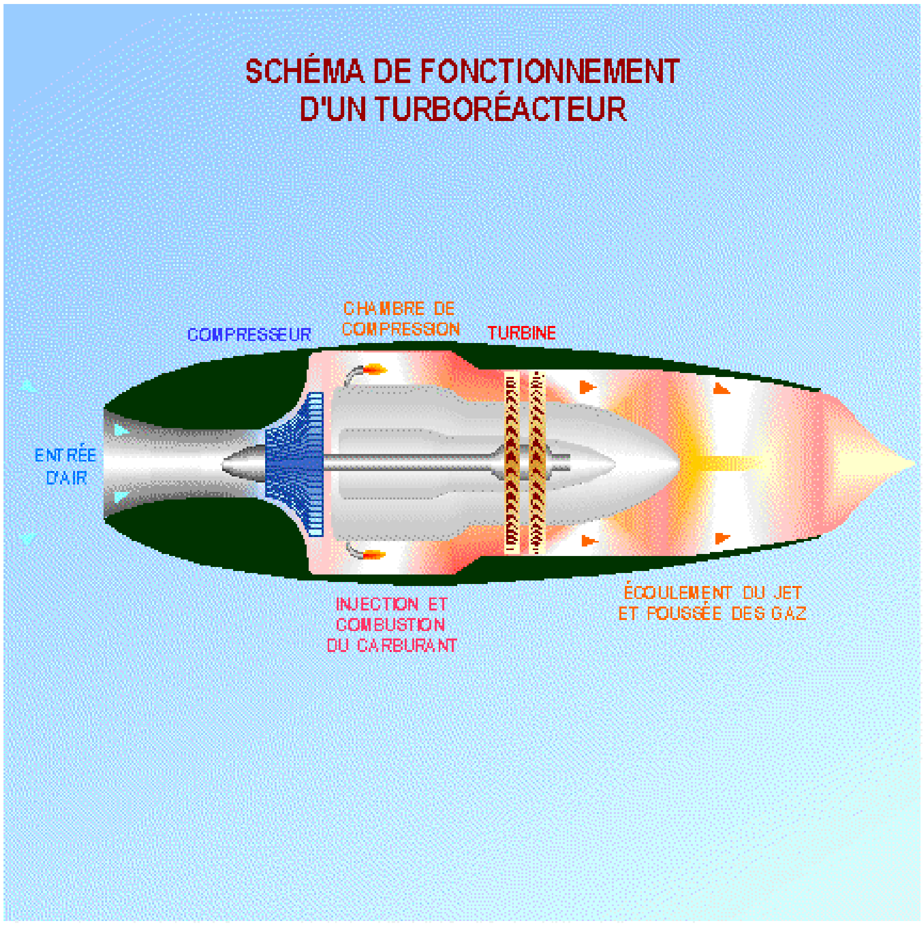
Today these problems are much better handled, but temperature still limits turbojet airspeeds in supersonic flight. At the very highest speeds, the compression of the intake air raises the temperatures throughout the engine to the point that the turbine blades would melt, forcing a reduction in fuel flow to lower temperatures, but giving a reduced thrust and thus limiting the top speed. Ramjets and scramjets do not have turbine blades; therefore they are able to fly faster, and rocket engines run even hotter still.

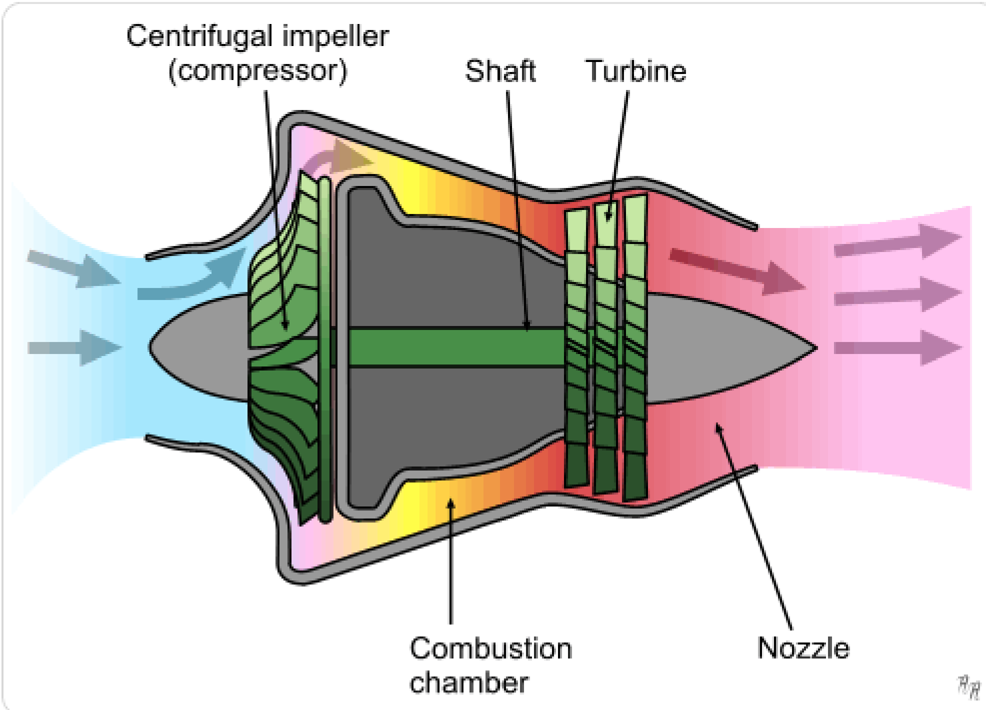
At lower speeds, better materials have increased the critical temperature, and automatic fuel management controls have made it nearly impossible to overheat the engine.

Design

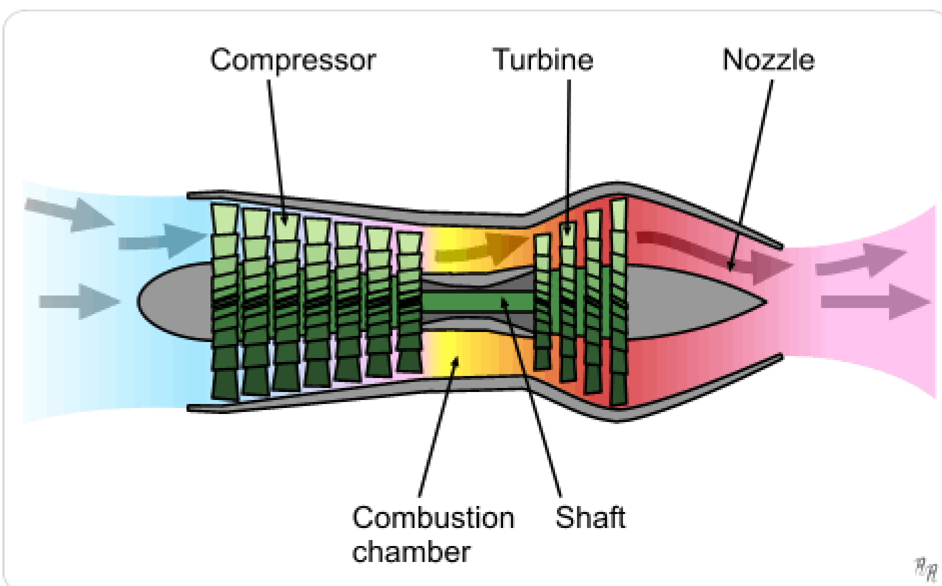


An image of an axial compressor. The stationary blades are the stators





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

Air intake

Preceding the compressor is the air intake (or inlet). It is designed to be as efficient as possible at recovering the ram pressure of the air stream tube approaching the intake. The air leaving the intake then enters the compressor. The stators (stationary blades) guide the airflow of the compressed gases.

Compressor

The compressor is driven by the turbine. The compressor rotates at very high speed, adding energy to the airflow and at the same time squeezing (compressing) it into a smaller space. Compressing the air increases 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 turbine cooling. Bleeding air off decreases the overall efficiency of the engine, but the usefulness of the compressed air outweighs the loss in efficiency.

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 incorporating variable compressor geometry, enabled later turbojets to have overall pressure ratios of 15:1 or more. For comparison, modern civil turbofan engines have overall pressure ratios of 44:1 or more.

After leaving the compressor section, the compressed air enters the combustion chamber.

Combustion chamber

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, but the pressure actually decreases a few percent.

The fuel-air mixture must be brought almost to a stop so that a stable flame can be maintained. This occurs just after the start of the combustion chamber. The aft part of this flame front is allowed to progress rearward. This ensures that all 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 required, 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 absorb the heating effects of the burning fuel.

Another difference between piston engines and jet engines is that the peak flame temperature in a piston engine is experienced only momentarily in a small portion of the full 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 a turbine can tolerate.

Turbine

Hot gases leaving the combustor are allowed to expand through the turbine. Turbines are usually made up of high temperature metals such as inconel to resist the high temperature, and frequently have built-in cooling channels.

In the first stage the turbine is largely an impulse 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 outside 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 with engine throttling.

Afterburner

An afterburner or "reheat jetpipe" is a device added to the rear of the jet engine. It provides a means of spraying fuel directly into the hot exhaust, where it ignites and boosts available thrust significantly; a drawback is its very high fuel consumption rate. Afterburners are used almost exclusively on supersonic aircraft – most of these are military aircraft. The two supersonic civilian transports, Concorde and the TU-144, also utilized afterburners but these two have now been retired from service. Scaled Composites White Knight, a carrier aircraft for the experimental SpaceShipOne suborbital spacecraft, also utilizes an afterburner.

Thrust reverser

A thrust reverser is, essentially, a pair of clamshell doors mounted at the rear of the engine which, when deployed, divert thrust normal to the jet engine flow to help slow an aircraft upon landing. They are often used in conjunction with spoilers. The accidental deployment of a thrust reverser during flight is a dangerous event that can lead to loss of control and destruction of the aircraft. Thrust reversers are more convenient than drogue parachutes, though mechanically more complex and expensive.

Net thrust

The net thrust F_N of a turbojet is given by:

$$F_N = (\dot{m}_{air} + \dot{m}_f)V_j - \dot{m}_{air}V$$

where:

$\dot{m}_{air}$	is the rate of flow of air through the engine
$\dot{m}_f$	is the rate of flow of fuel entering the engine
V_j	is the speed of the jet (the exhaust plume) and is assumed to be less than sonic velocity
V	is the true airspeed of the aircraft
$(\dot{m}_{air} + \dot{m}_f)V_j$	represents the nozzle gross thrust
$\dot{m}_{air}V$	represents the ram drag of the intake

If the speed of the jet is equal to sonic velocity the nozzle is said to be choked. If the nozzle is *choked* the pressure at the nozzle exit plane is greater than atmospheric pressure, and extra terms must be added to the above equation to account for the *pressure thrust*.

The rate of flow of fuel entering the engine is very small compared with the rate of flow of air. If the contribution of fuel to the nozzle gross thrust is ignored, the net thrust is:

$$F_N = \dot{m}_{air}(V_j - V)$$

The speed of the jet V_j must exceed the true airspeed of the aircraft V if there is to be a net forward thrust on the airframe. The speed V_j can be calculated thermodynamically based on adiabatic expansion.

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

Cycle improvements

Thermodynamics of a jet engine are modelled approximately by a Brayton Cycle.

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, while specific fuel consumption (fuel flow/net thrust) decreases.

Thus turbojets can be made more fuel efficient by raising overall pressure ratio and turbine inlet temperature in union. 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.

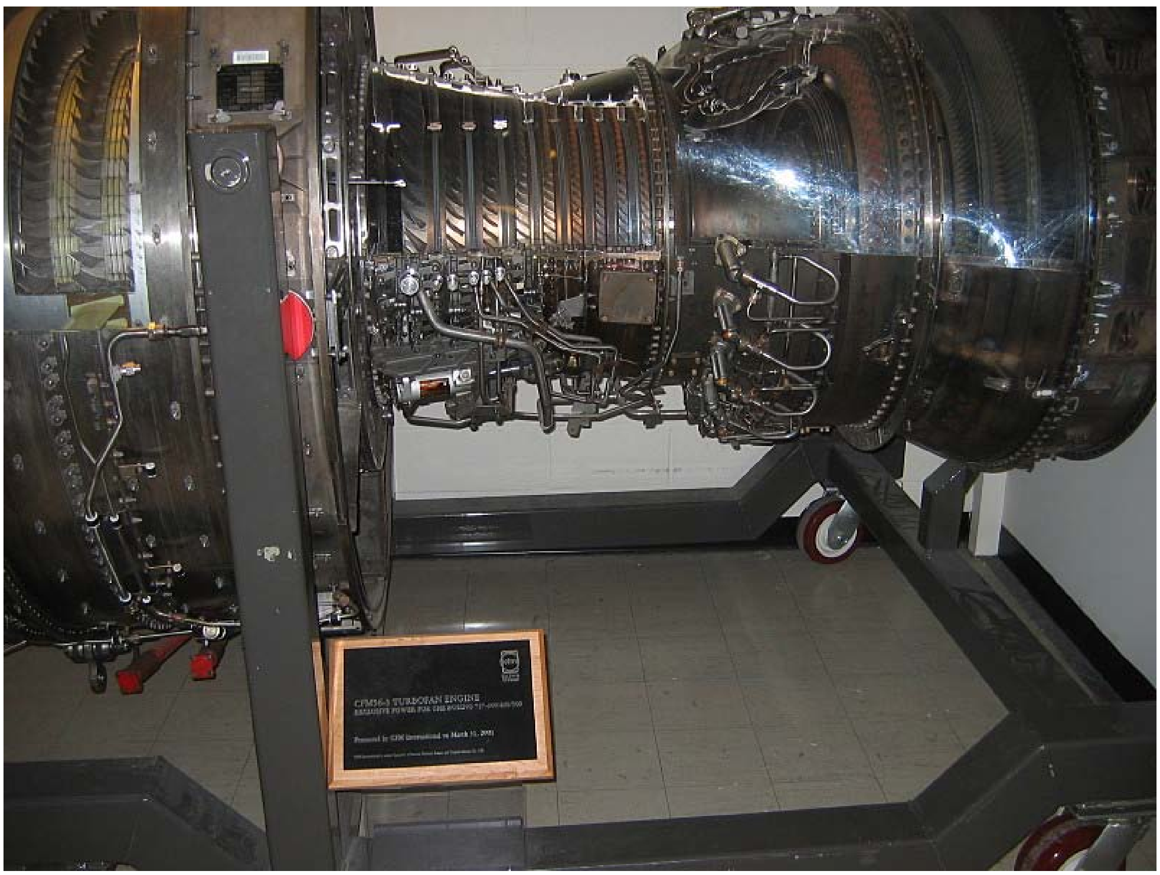
Minimizing heat losses and optimizing the inlet temperature ratio will increase the system's useful work and the thermal efficiency of the turbo jet engine.

Notable vehicles using turbojets

- Heinkel He 178: first airbreathing jet aircraft
- Messerschmitt Me 262: first jet fighter
- De Havilland Comet: first jet airliner
- Concorde: Mach 2 airliner (also some models of the Tupolev Tu-144)
- Thrust2: land speed record car that held the record for 14 years

Chapter- 3

Turbofan



CFM56-3 turbofan, lower half, side view

A Rolls-Royce RB211 turbofan mounted on a Boeing 747

The **turbofan** is a type of aircraft jet engine based around a gas turbine engine. Turbofans provide thrust using a combination of a ducted fan and a jet exhaust nozzle. Part of the airstream from the ducted fan passes through the core, providing oxygen to burn fuel to create power. However, the rest of the air flow bypasses the engine core and mixes with the faster stream from the core, significantly reducing exhaust noise. The substantially slower bypass airflow produces thrust more efficiently than the high-speed air from the core, and this reduces the specific fuel consumption.

A few designs work slightly differently, having the fan blades as a radial extension of an aft-mounted low-pressure turbine unit.

Turbofans have a net exhaust speed that is much lower than a turbojet. This makes them much more efficient at subsonic speeds than turbojets, and somewhat more efficient at supersonic speeds up to roughly Mach 1.6, but have also been found to be efficient when used with continuous afterburner at Mach 3 and above. However, the lower exhaust speed also reduces thrust at high vehicle speeds.

All of the jet engines used in currently manufactured commercial jet aircraft are turbofans. They are used commercially mainly because they are more efficient and quieter in operation than turbojets. Turbofans are also used in many military jet aircraft, such as the F-15 Eagle and in unmanned aerial vehicles such as the RQ-4 Global Hawk.

Introduction

Unlike a reciprocating engine, a turbojet undertakes a continuous-flow combustion process.

In a single-spool (or single-shaft) turbojet, which is the most basic form and the earliest type of turbojet to be developed, air enters an intake before being compressed to a higher pressure by a rotating (fan-like) compressor. The compressed air passes on to a combustor, where it is mixed with a fuel (*e.g.* kerosene) and ignited. The hot combustion gases then enter a windmill-like turbine, where power is extracted to drive the compressor. Although the expansion process in the turbine reduces the gas pressure (and temperature) somewhat, the remaining energy and pressure is employed to provide a high-velocity jet by passing the gas through a propelling nozzle. This process produces a net thrust opposite in direction to that of the jet flow.

After World War II, 2-spool (or 2-shaft) turbojets were developed to make it easier to throttle back compression systems with a high design overall pressure ratio (*i.e.,* combustor inlet pressure/intake delivery pressure). Adopting the 2-spool arrangement enables the compression system to be split in two, with a Low Pressure (LP) Compressor supercharging a High Pressure (HP) Compressor. Each compressor is mounted on a separate (co-axial) shaft, driven by its own turbine (i.e. HP Turbine and LP Turbine). Otherwise a 2-spool turbojet is much like a single-spool engine.

Modern turbofans evolved from the 2-spool axial-flow turbojet engine, essentially by increasing the relative size of the Low Pressure (LP) Compressor to the point where some (if not most) of the air exiting the unit actually bypasses the core (or gas-generator) stream, passing through the main combustor. This bypass air either expands through a separate propelling nozzle, or is mixed with the hot gases leaving the Low Pressure (LP) Turbine, before expanding through a Mixed Stream Propelling Nozzle. Owing to a lower jet velocity, a modern civil turbofan is quieter than the equivalent turbojet. Turbofans also have a better thermal efficiency, which is explained later in the chapter. In a turbofan, the LP Compressor is often called a fan. Civil-aviation turbofans usually have a single fan stage, whereas most military-aviation turbofans (e.g. combat and trainer aircraft applications) have multi-stage fans. Modern military transport turbofan engines are similar to those which propel civil jetliners.

Turboprop engines are gas-turbine engines that deliver almost all of their power to a shaft to drive a propeller. Turboprops remain popular on very small or slow aircraft, such as small commuter airliners, for their fuel efficiency at lower speeds, as well as on medium military transports and patrol planes, such as the C-130 Hercules and P-3 Orion, for their high takeoff performance and mission endurance benefits respectively.

If the turboprop is better at moderate flight speeds and the turbojet is better at very high speeds, it might be imagined that at some speed range in the middle a mixture of the two is best. Such an engine is the turbofan (originally termed *bypass turbojet* by the inventors at Rolls Royce). Another name sometimes used is ducted fan, though that term is also used for propellers and fans used in vertical-flight applications.

The difference between a turbofan and a propeller, besides direct thrust, is that the intake duct of the former slows the air before it arrives at the fan face. As both propeller and fan blades must operate at subsonic inlet velocities to be efficient, ducted fans allow efficient operation at higher vehicle speeds.

Duct work on an Dassault/Dornier Alpha Jet — the increasing diameter of the inlet duct slows incoming air according to the principle of continuity. As the incoming air slows, its pressure increases according to Bernoulli's Principle.

Depending on specific thrust (i.e. net thrust/intake airflow), ducted fans operate best from about 400 to 2000 km/h (250 to 1300 mph), which is why turbofans are the most common type of engine for aviation use today in airliners as well as subsonic/supersonic military fighter and trainer aircraft. It should be noted, however, that turbofans use extensive ducting to force incoming air to subsonic velocities (thus reducing shock waves throughout the engine).

Bypass ratio (bypassed airflow to combustor airflow) is a parameter often used for classifying turbofans, although specific thrust is a better parameter.

The noise of any type of jet engine is strongly related to the velocity of the exhaust gases, typically being proportional to the eighth power of the jet velocity. High-bypass-ratio (*i.e.,* low-specific-thrust) turbofans are relatively quiet compared to turbojets and low-bypass-ratio (*i.e.,* high-specific-thrust) turbofans. A low-specific-thrust engine has a low jet velocity by definition, as the following approximate equation for net thrust implies:

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

where:

$\dot{m} =$intake mass flow
$V_{jfe} =$fully expanded jet velocity (in the exhaust plume)
$V_a =$aircraft flight velocity

Rearranging the above equation, specific thrust is given by:

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

So for zero flight velocity, specific thrust is directly proportional to jet velocity. Relatively speaking, low-specific-thrust engines are large in diameter to accommodate the high airflow required for a given thrust.

Jet aircraft are often considered loud, but a conventional piston engine or a turboprop engine delivering the same thrust would be much louder.

Early turbofans

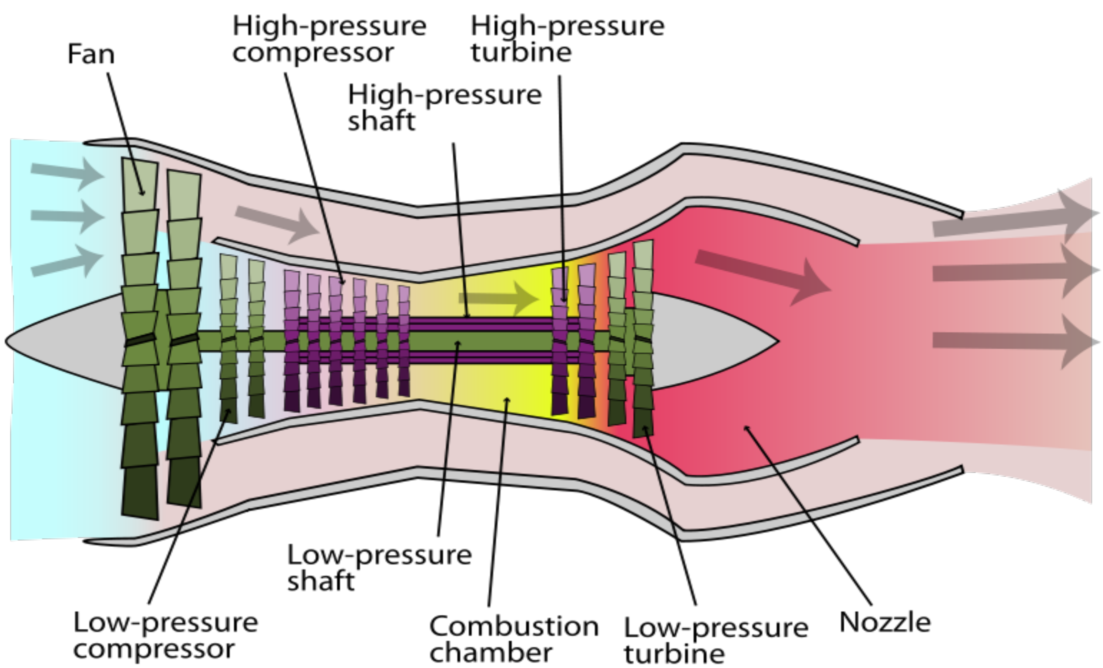
Early turbojet engines were very fuel-inefficient, as their overall pressure ratio and turbine inlet temperature were severely limited by the technology available at the time. The very first running turbofan was the German Daimler-Benz DB 670 (designated as the 109-007 by the RLM) which was operated on its testbed on April 1, 1943. The engine was abandoned later while the war went on and problems could not be solved. The British wartime Metrovick F.2 axial flow jet was given a fan to create the first British turbofan.

Improved materials, and the introduction of twin compressors such as in the Pratt & Whitney JT3C engine, increased the overall pressure ratio and thus the thermodynamic efficiency of engines, but they also led to a poor propulsive efficiency, as pure turbojets have a high specific thrust/high velocity exhaust better suited to supersonic flight.

The original **low-bypass turbofan** engines were designed to improve propulsive efficiency by reducing the exhaust velocity to a value closer to that of the aircraft. The Rolls-Royce Conway, the first production turbofan, had a bypass ratio of 0.3, similar to the modern General Electric F404 fighter engine. Civilian turbofan engines of the 1960s, such as the Pratt & Whitney JT8D and the Rolls-Royce Spey had bypass ratios closer to 1, but were not dissimilar to their military equivalents.

The unusual General Electric CF700 turbofan engine was developed as an aft-fan engine with a 2.0 bypass ratio. This was derived from the T-38 Talon and the Learjet General Electric J85/CJ610 turbojet (2,850 lbf or 12,650 N) to power the larger Rockwell Sabreliner 75/80 model aircraft, as well as the Dassault Falcon 20 with about a 50% increase in thrust (4,200 lbf or 18,700 N). The CF700 was the first small turbofan in the world to be certified by the Federal Aviation Administration (FAA). There are now over 400 CF700 aircraft in operation around the world, with an experience base of over 10 million service hours. The CF700 turbofan engine was also used to train Moon-bound astronauts in Project Apollo as the powerplant for the Lunar Landing Research Vehicle.

Low-bypass turbofan



Schematic diagram illustrating a 2-spool, low-bypass turbofan engine with a mixed exhaust, showing the low-pressure (green) and high-pressure (purple) spools. The fan (and booster stages) are driven by the low-pressure turbine, whereas the high-pressure compressor is powered by the high-pressure turbine

A high specific thrust/low bypass ratio turbofan normally has a multi-stage fan, developing a relatively high pressure ratio and, thus, yielding a high (mixed or cold) exhaust velocity. The core airflow needs to be large enough to give sufficient core power to drive the fan. A smaller core flow/higher bypass ratio cycle can be achieved by raising the (HP) turbine rotor inlet temperature.

Imagine a retrofit situation where a new low bypass ratio, mixed exhaust, turbofan is replacing an old turbojet, in a particular military application. Say the new engine is to have the same airflow and net thrust (i.e. same specific thrust) as the one it is replacing. A bypass flow can only be introduced if the turbine inlet temperature is allowed to increase, to compensate for a correspondingly smaller core flow. Improvements in turbine cooling/material technology would facilitate the use of a higher turbine inlet temperature, despite increases in cooling air temperature, resulting from a probable increase in overall pressure ratio.

Efficiently done, the resulting turbofan would probably operate at a higher nozzle pressure ratio than the turbojet, but with a lower exhaust temperature to retain net thrust. Since the temperature rise across the whole engine (intake to nozzle) would be lower, the (dry power) fuel flow would also be reduced, resulting in a better specific fuel consumption (SFC).

A few low-bypass ratio military turbofans (e.g. F404) have Variable Inlet Guide Vanes, with piano-style hinges, to direct air onto the first rotor stage. This improves the fan surge margin in the mid-flow range. The swing wing F-111 achieved a very high range/payload capability by pioneering the use of this engine, and it was also the heart of the famous F-14 Tomcat air superiority fighter which used the same engines in a smaller, more agile airframe to achieve efficient cruise and Mach 2 speed.

Afterburning turbofan

Damaged turbofan front blades caused by ingestion of debris in 2003 Baghdad DHL attempted shootdown incident

Since the 1970s, most jet fighter engines have been low/medium bypass turbofans with a mixed exhaust, afterburner and variable area final nozzle. An afterburner is a combustor located downstream of the turbine blades and directly upstream of the nozzle, which burns fuel from afterburner-specific fuel injectors. When lit, prodigious amounts of fuel are burnt in the afterburner, raising the temperature of exhaust gases by a significant degree, resulting in a higher exhaust velocity/engine specific thrust. The variable geometry nozzle must open to a larger throat area to accommodate the extra volume flow when the afterburner is lit. Afterburning is often designed to give a significant thrust boost for take off, transonic acceleration and combat maneuvers, but is very fuel intensive. Consequently afterburning can only be used for short portions of a mission.

Unlike the main combustor, where the downstream turbine blades must not be damaged by high temperatures, an afterburner can operate at the ideal maximum (stoichiometric) temperature (i.e. about 2100K/3780Ra/3320F). At a fixed total applied fuel:air ratio, the total fuel flow for a given fan airflow will be the same, regardless of the dry specific thrust of the engine. However, a high specific thrust turbofan will, by definition, have a higher nozzle pressure ratio, resulting in a higher afterburning net thrust and, therefore, a lower afterburning specific fuel consumption. However, high specific thrust engines have a high dry SFC. The situation is reversed for a medium specific thrust afterburning turbofan: i.e. poor afterburning SFC/good dry SFC. The former engine is suitable for a combat aircraft which must remain in afterburning combat for a fairly long period, but only has to fight fairly close to the airfield (e.g. cross border skirmishes) The latter engine is better for an aircraft that has to fly some distance, or loiter for a long time, before going into combat. However, the pilot can only afford to stay in afterburning for a short period, before aircraft fuel reserves become dangerously low.

Modern low-bypass military turbofans include the Pratt & Whitney F119, the Eurojet EJ200 and the General Electric F110 and F414, all of which feature a mixed exhaust, afterburner and variable area propelling nozzle. Non-afterburning engines include the Rolls-Royce/Turbomeca Adour (afterburning in the SEPECAT Jaguar) and the unmixed, vectored thrust, Rolls-Royce Pegasus.

High-bypass turbofan

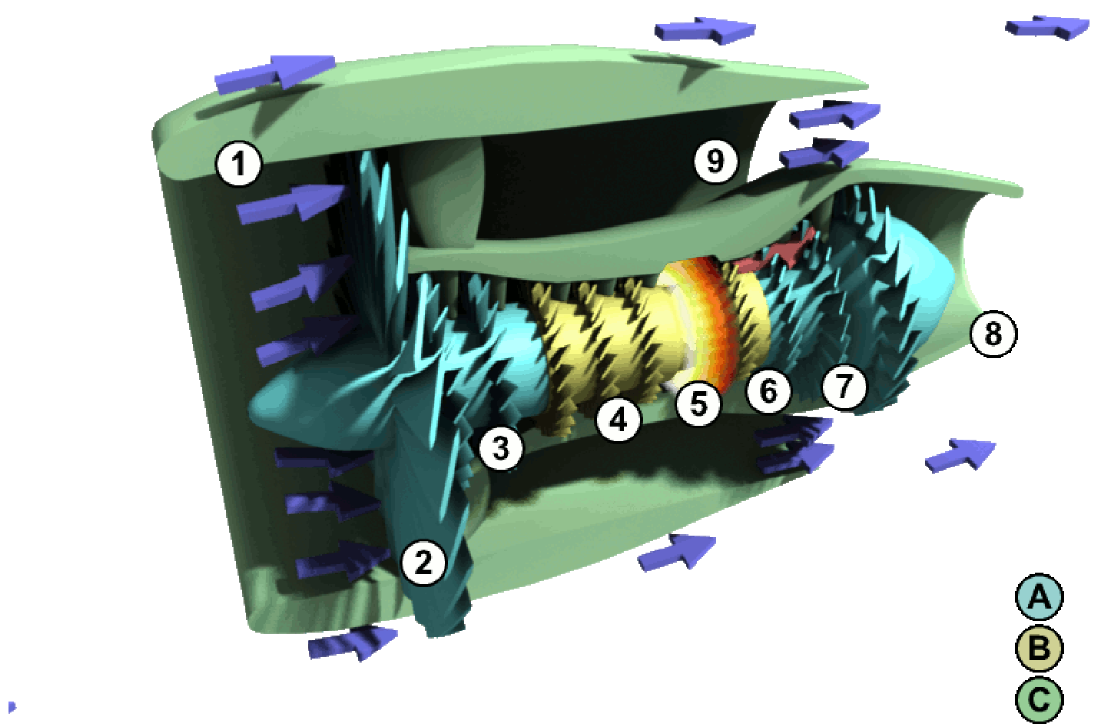
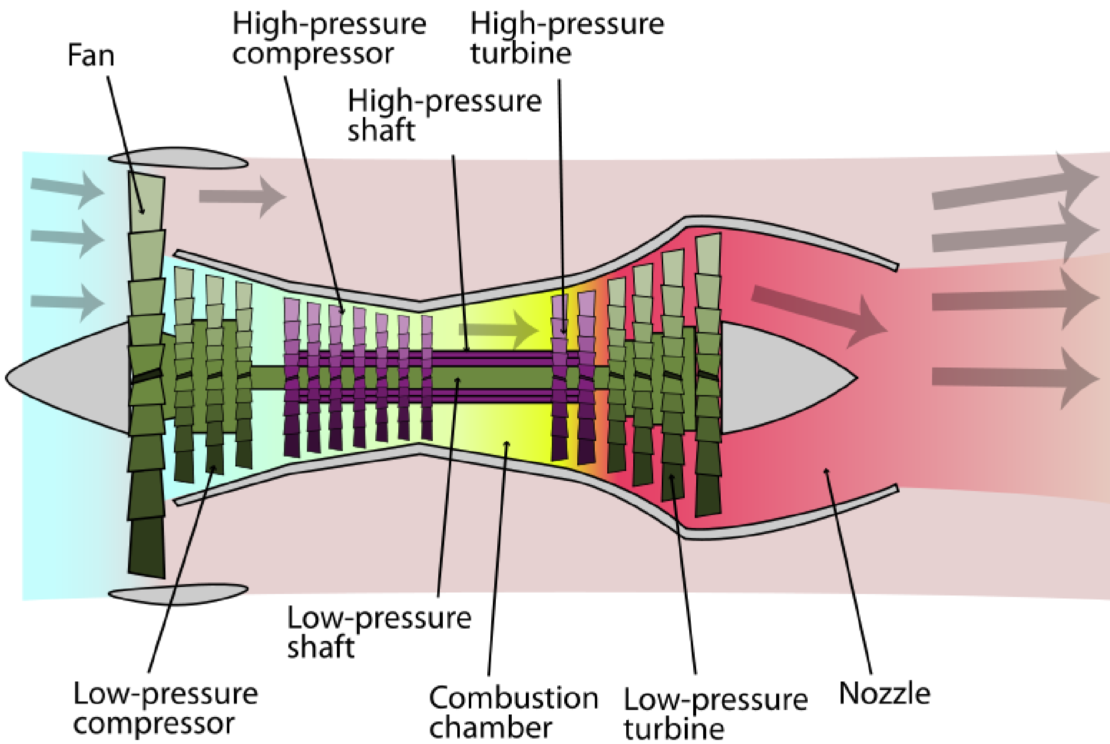


Image of a 2-spool, high-bypass turbofan.
A. Low pressure spool
B. High pressure spool
C. Stationary components
1. Nacelle
2. Fan
3. Low pressure compressor

4. High pressure compressor
5. Combustion chamber
6. High pressure turbine
7. Low pressure turbine
8. Core nozzle
9. Fan nozzle



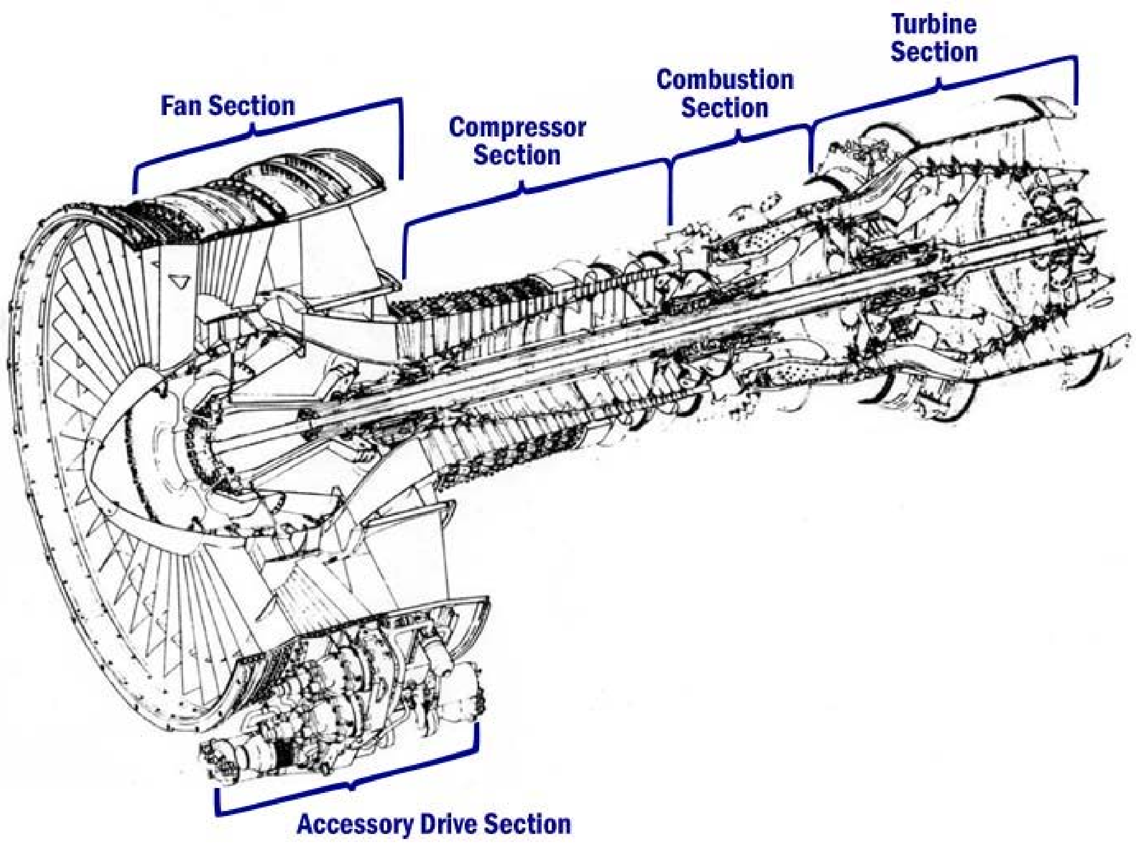
Schematic diagram illustrating a 2-spool, high-bypass turbofan engine with an unmixed exhaust. The low-pressure spool is coloured green and the high-pressure one purple. Again, the fan (and booster stages) are driven by the low-pressure turbine, but more stages are required. A mixed exhaust is often employed nowadays

The low specific thrust/high bypass ratio turbofans used in today's civil jetliners (and some military transport aircraft) evolved from the high specific thrust/low bypass ratio turbofans used in such [production] aircraft back in the 1960s.

Low specific thrust is achieved by replacing the multi-stage fan with a single stage unit. Unlike some military engines, modern civil turbofans do not have any stationary inlet guide vanes in front of the fan rotor. The fan is scaled to achieve the desired net thrust.

The core (or gas generator) of the engine must generate sufficient core power to at least drive the fan at its design flow and pressure ratio. Through improvements in turbine cooling/material technology, a higher (HP) turbine rotor inlet temperature can be used, thus facilitating a smaller (and lighter) core and (potentially) improving the core thermal efficiency. Reducing the core mass flow tends to increase the load on the LP turbine, so this unit may require additional stages to reduce the average stage loading and to maintain LP turbine efficiency. Reducing core flow also increases bypass ratio (5:1, or more, is now common).

Further improvements in core thermal efficiency can be achieved by raising the overall pressure ratio of the core. Improved blade aerodynamics reduces the number of extra compressor stages required. With multiple compressors (i.e. LPC, IPC, HPC) dramatic increases in overall pressure ratio have become possible. Variable geometry (i.e. stators) enable high pressure ratio compressors to work surge-free at all throttle settings.



Cutaway diagram of the General Electric CF6-6 engine

The first high-bypass turbofan engine was the General Electric TF39, designed in mid 1960s to power the Lockheed C-5 Galaxy military transport aircraft. The civil General Electric CF6 engine used a derived design. Other high-bypass turbofans are the Pratt & Whitney JT9D, the three-shaft Rolls-Royce RB211 and the CFM International CFM56. More recent large high-bypass turbofans include the Pratt & Whitney PW4000, the three-shaft Rolls-Royce Trent, the General Electric GE90/GEnx and the GP7000, produced jointly by GE and P&W.

High-bypass turbofan engines are generally quieter than the earlier low bypass ratio civil engines. This is not so much due to the higher bypass ratio as to the use of a low pressure ratio, single stage fan which significantly reduces specific thrust and, thereby, jet velocity. The combination of a higher overall pressure ratio and turbine inlet temperature improves thermal efficiency. This, together with a lower specific thrust (better propulsive efficiency), leads to a lower specific fuel consumption.

For reasons of fuel economy, and also of reduced noise, almost all of today's jet airliners are powered by high-bypass turbofans. Although modern combat aircraft tend to use low bypass ratio turbofans, military transport aircraft (e.g. C-17) mainly use high bypass ratio turbofans (or turboprops) for fuel efficiency.

Because of the implied low mean jet velocity, a high bypass ratio/low specific thrust turbofan has a high thrust lapse rate (with rising flight speed). Consequently the engine must be over-sized to give sufficient thrust during climb/cruise at high flight speeds (e.g. Mach 0.83). Because of the high thrust lapse rate, the static (i.e. Mach 0) thrust is relatively high. This enables heavily laden, wide body aircraft to accelerate quickly during take-off and consequently lift-off within a reasonable runway length.

The turbofans on twin engined airliners are further over-sized to cope with losing one engine during take-off, which reduces the aircraft's net thrust by 50%. Modern twin engined airliners normally climb very steeply immediately after take-off. If one engine is lost, the climb-out is much shallower, but sufficient to clear obstacles in the flightpath.

The Soviet Union's engine technology was less advanced than the West's and its first wide-body aircraft, the Ilyushin Il-86, was powered by low-bypass engines. The Yakovlev Yak-42, a medium-range, rear-engined aircraft seating up to 120 passengers introduced in 1980 was the first Soviet aircraft to use high-bypass engines.

Turbofan configurations

Turbofan engines come in a variety of engine configurations. For a given engine cycle (i.e. same airflow, bypass ratio, fan pressure ratio, overall pressure ratio and HP turbine rotor inlet temperature), the choice of turbofan configuration has little impact upon the design point performance (e.g. net thrust, SFC), as long as overall component performance is maintained. Off-design performance and stability is, however, affected by engine configuration.

As the design overall pressure ratio of an engine cycle increases, it becomes more difficult to throttle the compression system, without encountering an instability known as compressor surge. This occurs when some of the compressor aerofoils stall (like the wings of an aircraft) causing a violent change in the direction of the airflow. However, compressor stall can be avoided, at throttled conditions, by progressively:

1) opening interstage/intercompressor blow-off valves (inefficient)

and/or

2) closing variable stators within the compressor

Most modern American civil turbofans employ a relatively high pressure ratio High Pressure (HP) Compressor, with many rows of variable stators to control surge margin at part-throttle. In the three-spool RB211/Trent the core compression system is split into two, with the IP compressor, which supercharges the HP compressor, being on a different coaxial shaft and driven by a separate (IP) turbine. As the HP Compressor has a modest pressure ratio it can be throttled-back surge-free, without employing variable geometry. However, because a shallow IP compressor working line is inevitable, the IPC requires at least one stage of variable geometry.

Single shaft turbofan

Although far from common, the Single Shaft Turbofan is probably the simplest configuration, comprising a fan and high pressure compressor driven by a single turbine unit, all on the same shaft. The SNECMA M53, which powers Mirage fighter aircraft, is an example of a Single Shaft Turbofan. Despite the simplicity of the turbomachinery configuration, the M53 requires a variable area mixer to facilitate part-throttle operation.

Aft-fan turbofan

One of the earliest turbofans was a derivative of the General Electric J79 turbojet, known as the CJ805-23, which featured an integrated aft fan/low pressure (LP) turbine unit located in the turbojet exhaust jetpipe. Hot gas from the turbojet turbine exhaust expanded through the LP turbine, the fan blades being a radial extension of the turbine blades. This aft-fan configuration was later exploited in the General Electric GE-36 UDF (propfan) Demonstrator of the early 80's. One of the problems with the aft fan configuration is hot gas leakage from the LP turbine to the fan.

Basic two spool

Many turbofans have the Basic Two Spool configuration where both the fan and LP turbine (i.e. LP spool) are mounted on a second (LP) shaft, running concentrically with the HP spool (i.e. HP compressor driven by HP turbine). The BR710 is typical of this configuration. At the smaller thrust sizes, instead of all-axial blading, the HP compressor configuration may be axial-centrifugal (e.g. General Electric CFE738), double-centrifugal or even diagonal/centrifugal (e.g. Pratt & Whitney Canada PW600).

Boosted two spool

Higher overall pressure ratios can be achieved by either raising the HP compressor pressure ratio or adding an Intermediate Pressure (IP) Compressor between the fan and HP compressor, to supercharge or boost the latter unit helping to raise the overall pressure ratio of the engine cycle to the very high levels employed today (i.e. greater than 40:1, typically). All of the large American turbofans (e.g. General Electric CF6, GE90 and GEnx plus Pratt & Whitney JT9D and PW4000) feature an IP compressor mounted on the LP shaft and driven, like the fan, by the LP turbine, the mechanical speed of which is dictated by the tip speed and diameter of the fan. The high bypass ratios (i.e. fan duct flow/core flow) used in modern civil turbofans tends to reduce the relative diameter of the attached IP compressor, causing its mean tip speed to decrease. Consequently more IPC stages are required to develop the necessary IPC pressure rise.

Three spool

Rolls-Royce chose a three spool configuration for their large civil turbofans (i.e. the RB211 and Trent families), where the Intermediate Pressure (IP) compressor is mounted on a separate (IP) shaft, running concentrically with the LP and HP shafts, and is driven by a separate IP Turbine. Consequently, the IP compressor can rotate faster than the fan, increasing its mean tip speed, thereby reducing the number of IP stages required for a given IPC pressure rise. Because the RB211/Trent designs have a higher IPC pressure rise than the American engines, the HPC pressure rise is less resulting in a shorter, lighter engine. However, three spool engines are harder to both build and maintain.

Ivchenko Design Bureau chose the same configuration for their Lotarev D-36 engine, followed by Lotarev/Progress D-18T and Progress D-436.

The Turbo-Union RB199 military turbofan also has a three spool configuration, as does the Russian military Kuznetsov NK-321.

Geared fan

As bypass ratio increases, the mean radius ratio of the fan and LP turbine increases. Consequently, if the fan is to rotate at its optimum blade speed the LP turbine blading will spin slowly, so additional LPT stages will be required, to extract sufficient energy to drive the fan. Introducing a (planetary) reduction gearbox, with a suitable gear ratio, between the LP shaft and the fan enables both the fan and LP turbine to operate at their optimum speeds. Typical of this configuration are the long-established Honeywell TFE731, the Honeywell ALF 502/507, and the recent Pratt & Whitney PW1000G.

Military turbofans

Most of the configurations discussed above are used in civil turbofans, while modern military turbofans (e.g. SNECMA M88) are usually Basic Two Spool.

High Pressure Turbine

Most civil turbofans use a high efficiency, 2-stage HP turbine to drive the HP compressor. The CFM56 uses an alternative approach: a single stage, high-work unit. While this approach is probably less efficient, there are savings on cooling air, weight and cost. In the RB211 and Trent series, Rolls-Royce split the two stages into two discrete units; one on the HP shaft driving the HP compressor; the other on the IP shaft driving the IP (Intermediate Pressure) Compressor. Modern military turbofans tend to use single stage HP turbines.

Low Pressure Turbine

Modern civil turbofans have multi-stage LP turbines (e.g. 3, 4, 5, 6, 7). The number of stages required depends on the engine cycle bypass ratio and how much supercharging (i.e. IP compression) is on the LP shaft, behind the fan. A geared fan may reduce the number of required LPT stages in some applications. Because of the much lower bypass ratios employed, military turbofans only require one or two LP turbine stages.

Cycle improvements

Consider a mixed turbofan with a fixed bypass ratio and airflow. Increasing the overall pressure ratio of the compression system raises the combustor **entry** temperature. Therefore, at a fixed fuel flow there is an increase in (HP) turbine rotor inlet temperature. Although the higher temperature rise across the compression system implies a larger temperature drop over the turbine system, the mixed 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, causing an increase in the hot mixer entry pressure. Consequently, net thrust increases, whilst specific fuel consumption (fuel flow/net thrust) decreases. A similar trend occurs with unmixed turbofans.

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

Overall pressure ratio can be increased by improving fan (or) LP compressor pressure ratio and/or HP compressor pressure ratio. If the latter is held constant, the increase in (HP) compressor delivery temperature (from raising overall pressure ratio) implies an increase in HP mechanical speed. However, stressing considerations might limit this parameter, implying, despite an increase in overall pressure ratio, a reduction in HP compressor pressure ratio.

According to simple theory, if the ratio turbine rotor inlet temperature/(HP) compressor delivery temperature is maintained, the HP turbine throat area can be retained. However, this assumes that cycle improvements are obtained, whilst retaining the datum (HP) compressor exit flow function (non-dimensional flow). In practise, changes to the non-dimensional speed of the (HP) compressor and cooling bleed extraction would probably make this assumption invalid, making some adjustment to HP turbine throat area unavoidable. This means the HP turbine nozzle guide vanes would have to be different from the original! In all probability, the downstream LP turbine nozzle guide vanes would have to be changed anyway.

Thrust growth

Thrust growth is obtained by increasing core power. There are two basic routes available:

a) hot route: increase HP turbine rotor inlet temperature

b) cold route: increase core mass flow

Both routes require an increase in the combustor fuel flow and, therefore, the heat energy added to the core stream.

The hot route may require changes in turbine blade/vane materials and/or better blade/vane cooling. The cold route can be obtained by one of the following:

1. adding T-stages to the LP/IP compression
2. adding a zero-stage to the HP compression
3. improving the compression process, without adding stages (e.g. higher fan hub pressure ratio)

all of which increase both overall pressure ratio and core airflow.

Alternatively, the core size can be increased, to raise core airflow, without changing overall pressure ratio. This route is expensive, since a new (upflowed) turbine system (and possibly a larger IP compressor) is also required.

Changes must also be made to the fan to absorb the extra core power. On a civil engine, jet noise considerations mean that any significant increase in Take-off thrust must be accompanied by a corresponding increase in fan mass flow (to maintain a T/O specific thrust of about 30 lbf/lb/s), usually by increasing fan diameter. On military engines, the fan pressure ratio would probably be increased to improve specific thrust, jet noise not normally being an important factor.

Technical discussion

1. Specific Thrust (net thrust/intake airflow) is an important parameter for turbofans and jet engines in general. Imagine a fan (driven by an appropriately sized electric motor) operating within a pipe, which is connected to a propelling nozzle. Fairly obviously, the higher the Fan Pressure Ratio (fan discharge pressure/fan inlet pressure), the higher the jet velocity and the corresponding specific thrust. Now imagine we replace this set-up with an equivalent turbofan - same airflow and same fan pressure ratio. Obviously, the core of the turbofan must produce sufficient power to drive the fan via the Low Pressure (LP) Turbine. If we choose a low (HP) Turbine Inlet Temperature for the gas generator, the core airflow needs to be relatively high to compensate. The corresponding bypass ratio is therefore relatively low. If we raise the Turbine Inlet Temperature, the core airflow can be smaller, thus increasing bypass ratio. Raising turbine inlet

temperature tends to increase thermal efficiency and, therefore, improve fuel efficiency.

2. Naturally, as altitude increases there is a decrease in air density and, therefore, the net thrust of an engine. There is also a flight speed effect, termed Thrust Lapse Rate. Consider the approximate equation for net thrust again:

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

With a high specific thrust (e.g. fighter) engine, the jet velocity is relatively high, so intuitively one can see that increases in flight velocity have less of an impact upon net thrust than a medium specific thrust (e.g. trainer) engine, where the jet velocity is lower. The impact of thrust lapse rate upon a low specific thrust (e.g. civil) engine is even more severe. At high flight speeds, high specific thrust engines can pick-up net thrust through the ram rise in the intake, but this effect tends to diminish at supersonic speeds because of shock wave losses.

3. Thrust growth on civil turbofans is usually obtained by increasing fan airflow, thus preventing the jet noise becoming too high. However, the larger fan airflow requires more power from the core. This can be achieved by raising the Overall Pressure Ratio (combustor inlet pressure/intake delivery pressure) to induce more airflow into the core and by increasing turbine inlet temperature. Together, these parameters tend to increase core thermal efficiency and improve fuel efficiency.
4. Some high bypass ratio civil turbofans use an extremely low area ratio (less than 1.01), convergent-divergent, nozzle on the bypass (or mixed exhaust) stream, to control the fan working line. The nozzle acts as if it has variable geometry. At low flight speeds the nozzle is unchoked (less than a Mach Number of unity), so the exhaust gas speeds up as it approaches the throat and then slows down slightly as it reaches the divergent section. Consequently, the nozzle exit area controls the fan match and, being larger than the throat, pulls the fan working line slightly away from surge. At higher flight speeds, the ram rise in the intake increases nozzle pressure ratio to the point where the throat becomes choked (M=1.0). Under these circumstances, the throat area dictates the fan match and, being smaller than the exit, pushes the fan working line slightly towards surge. This is not a problem, since fan surge margin is much better at high flight speeds.
5. The off-design behaviour of turbofans is illustrated under compressor map and turbine map.
6. Because modern civil turbofans operate at low specific thrust, they only require a single fan stage to develop the required fan pressure ratio. The desired overall pressure ratio for the engine cycle is usually achieved by multiple axial stages on the core compression. Rolls-Royce tend to split the core compression into two with an intermediate pressure (IP) supercharging the HP compressor, both units being driven by turbines with a single stage, mounted on separate shafts. Consequently, the HP compressor need only develop a modest pressure ratio (e.g.~4.5:1). US civil engines use much higher HP compressor pressure ratios (e.g. ~23:1 on the General Electric GE90) and tend to be driven by a two stage HP

turbine. Even so, there are usually a few IP axial stages mounted on the LP shaft, behind the fan, to further supercharge the core compression system. Civil engines have multi-stage LP turbines, the number of stages being determined by the bypass ratio, the amount of IP compression on the LP shaft and the LP turbine blade speed.

7. Because military engines usually have to be able to fly very fast at Sea Level, the limit on HP compressor delivery temperature is reached at a fairly modest design overall pressure ratio, compared with that of a civil engine. Also the fan pressure ratio is relatively high, to achieve a medium to high specific thrust. Consequently, modern military turbofans usually only have 5 or 6 HP compressor stages and only require a single stage HP turbine. Low bypass ratio military turbofans usually have one LP turbine stage, but higher bypass ratio engines need two stages. In theory, by adding IP compressor stages, a modern military turbofan HP compressor could be used in a civil turbofan derivative, but the core would tend to be too small for high thrust applications.

Recent developments in blade technology

The turbine blades in a turbofan engine are subject to high heat and stress, and require special fabrication. New material construction methods and material science have allowed blades, which were originally polycrystalline (regular metal), to be made from lined up metallic crystals and more recently mono-crystalline (i.e. single crystal) blades, which can operate at higher temperatures with less distortion.

Nickel-based superalloys are used for HP turbine blades in almost all modern jet engines. The temperature capabilities of turbine blades have increased mainly through four approaches: the manufacturing (casting) process, cooling path design, thermal barrier coating (TBC), and alloy development.

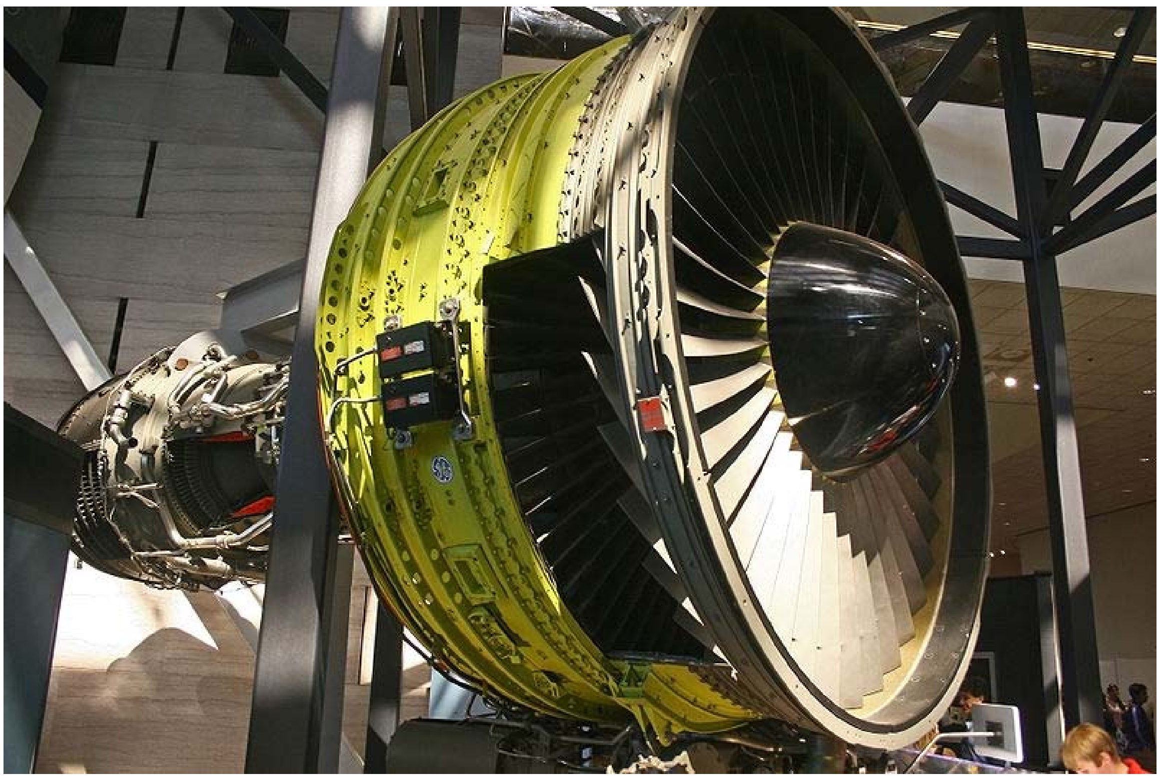
Although turbine blade (and vane) materials have improved over the years, much of the increase in (HP) turbine inlet temperatures is due to improvements in blade/vane cooling technology. Relatively cool air is bled from the compression system, bypassing the combustion process, and enters the hollow blade or vane. After picking up heat from the blade/vane, the cooling air is dumped into the main gas stream. If the local gas temperatures are low enough, downstream blades/vanes are uncooled and not adversely affected.

Strictly speaking, cycle-wise the HP Turbine Rotor Inlet Temperature (after the temperature drop across the HPT stator) is more important than the (HP) turbine inlet temperature. Although some modern military and civil engines have peak RITs of the order of 1,560 °C (2,840 °F), such temperatures are only experienced for a short time (during take-off) on civil engines.

Turbofan engine manufacturers

The turbofan engine market is dominated by General Electric, Rolls-Royce plc and Pratt & Whitney, in order of market share. GE and SNECMA of France have a joint venture, CFM International which, as the 3rd largest manufacturer in terms of market share, fits between Rolls Royce and Pratt & Whitney. Rolls Royce and Pratt & Whitney also have a joint venture, International Aero Engines, specializing in engines for the Airbus A320 family, whilst finally, Pratt & Whitney and General Electric have a joint venture, Engine Alliance marketing a range of engines for aircraft such as the Airbus A380. Williams International is the world leader in smaller business jet turbofans.

General Electric



GE CF6 Turbofan engine

GE Aviation, part of the General Electric Conglomerate, currently has the largest share of the turbofan engine market. Some of their engine models include the CF6 (available on the Boeing 767, Boeing 747, Airbus A330 and more), GE90 (only the Boeing 777) and GEnx (developed for the Boeing 747-8 & Boeing 787 and proposed for the Airbus A350, currently in development) engines. On the military side, GE engines power many U.S. military aircraft, including the F110, powering 80% of the US Air Force's F-16 Fighting Falcons, and the F404 and F414 engines, which power the Navy's F/A-18 Hornet and Super Hornet. Rolls Royce and General Electric are jointly developing the F136 engine to power the Joint Strike Fighter.

CFM International

CFM International is a joint venture between GE Aircraft Engines and SNECMA of France. They have created the very successful CFM56 series, used on Boeing 737, Airbus A340, and Airbus A320 family aircraft.

Rolls-Royce

Rolls-Royce plc is the second largest manufacturer of turbofans and is most noted for their RB211 and Trent series, as well as their joint venture engines for the Airbus A320 and Boeing MD-90 families (IAE V2500 with Pratt & Whitney and others), the Panavia Tornado (Turbo-Union RB199) and the Boeing 717 (BR700). Rolls Royce, as owners of the Allison Engine Company, have their engines powering the C-130 Hercules and several Embraer regional jets. Rolls-Royce Trent 970s were the first engines to power the new Airbus A380. It was also Rolls-Royce Olympus/SNECMA jets that powered the now retired Concorde although they were turbojets rather than turbofans. The famous thrust vectoring Pegasus engine is the primary powerplant of the Harrier "Jump Jet" and its derivatives.

Pratt & Whitney

Pratt & Whitney is third behind GE and Rolls-Royce in market share. The JT9D has the distinction of being chosen by Boeing to power the original Boeing 747 "Jumbo jet". The PW4000 series is the successor to the JT9D, and powers some Airbus A310, Airbus A300, Boeing 747, Boeing 767, Boeing 777, Airbus A330 and MD-11 aircraft. The PW4000 is certified for 180-minute ETOPS when used in twinjets. The first family has a 94-inch (2.4 m) fan diameter and is designed to power the Boeing 767, Boeing 747, MD-11, and the Airbus A300. The second family is the 100 inch (2.5 m) fan engine developed specifically for the Airbus A330 twinjet, and the third family has a diameter of 112-inch (2.8 m) designed to power Boeing 777. The Pratt & Whitney F119 and its derivative, the F135, power the United States Air Force's F-22 Raptor and the international F-35 Lightning II, respectively. Rolls Royce are responsible for the lift fan which will provide the F-35B variants with a STOVL capability. The F100 engine was first used on the F-15 Eagle and F-16 Fighting Falcon. Newer Eagles and Falcons also come with GE F110 as an option, and the two are in competition.

Aviadvigatel

Aviadvigatel (Russian:Авиационный Двиѓатель) is a Russian manufacturer of aircraft engines that succeeded the Soviet Soloviev Design Bureau. The company currently offers several versions of the Aviadvigatel PS-90 engine that powers Ilyushin Il-96-300/400/400T, Tupolev Tu-204, Tu-214 series and the Ilyushin Il-76-MD-90. The company is also developing the new Aviadvigatel PD-14 engine for the new Russian MS-21 airliner.

Ivchenko-Progress

Ivchenko-Progress is the Ukrainian aircraft engine company that succeeded the Soviet Ivchenko Design Bureau. Some of their engine models include Progress D-436 available on the Antonov An-72/74, Yakovlev Yak-42, Beriev Be-200, Antonov An-148 and Tupolev Tu-334 and Progress D-18T that powers two of the world largest airplanes, Antonov An-124 and Antonov An-225.

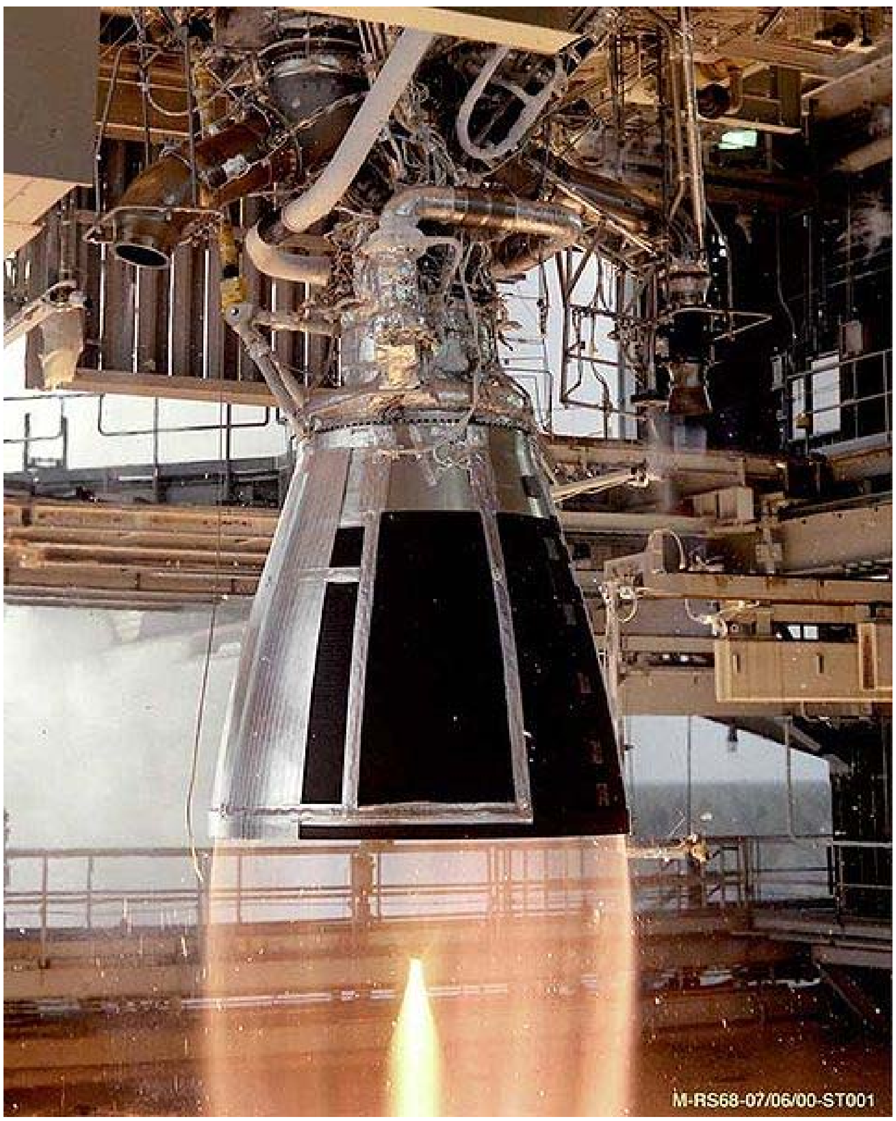
Extreme bypass jet engines

In the 1970s Rolls-Royce/SNECMA tested a M45SD-02 turbofan fitted with variable pitch fan blades to improve handling at ultra low fan pressure ratios and to provide thrust reverse down to zero aircraft speed. The engine was aimed at ultra quiet STOL aircraft operating from city centre airports.

In a bid for increased efficiency with speed, a development of the *turbofan* and *turboprop* known as a propfan engine was created that had an unducted fan. The fan blades are situated outside of the duct, so that it appears like a turboprop with wide scimitar-like blades. Both General Electric and Pratt & Whitney/Allison demonstrated propfan engines in the 1980s. Excessive cabin noise and relatively cheap jet fuel prevented the engines being put into service.

Chapter- 4

Rocket Engine



RS-68 being tested at NASA's Stennis Space Center. The nearly transparent exhaust is due to this engine's exhaust being mostly superheated steam (water vapor from its propellants, hydrogen and oxygen)

Viking 5C rocket engine

A **rocket engine**, or simply "rocket," is a jet engine that uses only propellant mass for forming its high speed propulsive jet. Rocket engines are reaction engines and obtain thrust in accordance with Newton's third law. Since they need no external material to form their jet, rocket engines can be used for spacecraft propulsion as well as terrestrial uses, such as missiles. Most rocket engines are internal combustion engines, although non combusting forms also exist.

Rocket engines as a group have the highest exhaust velocities, are by far the lightest, and are the most energy efficient (at least at very high speed) of all types of jet engines. However, for the thrust they give, due to the high exhaust velocity and relatively low specific energy of rocket propellant, they consume propellant very rapidly.

Terminology

Chemical rockets are rockets powered by exothermic chemical reactions of the propellant.

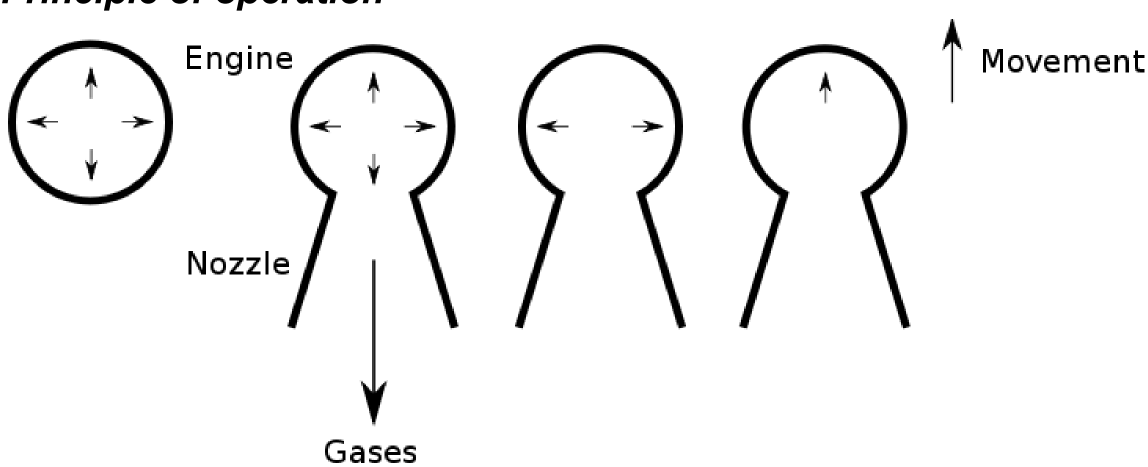
Rocket motor (or **solid-propellant rocket motor**) is a synonymous term with rocket engine that usually refers to solid rocket engines.

Liquid rockets (or **liquid-propellant rocket engine**) use one or more liquid propellants that are held in tanks prior to burning.

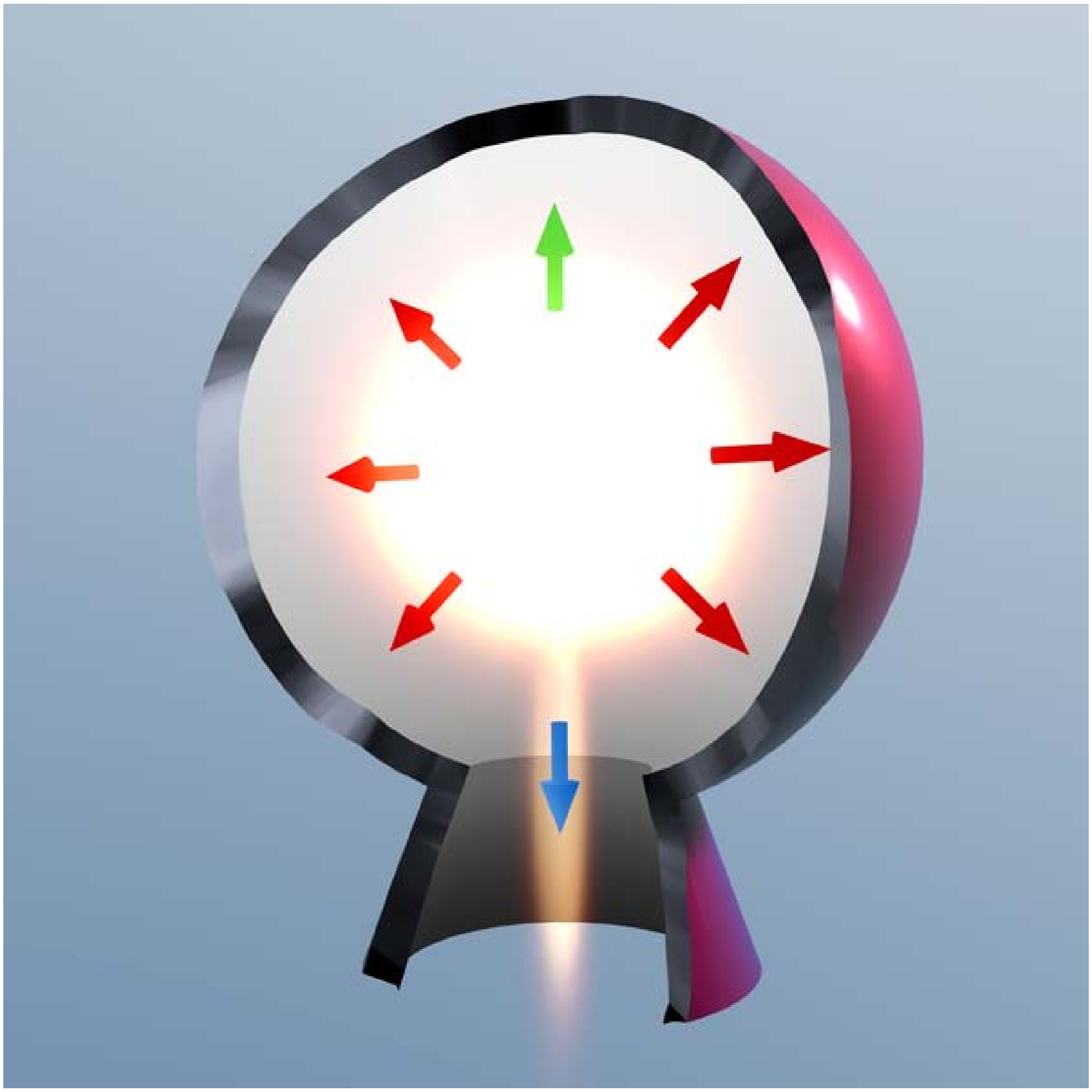
Hybrid rockets have a solid propellant in the combustion chamber and a second liquid or gas propellant is added to permit it to burn.

Thermal rockets are rockets where the propellant is inert, but is heated by a power source such as solar or nuclear power or beamed energy.

Principle of operation



How rocket engines work



Rocket engines give part of their thrust due to unopposed pressure on the combustion chamber

Rocket engines produce thrust by the expulsion of a high-speed fluid exhaust. This fluid is nearly always a gas which is created by high pressure (10-200 bar) combustion of solid or liquid propellants, consisting of fuel and oxidiser components, within a combustion chamber.

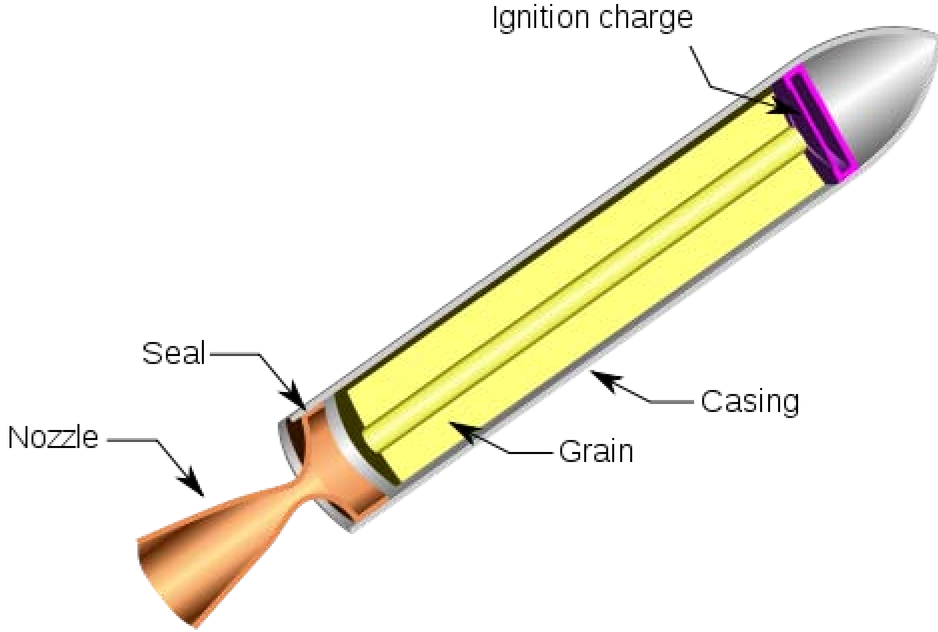
The fluid exhaust is then passed through a propelling nozzle which typically uses the heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction.

In rocket engines, high temperatures and pressures are highly desirable for good performance as this permits a longer nozzle to be fitted to the engine, which gives higher exhaust speeds, as well as giving better thermodynamic efficiency.

Introducing propellant into a combustion chamber

Rocket propellant is mass that is stored, usually in some form of propellant tank, prior to being ejected from a rocket engine in the form of a fluid jet to produce thrust.

Chemical rocket propellants are most commonly used, which undergo exothermic chemical reactions which produce hot gas which is used by a rocket for propulsive purposes. Alternatively, a chemically inert reaction mass can be heated using a high-energy power source via a heat exchanger, and then no combustion chamber is used.



A solid rocket motor

Solid rocket propellants are prepared as a mixture of fuel and oxidizing components called 'grain' and the propellant storage casing effectively becomes the combustion chamber. Liquid-fueled rockets typically pump separate fuel and oxidiser components into the combustion chamber, where they mix and burn. Hybrid rocket engines use a combination of solid and liquid or gaseous propellants. Both liquid and hybrid rockets use *injectors* to introduce the propellant into the chamber. These are often an array of simple jets- holes through which the propellant escapes under pressure; but sometimes may be more complex spray nozzles. When two or more propellants are injected the jets usually deliberately collide the propellants as this breaks up the flow into smaller droplets that burn more easily.

Combustion chamber

For chemical rockets the combustion chamber is typically just a cylinder, and flame holders are rarely used. The dimensions of the cylinder are such that the propellant is able to combust thoroughly; different propellants require different combustion chamber sizes for this to occur. This leads to a number called L^*:

$$L^* = \frac{V_c}{A_t}$$

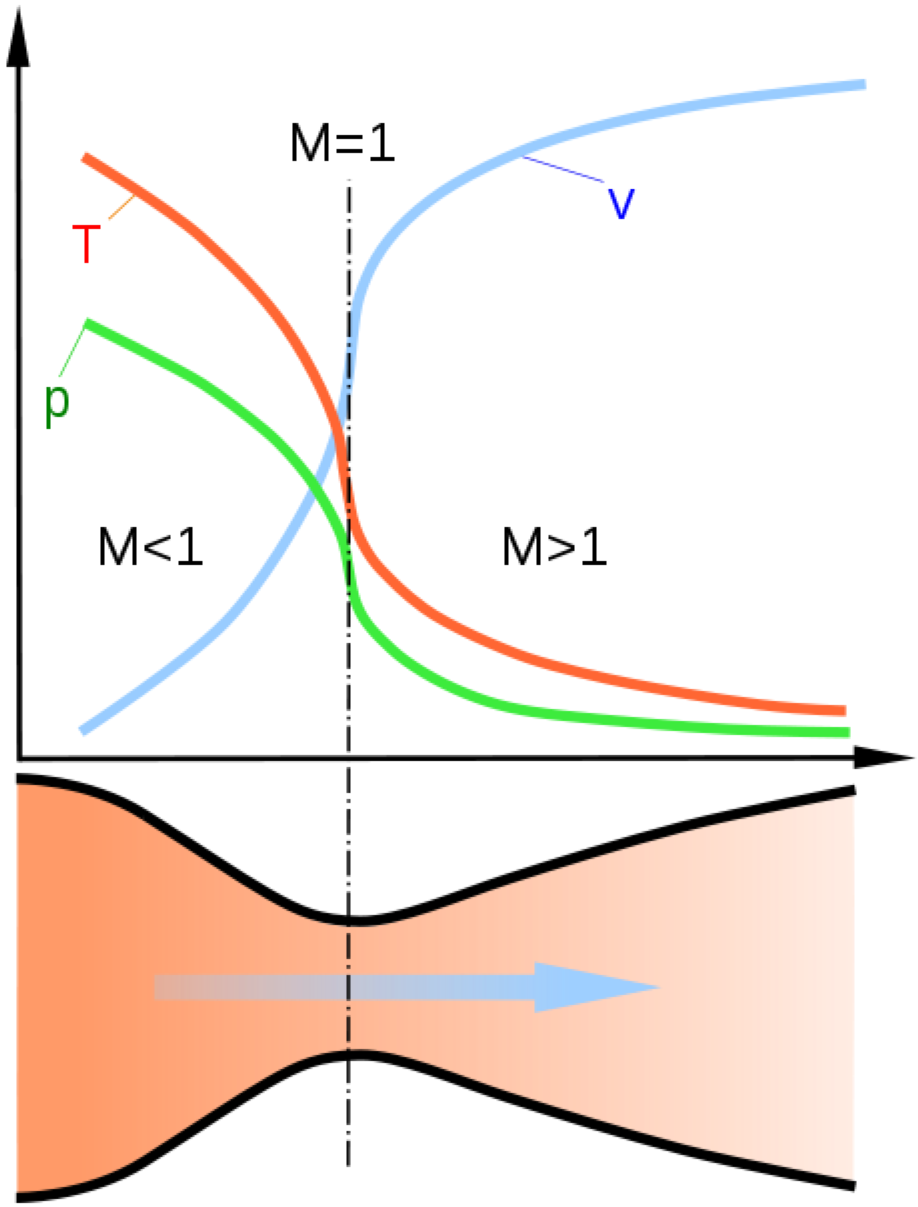
where:

- V_c is the volume of the chamber
- A_t is the area of the throat

L* is typically in the range of 25–60 inches (0.63–1.5 m).

The combination of temperatures and pressures typically reached in a combustion chamber is usually extreme by any standards. Unlike in air-breathing jet engines, no atmospheric nitrogen is present to dilute and cool the combustion, and the temperature can reach true stoichiometric. This, in combination with the high pressures, means that the rate of heat conduction through the walls is very high.

Rocket nozzles



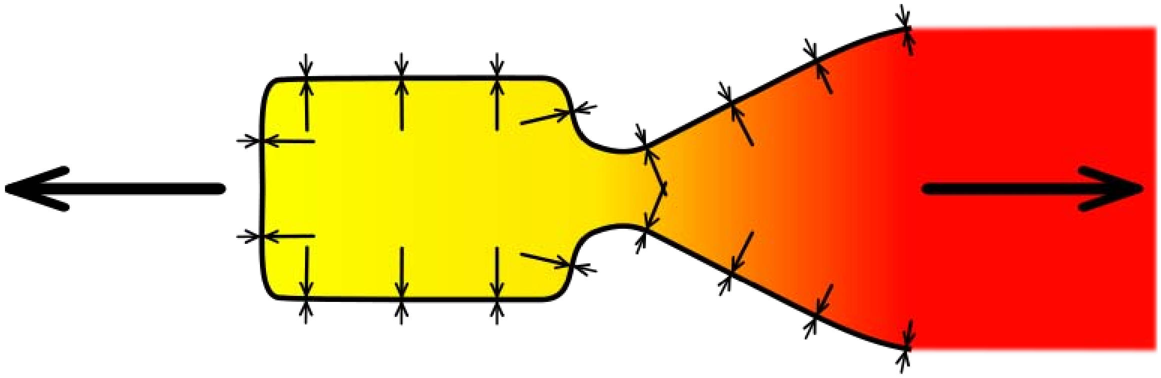
Typical temperatures (T) and pressures (p) and speeds (v) in a De Laval Nozzle

The large bell or cone shaped expansion nozzle gives a rocket engine its characteristic shape.

In rockets the hot gas produced in the combustion chamber is permitted to escape from the combustion chamber through an opening (the "throat"), within a high expansion-ratio 'de Laval' nozzle.

Provided sufficient pressure is provided to the nozzle (about 2.5-3x above ambient pressure) the nozzle *chokes* and a supersonic jet is formed, dramatically accelerating the gas, converting most of the thermal energy into kinetic energy.

The exhaust speeds vary, depending on the expansion ratio the nozzle is designed to give, but exhaust speeds as high as ten times the speed of sound of sea level air are not uncommon.



Rocket thrust is caused by pressures acting in the combustion chamber and nozzle. From Newton's third law, equal and opposite pressures act on the exhaust, and this accelerates it to high speeds.

About half of the rocket engine's thrust comes from the unbalanced pressures inside the combustion chamber and the rest comes from the pressures acting against the inside of the nozzle (see diagram). As the gas expands (adiabatically) the pressure against the nozzle's walls forces the rocket engine in one direction while accelerating the gas in the other.

Propellant efficiency

For a rocket engine to be propellant efficient, it is important that the maximum pressures possible be created on the walls of the chamber and nozzle by a specific amount of propellant; as this is the source of the thrust. This can be achieved by all of:

- heating the propellant to as high a temperature as possible (using a high energy fuel, containing hydrogen and carbon and sometimes metals such as aluminium, or even using nuclear energy)
- using a low specific density gas (as hydrogen rich as possible)
- using propellants which are, or decompose to, simple molecules with few degrees of freedom to maximise translational velocity

Since all of these things minimise the mass of the propellant used, and since pressure is proportional to the mass of propellant present to be accelerated as it pushes on the engine, and since from Newton's third law the pressure that acts on the engine also reciprocally acts on the propellant, it turns out that for any given engine the speed that the propellant leaves the chamber is unaffected by the chamber pressure (although the thrust is proportional). However, speed is significantly affected by all three of the above factors and the exhaust speed is an excellent measure of the engine propellant efficiency. This is termed *exhaust velocity*, and after allowance is made for factors that can reduce it, the

effective exhaust velocity is one of the most important parameters of a rocket engine (although weight, cost, ease of manufacture etc. are usually also very important).

For aerodynamic reasons the flow goes sonic ("chokes") at the narrowest part of the nozzle, the 'throat'. Since the speed of sound in gases increases with the square root of temperature, the use of hot exhaust gas greatly improves performance. By comparison, at room temperature the speed of sound in air is about 340 m/s while the speed of sound in the hot gas of a rocket engine can be over 1700 m/s; much of this performance is due to the higher temperature, but additionally rocket propellants are chosen to be of low molecular mass, and this also gives a higher velocity compared to air.

Expansion in the rocket nozzle then further multiplies the speed, typically between 1.5 and 2 times, giving a highly collimated hypersonic exhaust jet. The speed increase of a rocket nozzle is mostly determined by its area expansion ratio—the ratio of the area of the throat to the area at the exit, but detailed properties of the gas are also important. Larger ratio nozzles are more massive but are able to extract more heat from the combustion gases, increasing the exhaust velocity.

Nozzle efficiency is affected by operation in the atmosphere because atmospheric pressure changes with altitude; but due to the supersonic speeds of the gas exiting from a rocket engine, the pressure of the jet may be either below or above ambient, and equilibrium between the two is not reached at all altitudes.

Back pressure and optimal expansion

For optimal performance the pressure of the gas at the end of the nozzle should just equal the ambient pressure: if the exhaust's pressure is lower than the ambient pressure, then the vehicle will be slowed by the difference in pressure between the top of the engine and the exit; on the other hand, if the exhaust's pressure is higher, then exhaust pressure that could have been converted into thrust is not converted, and energy is wasted.

To maintain this ideal of equality between the exhaust's exit pressure and the ambient pressure, the diameter of the nozzle would need to increase with altitude, giving the pressure a longer nozzle to act on (and reducing the exit pressure and temperature). This increase is difficult to arrange in a lightweight fashion, although is routinely done with other forms of jet engines. In rocketry a lightweight compromise nozzle is generally used and some reduction in atmospheric performance occurs when used at other than the 'design altitude' or when throttled. To improve on this, various exotic nozzle designs such as the plug nozzle, stepped nozzles, the expanding nozzle and the aerospike have been proposed, each providing some way to adapt to changing ambient air pressure and each allowing the gas to expand further against the nozzle, giving extra thrust at higher altitudes.

When exhausting into a sufficiently low ambient pressure (vacuum) several issues arise. One is the sheer weight of the nozzle- beyond a certain point, for a particular vehicle, the extra weight of the nozzle outweighs any performance gained. Secondly, as the exhaust gases adiabatically expand within the nozzle they cool, and eventually some of the chemicals can freeze, producing 'snow' within the jet. This causes instabilities in the jet and must be avoided.

On a De Laval nozzle, exhaust gas flow detachment will occur in a grossly over-expanded nozzle. As the detachment point will not be uniform around the axis of the engine, a side force may be imparted to the engine. This side force may change over time and result in control problems with the launch vehicle.

Thrust vectoring

Many engines require the overall thrust to change direction over the length of the burn. A number of different ways to achieve this have been flown:

- The entire engine is mounted on a hinge or gimbal and any propellant feeds reach the engine via low pressure flexible pipes or rotary couplings.
- Just the combustion chamber and nozzle is gimbled, the pumps are fixed, and high pressure feeds attach to the engine
- multiple engines (often canted at slight angles) are deployed but throttled to give the overall vector that is required, giving only a very small penalty
- fixed engines with vernier thrusters
- high temperature vanes held in the exhaust that can be tilted to deflect the jet

Overall rocket engine performance

Rocket technology can combine very high thrust (meganewtons), very high exhaust speeds (around 10 times the speed of sound in air at sea level) and very high thrust/weight ratios (>100) *simultaneously* as well as being able to operate outside the atmosphere, and while permitting the use of low pressure and hence lightweight tanks and structure.

Rockets can be further optimised to even more extreme performance along one or more of these axes at the expense of the others.

Specific impulse

The most important metric for the efficiency of a rocket engine is impulse per unit of propellant, this is called specific impulse (usually written I_{sp}). This is either measured as a speed (the *effective exhaust velocity* V_e in metres/second or ft/s) or as a time (seconds). An engine that gives a large specific impulse is normally highly desirable.

The specific impulse that can be achieved is primarily a function of the propellant mix (and ultimately would limit the specific impulse), but practical limits on chamber pressures and the nozzle expansion ratios reduce the performance that can be achieved.

Typical performances of common propellants

Propellant mix	Vacuum Isp (seconds)	Effective exhaust velocity (m/s)
liquid oxygen/ liquid hydrogen	455	4462
liquid oxygen/ kerosene (RP-1)	358	3510
nitrogen tetroxide/ hydrazine	305	2993

Net thrust

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

$$F_n = \dot{m}\, V_e = \dot{m}\, V_{e-act} + A_e(P_e - P_{amb})$$

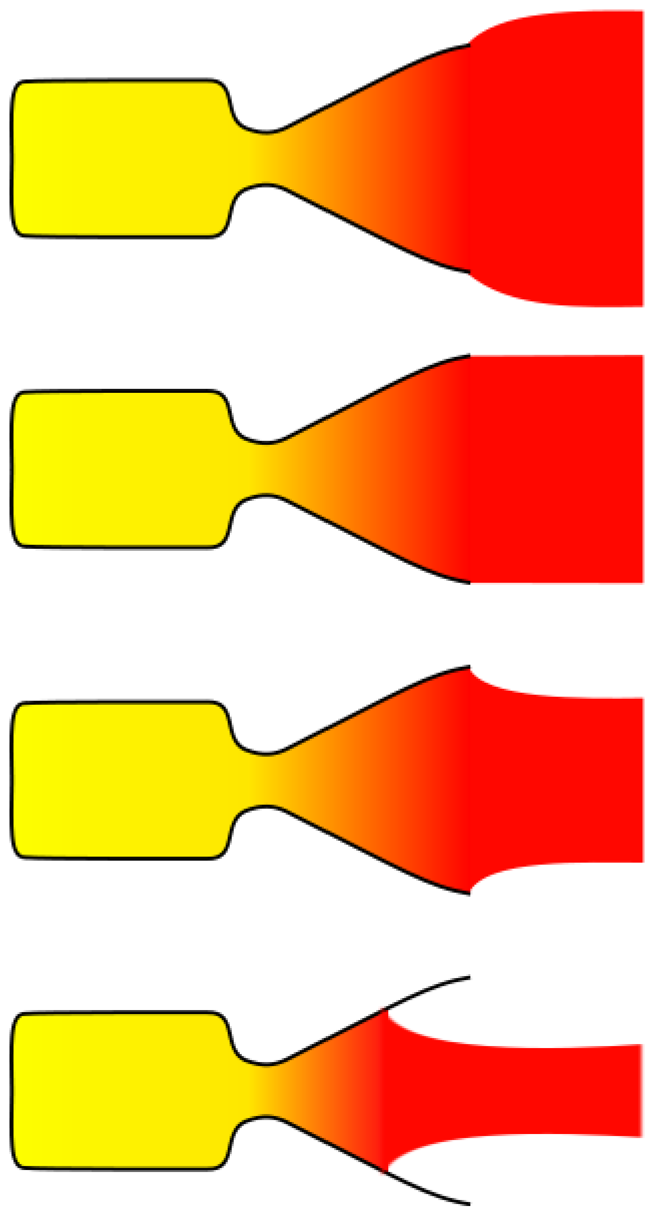
where:

$\dot{m}$ =exhaust gas mass flow
V_e =effective exhaust velocity
V_{e-act} =actual jet velocity at nozzle exit plane
A_e =flow area at nozzle exit plane (or the plane where the jet leaves the nozzle if separated flow)
P_e =static pressure at nozzle exit plane
P_{amb} =ambient (or atmospheric) pressure

Since, unlike a jet engine, a conventional rocket motor lacks an air intake, there is no 'ram drag' to deduct from the gross thrust. Consequently the net thrust of a rocket motor is equal to the gross thrust (apart from static back pressure).

The $\dot{m}\, V_{e-act}$term represents the momentum thrust, which remains constant at a given throttle setting, whereas the $A_e(P_e - P_{amb})$term represents the pressure thrust term. At full throttle, the net thrust of a rocket motor improves slightly with increasing altitude, because as atmospheric pressure decreases with altitude, the pressure thrust term increases. At the surface of the Earth the pressure thrust may be reduced by up to 30%,depending on the engine design. This reduction drops roughly exponentially to zero with increasing altitude.

Maximum thrust for a rocket engine is achieved by maximizing the momentum contribution of the equation without incurring penalties from over expanding the exhaust. This occurs when $P_e = P_{amb}$. Since ambient pressure changes with altitude, most rocket engines spend very little time operating at peak efficiency.



If the pressure of the exhaust jet varies from atmospheric pressure, nozzles can be said to be (top to bottom):

Underexpanded
Ambient
Overexpanded
Grossly overexpanded

If under or overexpanded then loss of efficiency occurs, grossly overexpanded nozzles lose less efficiency, but can cause mechanical issues with the nozzle. Rockets become progressively more underexpanded as they gain altitude. Note that almost all rocket engines will be momentarily grossly overexpanded during startup in an atmosphere.

Vacuum Isp

Due to the specific impulse varying with pressure, a quantity that is easy to compare and calculate with is useful. Because rockets choke at the throat, and because the supersonic exhaust prevents external pressure influences travelling upstream, it turns out that the pressure at the exit is ideally exactly proportional to the propellant flow $\dot{m}$, provided the mixture ratios and combustion efficiencies are maintained. It is thus quite usual to rearrange the above equation slightly:

$$F_{vac} = C_f \dot{m} c^*$$

and so define the *vacuum Isp* to be:

$$V_{evac} = C_f c^*$$

Where:

$c^* =$ the speed of sound constant at the throat
$C_f =$ the thrust coefficient constant of the nozzle (typically about 2)

And hence:

$$F_n = \dot{m} V_{evac} - A_e P_{amb}$$

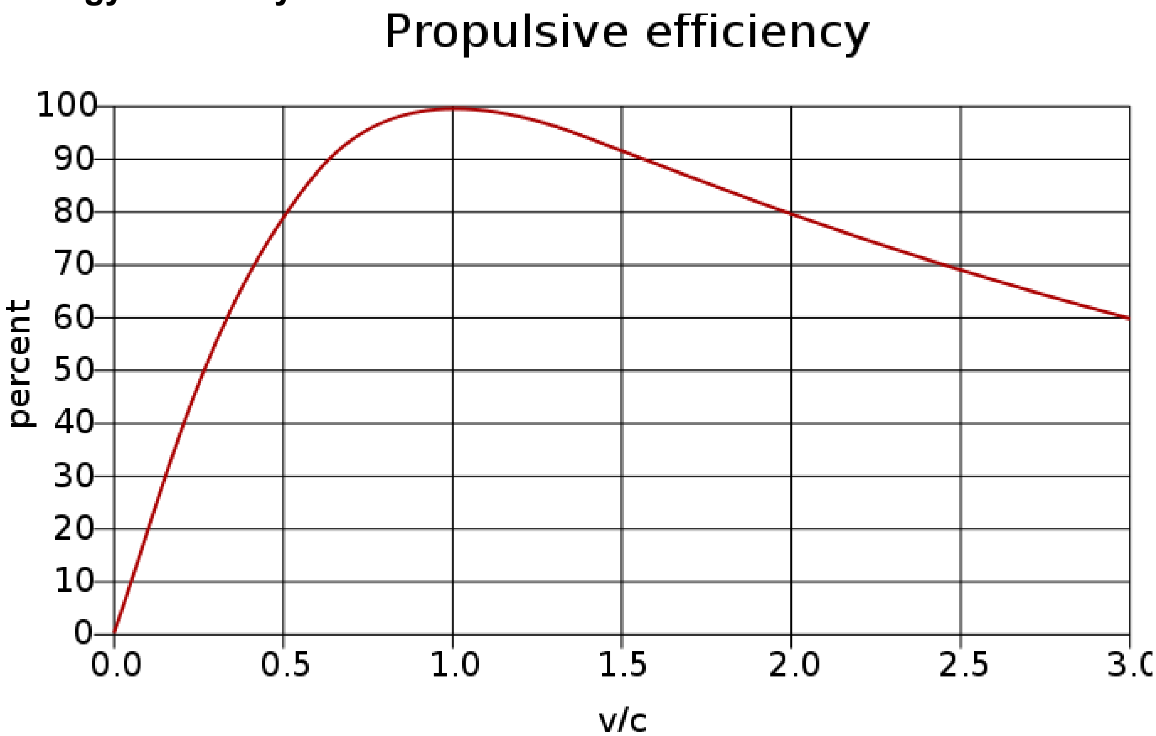
Throttling

Rockets can be throttled by controlling the propellant combustion rate $\dot{m}$ (usually measured in kg/s or lb/s). In liquid and hybrid rockets, the propellant flow entering the chamber is controlled using valves, in solid rockets it is controlled by changing the area of propellant that is burning and this can be designed into the propellant grain (and hence cannot be controlled in real-time).

Rockets can usually be throttled down to an exit pressure of about one-third of ambient pressure (often limited flow separation in nozzles) and up to a maximum limit determined only by the mechanical strength of the engine.

In practice, the degree to which rockets can be throttled varies greatly, but most rockets can be throttled by a factor of 2 without great difficulty; the typical limitation is combustion stability, as for example, injectors need a minimum pressure to avoid triggering damaging oscillations (chugging or combustion instabilities); but injectors can often be optimised and tested for wider ranges. Solid rockets can be throttled by using shaped grains that will vary their surface area over the course of the burn.

Energy efficiency



Rocket energy efficiency as a function of vehicle speed divided by effective exhaust speed

Rocket engine nozzles are surprisingly efficient heat engines for generating a high speed jet, as a consequence of the high combustion temperature and high compression ratio. Rocket nozzles give an excellent approximation to adiabatic expansion which is a reversible process, and hence they give efficiencies which are very close to that of the Carnot cycle. Given the temperatures reached, over 60% efficiency can be achieved with chemical rockets.

For a *vehicle* employing a rocket engine the energetic efficiency is very good if the vehicle speed approaches or somewhat exceeds the exhaust velocity (relative to launch); but at low speeds the energy efficiency goes to 0% at zero speed (as with all jet propulsion.)

Thrust to weight ratio

Rockets, of all the jet engines, indeed of essentially all engines, have the highest thrust to weight ratio. This is especially true for liquid rocket engines.

This high performance is due to the small volume of pressure vessels that make up the engine- the pumps, pipes and combustion chambers involved. The lack of inlet duct and the use of dense liquid propellant allows the pressurisation system to be small and lightweight, whereas duct engines have to deal with air which has a density about one thousand times lower.

Jet or Rocket engine	Mass, kg	Jet or rocket thrust, kN	Thrust-to-weight ratio
RD-0410 nuclear rocket engine	2000	35.2	1.8
J-58 (SR-71 Blackbird jet engine)	2722	150	5.2
Concorde's Rolls-Royce/Snecma Olympus 593 turbojet with reheat	3175	169.2	5.4
RD-0750 rocket engine, three-propellant mode	4621	1413	31.2
RD-0146 rocket engine	260	98	38.5
Space Shuttle's SSME **rocket engine**	3177	2278	73.2
RD-180 rocket engine	5393	4152	78.6
F-1 (Saturn V first stage)	8391	7740.5	94.1
NK-33 rocket engine	1222	1638	136.8

Of the liquid propellants used, density is worst for liquid hydrogen. Although this propellant is marvellous in many ways, it has a very low density, about one fourteenth that of water. This makes the turbopumps and pipework larger and heavier, and this is reflected in the thrust-to-weight ratio of engines that use it (for example the SSME) compared to those that do not (NK-33).

Cooling

For efficiency reasons, and because they physically can, rockets run with combustion temperatures that can reach ~3500 K (~5800 °F)(~3227 °C).

Most other jet engines have gas turbines in the hot exhaust. Due to their larger surface area, they are harder to cool and hence there is a need to run the combustion processes at much lower temperatures, losing efficiency. In addition duct engines use air as an oxidant, which contains 80% largely unreactive nitrogen, which dilutes the reaction and lowers the temperatures. Rockets have none of these inherent disadvantages.

Therefore in rockets temperatures employed are very often far higher than the melting point of the nozzle and combustion chamber materials, two exceptions are graphite and tungsten (~1200 K for copper), however both are subject to oxidation if not protected. Indeed many construction materials can make perfectly acceptable propellants in their own right. It is important that these materials be prevented from combusting, melting or vaporising to the point of failure. This is sometimes somewhat facetiously termed an 'engine rich exhaust'. Materials technology could potentially place an upper limit on the exhaust temperature of chemical rockets.

Alternatively, rockets may use more common construction materials such as aluminium, steel, nickel or copper alloys and employ cooling systems that prevent the construction material itself becoming too hot. Regenerative cooling, where the propellant is passed through tubes around the combustion chamber or nozzle, and other techniques, such as curtain cooling or film cooling, are employed to give longer nozzle and chamber life. These techniques ensure that a gaseous thermal boundary layer touching the material is kept below the temperature which would cause the material to catastrophically fail.

In rockets, the heat fluxes that can pass through the wall are among the highest in engineering, fluxes are generally in the range of 1-200 MW/m^2. The strongest heat fluxes are found at the throat, which often sees twice that found in the associated chamber and nozzle. This is due to the combination of high speeds (which gives a very thin boundary layer), and although lower than the chamber, the high temperatures seen there.

In rockets the coolant methods include:

1. uncooled (used for short runs mainly during testing)
2. ablative walls (walls are lined with a material that is continuously vaporised and carried away).
3. radiative cooling (the chamber becomes almost white hot and radiates the heat away)
4. dump cooling (a propellant, usually hydrogen, is passed around the chamber and dumped)
5. regenerative cooling (liquid rockets use the fuel, or occasionally the oxidiser, to cool the chamber via a cooling jacket before being injected)
6. curtain cooling (propellant injection is arranged so the temperature of the gases is cooler at the walls)
7. film cooling (surfaces are wetted with liquid propellant, which cools as it evaporates)

In all cases the cooling effect that prevents the wall from being destroyed is caused by a thin layer of insulating fluid (a boundary layer) that is in contact with the walls that is far cooler than the combustion temperature. Provided this boundary layer is intact the wall will not be damaged.

Disruption of the boundary layer may occur during cooling failures or combustion instabilities, and wall failure typically occurs soon after.

With regenerative cooling a second boundary layer is found in the coolant channels around the chamber. This boundary layer thickness needs to be as small as possible, since the boundary layer acts as an insulator between the wall and the coolant. This may be achieved by making the coolant velocity in the channels as high as possible.

In practice, regenerative cooling is nearly always used in conjunction with curtain cooling and/or film cooling.

Liquid fuelled engines are often run fuel rich, which results in a cooler burning exhaust. Cooler exhaust reduces heat loads on the engine allowing lower cost materials, a simplified cooling system, and a lower performance engine.

Mechanical issues

Rocket combustion chambers are normally operated at fairly high pressure, typically 10-200 bar (1 to 20 MPa, 150-3000 psi). When operated within significant atmospheric pressure, higher combustion chamber pressures give better performance by permitting a larger and more efficient nozzle to be fitted without it being grossly overexpanded.

However, these high pressures cause the outermost part of the chamber to be under very large hoop stresses – rocket engines are pressure vessels.

Worse, due to the high temperatures created in rocket engines the materials used tend to have a significantly lowered working tensile strength.

In addition, significant temperature gradients are set up in the walls of the chamber and nozzle, these cause differential expansion of the inner liner that create internal stresses.

Acoustic issues

In addition, the extreme vibration and acoustic environment inside a rocket motor commonly result in peak stresses well above mean values, especially in the presence of organ pipe-like resonances and gas turbulence.

Combustion instabilities

The combustion may display undesired instabilities, of sudden or periodic nature. The pressure in the injection chamber may increase until the propellant flow through the injector plate decreases; a moment later the pressure drops and the flow increases, injecting more propellant in the combustion chamber which burns a moment later, and again increases the chamber pressure, repeating the cycle. This may lead to high-amplitude pressure oscillations, often in ultrasonic range, which may damage the motor. Oscillations of ±200 psi at 25 kHz were the cause of failures of early versions of the Titan II missile second stage engines. The other failure mode is a deflagration to detonation transition; the supersonic pressure wave formed in the combustion chamber may destroy the engine.

The combustion instabilities can be provoked by remains of cleaning solvents in the engine, reflected shock wave, initial instability after ignition, explosion near the nozzle that reflects into the combustion chamber, and many more factors. In stable engine designs the oscillations are quickly suppressed; in unstable designs they persist for prolonged periods. Oscillation suppressors are commonly used.

Periodic variations of thrust, caused by combustion instability or longitudinal vibrations of structures between the tanks and the engines which modulate the propellant flow, are known as "pogo oscillations" or "pogo", named after the pogo stick.

Three different types of combustion instabilities occur:

Chugging

This is a low frequency oscillation at a few Hertz in chamber pressure usually caused by pressure variations in feed lines due to variations in acceleration of the vehicle. This can cause cyclic variation in thrust, and the effects can vary from merely annoying to actually damaging the payload or vehicle. Chugging can be minimised by using gas-filled damping tubes on feed lines of high density propellants.

Buzzing

This can be caused due to insufficient pressure drop across the injectors. It generally is mostly annoying, rather than being damaging. However, in extreme cases combustion can end up being forced backwards through the injectors – this can cause explosions with monopropellants.

Screeching

This is the most immediately damaging, and the hardest to control. It is due to acoustics within the combustion chamber that often couples to the chemical combustion processes that are the primary drivers of the energy release, and can lead to unstable resonant "screeching" that commonly leads to catastrophic failure due to thinning of the insulating thermal boundary layer. Such effects are very difficult to predict analytically during the design process, and have usually been addressed by expensive, time consuming and extensive testing, combined with trial and error remedial correction measures.

Screeching is often dealt with by detailed changes to injectors, or changes in the propellant chemistry, or vaporizing the propellant before injection, or use of Helmholtz dampers within the combustion chambers to change the resonant modes of the chamber.

Testing for the possibility of screeching is sometimes done by exploding small explosive charges outside the combustion chamber with a tube set tangentially to the combustion chamber near the injectors to determine the engine's impulse response and then evaluating the time response of the chamber pressure- a fast recovery indicates a stable system.

Exhaust noise

For all but the very smallest sizes, rocket exhaust compared to other engines is generally very noisy. As the hypersonic exhaust mixes with the ambient air, shock waves are formed. The Space Shuttle generates over 200 dB(A) of noise around its base.

The Saturn V launch was detectable on seismometers a considerable distance from the launch site. The sound intensity from the shock waves generated depends on the size of the rocket and on the exhaust velocity. Such shock waves seem to account for the characteristic crackling and popping sounds produced by large rocket engines when heard live. These noise peaks typically overload microphones and audio electronics, and so are generally weakened or entirely absent in recorded or broadcast audio reproductions. For large rockets at close range, the acoustic effects could actually kill.

More worryingly for space agencies, such sound levels can also damage the launch structure, or worse, be reflected back at the comparatively delicate rocket above. This is why so much water is typically used at launches. The water spray changes the acoustic qualities of the air and reduces or deflects the sound energy away from the rocket.

Generally speaking noise is most intense when a rocket is close to the ground, since the noise from the engines radiates up away from the plume, as well as reflecting off the ground. Also, when the vehicle is moving slowly, little of the chemical energy input to the engine can go into increasing the kinetic energy of the rocket (since useful power P transmitted to the vehicle is $P = F * V$ for thrust F and speed V). Then the largest portion of the energy is dissipated in the exhaust's interaction with the ambient air, producing noise. This noise can be reduced somewhat by flame trenches with roofs, by water injection around the plume and by deflecting the plume at an angle.

Testing

Rocket engines are usually statically tested at a test facility before being put into production. For high altitude engines, either a shorter nozzle must be used, or the rocket must be tested in a large vacuum chamber.

Safety

Rockets have a reputation for unreliability and danger; especially catastrophic failures. Contrary to this reputation, carefully designed rockets can be made arbitrarily reliable. In military use, rockets are not unreliable. However, one of the main non-military uses of rockets is for orbital launch. In this application, the premium is on minimum weight, and it is difficult to achieve high reliability and low weight simultaneously. In addition, if the number of flights launched is low, there is a very high chance of a design, operations or manufacturing error causing destruction of the vehicle. Essentially all launch vehicles are test vehicles by normal aerospace standards (as of 2006).

The X-15 rocket plane achieved a 0.5% failure rate, with a single catastrophic failure during ground test, and the SSME has managed to avoid catastrophic failures in over 350 engine-flights.

Chemistry

Rocket propellants require a high specific energy (energy per unit mass), because ideally all the reaction energy appears as kinetic energy of the exhaust gases, and exhaust velocity is the single most important performance parameter of an engine, on which vehicle performance depends.

Aside from inevitable losses and imperfections in the engine, incomplete combustion, etc., after specific reaction energy, the main theoretical limit reducing the exhaust velocity obtained is that, according to the laws of thermodynamics, a fraction of the chemical energy may go into rotation of the exhaust molecules, where it is unavailable for producing thrust. Monatomic gases like helium have only three degrees of freedom, corresponding to the three dimensions of space, $\{x,y,z\}$, and only such spherically symmetric molecules escape this kind of loss. A diatomic molecule like H_2 can rotate about either of the two axes perpendicular to the one joining the two atoms, and as the equipartition law of statistical mechanics demands that the available thermal energy be divided equally among the degrees of freedom, for such a gas in thermal equilibrium 3/5 of the energy can go into unidirectional motion, and 2/5 into rotation. A triatomic molecule like water has six degrees of freedom, so the energy is divided equally among rotational and translational degrees of freedom. For most chemical reactions the latter situation is the case. This issue is traditionally described in terms of the ratio, gamma, of the specific heat of the gas at constant volume to that at constant pressure. The rotational energy loss is largely recovered in practice if the expansion nozzle is large enough to allow the gases to expand and cool sufficiently, the function of the nozzle being to convert the random thermal motions of the molecules in the combustion chamber into the unidirectional translation that produces thrust. As long as the exhaust gas remains in equilibrium as it expands, the initial rotational energy will be largely returned to translation in the nozzle.

Although the specific reaction energy per unit mass of reactants is key, low mean molecular weight in the reaction products is also important in practice in determining exhaust velocity. This is because the high gas temperatures in rocket engines pose serious problems for the engineering of survivable motors. Because temperature is proportional to the mean *energy per molecule*, a given amount of energy distributed among more molecules of lower mass permits a higher exhaust velocity at a given temperature. This means low atomic mass elements are favoured. Liquid hydrogen (LH2) and oxygen (LOX, or LO2), are the most effective propellants in terms of exhaust velocity that have been widely used to date, though a few exotic combinations involving boron or liquid ozone are potentially somewhat better in theory if various practical problems could be solved.

It is important to note in computing the specific reaction energy, that the *entire mass of the propellants, including both fuel and oxidizer*, must be included. The fact that air-breathing engines are typically able to obtain oxygen "for free" without having to carry it along, accounts for one factor of why air-breathing engines are very much more propellant-mass efficient, and one reason that rocket engines are far less suitable for most ordinary terrestrial applications. Fuels for automobile or turbojet engines, utilize atmospheric oxygen and so have a much better effective energy output per unit mass of propellant that must be carried, but are similar per unit mass of fuel.

Computer programs that predict the performance of propellants in rocket engines are available.

Ignition

With liquid and hybrid rockets, immediate ignition of the propellant(s) as they first enter the combustion chamber is essential.

With liquid propellants (but not gaseous), failure to ignite within milliseconds usually causes too much liquid propellant to be within the chamber, and if/when ignition occurs the amount of hot gas created will often exceed the maximum design pressure of the chamber. The pressure vessel will often fail catastrophically. This is sometimes called a *hard start*.

Ignition can be achieved by a number of different methods; a pyrotechnic charge can be used, a plasma torch can be used, or electric spark plugs may be employed. Some fuel/oxidizer combinations ignite on contact (hypergolic), and non-hypergolic fuels can be "chemically ignited" by priming the fuel lines with hypergolic propellants (popular in Russian engines).

Gaseous propellants generally will not cause hard starts, with rockets the total injector area is less than the throat thus the chamber pressure tends to ambient prior to ignition and high pressures cannot form even if the entire chamber is full of flammable gas at ignition.

Solid propellants are usually ignited with one-shot pyrotechnic devices.

Once ignited, rocket chambers are self sustaining and igniters are not needed. Indeed chambers often spontaneously reignite if they are restarted after being shut down for a few seconds. However, when cooled, many rockets cannot be restarted without at least minor maintenance, such as replacement of the pyrotechnic igniter.

Plume physics

Armadillo aerospace's quad vehicle showing visible banding (shock diamonds) in the exhaust plume

Rocket plume varies depending on the rocket engine, design altitude, altitude, thrust and other factors.

Carbon rich exhausts from kerosene fuels are often orange in colour due to the black body radiation of the unburned particles, in addition to the blue Swan bands. Peroxide oxidiser based rockets and hydrogen rocket plumes contain largely steam and are nearly invisible to the naked eye but shine brightly in the ultraviolet and infrared. Plumes from solid rockets can be highly visible as the propellant frequently contains metals such as elemental aluminium which burns with an orange-white flame and adds energy to the combustion process.

Some exhausts, notably alcohol fuelled rockets, can show visible shock diamonds. These are due to cyclic variations in the plume pressure relative to ambient creating shock waves that form 'mach disks'.

The shape of the plume varies from the design altitude, at high altitude all rockets are grossly under-expanded, and a quite small percentage of exhaust gases actually end up expanding forwards.

Types of rocket engines

Physically powered

Type	Description	Advantages	Disadvantages
water rocket	Partially filled pressurised carbonated drinks container with tail and nose weighting	Very simple to build	Altitude typically limited to a few hundred feet or so (world record is 623 meters/2044 feet)
cold gas thruster	A non combusting form, used for vernier thrusters	Non contaminating exhaust	Extremely low performance
hot water rocket	Hot water is stored in a tank at high temperature/pressure and turns to steam in nozzle	Simple, fairly safe, under 200 seconds Isp	Low overall performance due to heavy tank

Chemically powered

Type	Description	Advantages	Disadvantages
Solid rocket	Ignitable, self sustaining solid fuel/oxidiser mixture ("grain") with central hole and nozzle	Simple, often no moving parts, reasonably good mass fraction, reasonable I_{sp}. A thrust schedule can be designed into the grain.	Once lit, extinguishing it is difficult although often possible, cannot be throttled in real time; handling issues from ignitable mixture, lower performance than liquid rockets, if grain cracks it can block nozzle with disastrous results, cracks burn and widen during burn. Refuelling grain harder than simply filling tanks, Lower specific Impulse than Liquid Rockets.
Hybrid rocket	Separate oxidiser/fuel, typically oxidiser is liquid and kept in a tank, the other solid with central hole	Quite simple, solid fuel is essentially inert without oxidiser, safer; cracks do not escalate, throttleable and easy to switch off.	Some oxidisers are monopropellants, can explode in own right; mechanical failure of solid propellant can block nozzle (very rare with rubberised propellant), central hole widens over burn and negatively affects mixture ratio.

Monopropellant rocket	Propellant such as Hydrazine, Hydrogen Peroxide or Nitrous Oxide, flows over catalyst and exothermically decomposes and hot gases are emitted through nozzle	Simple in concept, throttleable, low temperatures in combustion chamber	catalysts can be easily contaminated, monopropellants can detonate if contaminated or provoked, I_{sp} is perhaps 1/3 of best liquids
Liquid Bipropellant rocket	Two fluid (typically liquid) propellants are introduced through injectors into combustion chamber and burnt	Up to ~99% efficient combustion with excellent mixture control, throttleable, can be used with turbopumps which permits incredibly lightweight tanks, can be safe with extreme care	Pumps needed for high performance are expensive to design, huge thermal fluxes across combustion chamber wall can impact reuse, failure modes include major explosions, a lot of plumbing is needed.
Dual mode propulsion rocket	Rocket takes off as a bipropellant rocket, then turns to using just one propellant as a monopropellant	Simplicity and ease of control	Lower performance than bipropellants
Tripropellant rocket	Three different propellants (usually hydrogen, hydrocarbon and liquid oxygen) are introduced into a combustion chamber in variable mixture ratios, or multiple engines are used with fixed propellant mixture ratios and throttled or shut down	Reduces take-off weight, since hydrogen is lighter; combines good thrust to weight with high average I_{sp}, improves payload for launching from Earth by a sizeable percentage	Similar issues to bipropellant, but with more plumbing, more R&D
Air-augmented rocket	Essentially a ramjet where intake air is compressed and burnt with the exhaust from a rocket	Mach 0 to Mach 4.5+ (can also run exoatmospheric), good efficiency at Mach 2 to 4	Similar efficiency to rockets at low speed or exoatmospheric, inlet difficulties, a relatively undeveloped and unexplored type, cooling difficulties, very noisy,

			thrust/weight ratio is similar to ramjets.
Turborocket	A combined cycle turbojet/rocket where an additional oxidizer such as oxygen is added to the airstream to increase maximum altitude	Very close to existing designs, operates in very high altitude, wide range of altitude and airspeed	Atmospheric airspeed limited to same range as turbojet engine, carrying oxidizer like LOX can be dangerous. Much heavier than simple rockets.
Precooled jet engine / LACE (combined cycle with rocket)	Intake air is chilled to very low temperatures at inlet before passing through a ramjet or turbojet engine. Can be combined with a rocket engine for orbital insertion.	Easily tested on ground. High thrust/weight ratios are possible (~14) together with good fuel efficiency over a wide range of airspeeds, mach 0-5.5+; this combination of efficiencies may permit launching to orbit, single stage, or very rapid intercontinental travel.	Exists only at the lab prototyping stage. Examples include RB545, SABRE, ATREX

Electrically powered

Type	Description	Advantages	Disadvantages
Resistojet rocket (electric heating)	A monopropellant is electrically heated by a filament for extra performance	Higher I_{sp} than monopropellant alone, about 40% higher.	Uses a lot of power and hence gives typically low thrust
Arcjet rocket (chemical burning aided by electrical discharge)	Similar to resistojet in concept but with inert propellant, except an arc is used which allows higher temperatures	1600 seconds I_{sp}	Very low thrust and high power, performance is similar to Ion drive.
Pulsed plasma thruster (electric arc heating; emits plasma)	Plasma is used to erode a solid propellant	High I_{sp}, can be pulsed on and off for attitude control	Low energetic efficiency
Variable specific impulse magnetoplasma	Microwave heated plasma with magnetic	Variable I_{sp} from 1000 seconds to 10,000 seconds	similar thrust/weight ratio with ion drives (worse), thermal issues, as with ion

rocket	throat/nozzle		drives very high power requirements for significant thrust, really needs advanced nuclear reactors, never flown, requires low temperatures for superconductors to work

Solar powered

The Solar thermal rocket would make use of solar power to directly heat reaction mass, and therefore does not require an electrical generator as most other forms of solar-powered propulsion do. A solar thermal rocket only has to carry the means of capturing solar energy, such as concentrators and mirrors. The heated propellant is fed through a conventional rocket nozzle to produce thrust. The engine thrust is directly related to the surface area of the solar collector and to the local intensity of the solar radiation and inversely proportional to the I_{sp}.

Type	Description	Advantages	Disadvantages
Solar thermal rocket	Propellant is heated by solar collector	Simple design. Using hydrogen propellant, 900 seconds of I_{sp} is comparable to Nuclear Thermal rocket, without the problems and complexity of controlling a fission reaction. Using higher–molecular-weight propellants, for example water, lowers performance.	Only useful once in space, as thrust is fairly low, but hydrogen is not easily stored in space, otherwise moderate/low I_{sp} if higher–molecular-mass propellants are used

Beam powered

Type	Description	Advantages	Disadvantages
light beam powered rocket	Propellant is heated by light beam (often laser) aimed at vehicle from a distance, either directly or indirectly via heat exchanger	simple in principle, in principle very high exhaust speeds can be achieved	~1 MW of power per kg of payload is needed to achieve orbit, relatively high accelerations, lasers are blocked by clouds, fog, reflected laser light may be dangerous, pretty much needs hydrogen monopropellant for good performance which needs heavy tankage, some designs are limited to ~600 seconds due to reemission of light since propellant/heat exchanger gets white hot
microwave beam powered	Propellant is heated by microwave beam aimed at	microwaves avoid reemission of energy, so	~1 MW of power per kg of payload is needed to achieve orbit, relatively high accelerations, microwaves are

rocket	vehicle from a distance	~900 seconds exhaust speeds might be achieveable	absorbed to a degree by rain, reflected microwaves may be dangerous, pretty much needs hydrogen monopropellant for good performance which needs heavy tankage, transmitter diameter is measured in kilometres to achieve a fine enough beam to hit a vehicle at up to 100 km.

Nuclear powered

Nuclear propulsion includes a wide variety of propulsion methods that use some form of nuclear reaction as their primary power source. Various types of nuclear propulsion have been proposed, and some of them tested, for spacecraft applications:

Type	Description	Advantages	Disadvantages
Radioisotope rocket/"Poodle thruster" (radioactive decay energy)	Heat from radioactive decay is used to heat hydrogen	about 700–800 seconds, almost no moving parts	low thrust/weight ratio.
Nuclear thermal rocket (nuclear fission energy)	propellant (typ. hydrogen) is passed through a nuclear reactor to heat to high temperature	I_{sp} can be high, perhaps 900 seconds or more, above unity thrust/weight ratio with some designs	Maximum temperature is limited by materials technology, some radioactive particles can be present in exhaust in some designs, nuclear reactor shielding is heavy, unlikely to be permitted from surface of the Earth, thrust/weight ratio is not high.
Gas core reactor rocket (nuclear fission energy)	Nuclear reaction using a gaseous state fission reactor in intimate contact with propellant	Very hot propellant, not limited by keeping reactor solid, I_{sp} between 1500 and 3000 seconds but with very high thrust	Difficulties in heating propellant without losing fissionables in exhaust, massive thermal issues particularly for nozzle/throat region, exhaust almost inherently highly radioactive. Nuclear lightbulb variants can contain fissionables, but cut I_{sp} in half.
Fission-fragment rocket (nuclear fission energy)	Fission products are directly exhausted to		Theoretical only at this point.

	give thrust		
Fission sail (nuclear fission energy)	A sail material is coated with fissionable material on one side	No moving parts, works in deep space	Theoretical only at this point.
Nuclear salt-water rocket (nuclear fission energy)	Nuclear salts are held in solution, caused to react at nozzle	Very high I_{sp}, very high thrust	Thermal issues in nozzle, propellant could be unstable, highly radioactive exhaust. Theoretical only at this point.
Nuclear pulse propulsion (exploding fission/fusion bombs)	Shaped nuclear bombs are detonated behind vehicle and blast is caught by a 'pusher plate'	Very high I_{sp}, very high thrust/weight ratio, no show stoppers are known for this technology	Never been tested, pusher plate may throw off fragments due to shock, minimum size for nuclear bombs is still pretty big, expensive at small scales, nuclear treaty issues, fallout when used below Earth's magnetosphere.
Antimatter catalyzed nuclear pulse propulsion (fission and/or fusion energy)	Nuclear pulse propulsion with antimatter assist for smaller bombs	Smaller sized vehicle might be possible	Containment of antimatter, production of antimatter in macroscopic quantities isn't currently feasible. Theoretical only at this point.
Fusion rocket (nuclear fusion energy)	Fusion is used to heat propellant	Very high exhaust velocity	Largely beyond current state of the art.
Antimatter rocket (annihilation energy)	Antimatter annihilation heats propellant	Extremely energetic, very high theoretical exhaust velocity	Problems with antimatter production and handling; energy losses in neutrinos, gamma rays, muons; thermal issues. Theoretical only at this point

History of rocket engines

According to the writings of the Roman Aulus Gellius, in c. 400 BC, a Greek Pythagorean named Archytas, propelled a wooden bird along wires using steam. However, it would not appear to have been powerful enough to take off under its own thrust.

The *aeolipile* described in the first century BC (often known as *Hero's engine*) essentially consists of a steam rocket on a bearing. It was created almost two millennia before the Industrial Revolution but the principles behind it were not well understood, and its full potential was not realized for a millennium.

The availability of black powder to propel projectiles was a precursor to the development of the first solid rocket. Ninth Century Chinese Taoist alchemists discovered black powder in a search for the Elixir of life; this accidental discovery led to fire arrows which were the first rocket engines to leave the ground.

Rocket engines were also brought in use by Tippu Sultan, The king of Mysore. These rockets could be of various sizes, but usually consisted of a tube of soft hammered iron about 8" long and 1½ - 3" diameter, closed at one end and strapped to a shaft of bamboo about 4 ft. long. The iron tube acted as a combustion chamber and contained well packed black powder propellant. A rocket carrying about one pound of powder could travel almost 1,000 yards. These 'rockets', fitted with swords used to travel long distance, several meters above in air before coming down with swords edges facing the enemy. These rockets were used against British empire very effectively.

Slow development of this technology continued up to the later 20th Century, when the writings of Konstantin Tsiolkovsky first talked about liquid fuelled rocket engines.

These independently became a reality thanks to Robert Goddard. Goddard also used a De Laval nozzle for the first time on a rocket, doubling the thrust and multiplying up the efficiency by several times.

During the late 1930s, German scientists, such as Wernher von Braun and Hellmuth Walter, investigated installing liquid-fuelled rockets in aircraft (Heinkel He 112, He 111, He 176 and Messerschmitt Me 163).

The turbopump was first employed by German scientists in WWII. At this time cooling the nozzle was often problematic, and the V2 ballistic missile used dilute alcohol for the fuel, which reduced the combustion temperature somewhat.

Staged combustion (*Замкнутая схема*) was first proposed by Alexey Isaev in 1949. The first staged combustion engine was the S1.5400 used in the Soviet planetary rocket, designed by Melnikov, a former assistant to Isaev. About the same time (1959), Nikolai Kuznetsov began work on the closed cycle engine NK-9 for Korolev's orbital ICBM, GR-1. Kuznetsov later evolved that design into the NK-15 and NK-33 engines for the unsuccessful Lunar N1 rocket.

In the West, the first laboratory staged-combustion test engine was built in Germany in 1963, by Ludwig Boelkow.

Hydrogen peroxide / kerosene fuelled engines such as the British Gamma of the 1950s used a closed-cycle process (arguably not *staged combustion*, but that's mostly a question of semantics) by catalytically decomposing the peroxide to drive turbines *before* combustion with the kerosene in the combustion chamber proper. This gave the efficiency advantages of staged combustion, whilst avoiding the major engineering problems.

Liquid hydrogen engines were first successfully developed in America, the RL-10 engine first flew in 1962. Hydrogen engines were used as part of the Project Apollo; the liquid hydrogen fuel giving a rather lower stage mass and thus reducing the overall size and cost of the vehicle.

The Space Shuttle's SSME is the highest ground-launched specific impulse rocket engine to fly.

Chapter- 5

Airbreathing Jet Engine

An **airbreathing jet engine** (or *ducted jet engine*) is a jet engine that has an inlet duct that admits air for the combustion of fuel in the air stream which forms a jet of hot gases used for propulsion. Airbreathing jet engines are mostly used for powering jet aircraft.

Types of airbreathing jet engines

Airbreathing jet engines are internal combustion engines that obtain propulsion from the combustion of fuel inside the engine. Oxygen present in the atmosphere is used to oxidise a fuel source, typically a hydrocarbon-based jet fuel. The burning mixture expands greatly in volume, driving heated air through a propelling nozzle.

Gas turbine powered engines:

- turbojet
- turbofan

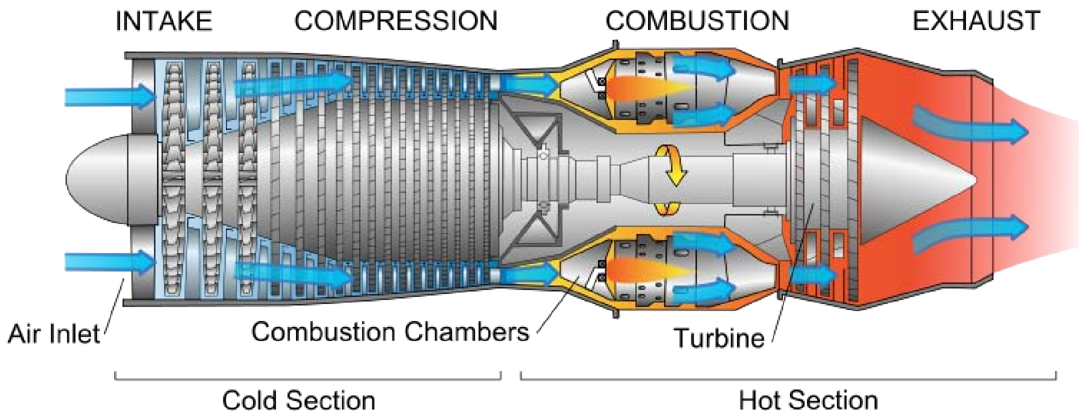
Ram powered jet engine:

- ramjet
- scramjet

Pulsed combustion jet engine:

- pulse detonation engine
- pulse jet engine
- motorjet

Turbojet engine



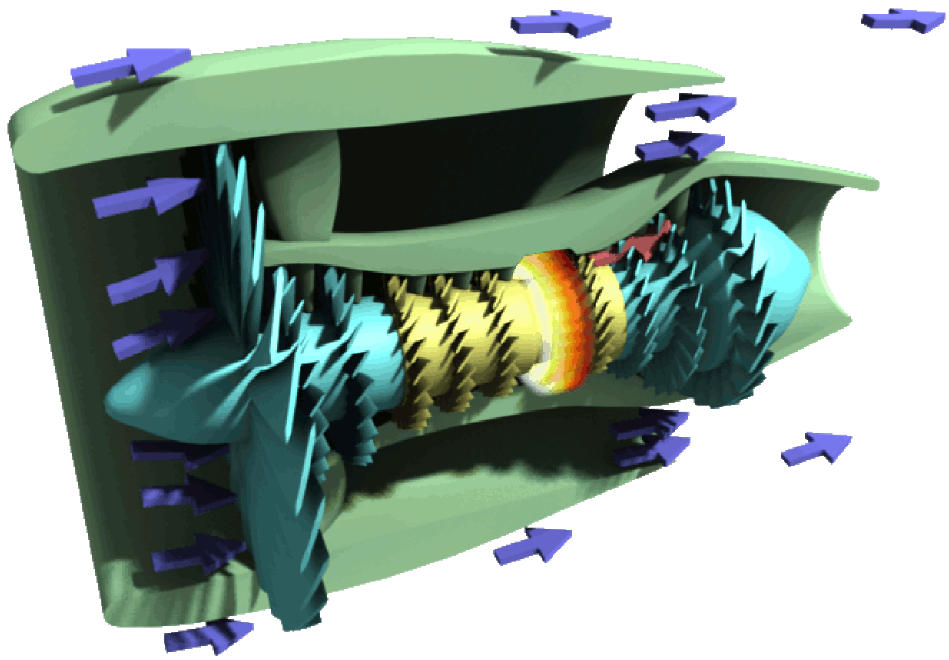
Turbojet engine layout

The **turbojet** is the oldest kind of general-purpose jet engine. Two engineers, Frank Whittle in the United Kingdom and Hans von Ohain in Germany, developed the concept independently into practical engines during the late 1930s.

Turbojets consist of an air inlet, an air compressor, a combustion chamber, a gas turbine (that drives the air compressor) and a nozzle. The air is compressed into the chamber, heated and expanded by the fuel combustion and then allowed to expand out through the turbine into the nozzle where it is accelerated to high speed to provide propulsion.

Turbojets are quite inefficient if flown below about Mach 2. and very noisy. Most modern aircraft use turbofans instead for economic reasons. Turbojets are still very common in medium range cruise missiles, due to their high exhaust speed, low frontal area and relative simplicity.

Turbofan engine



Turbofan engine

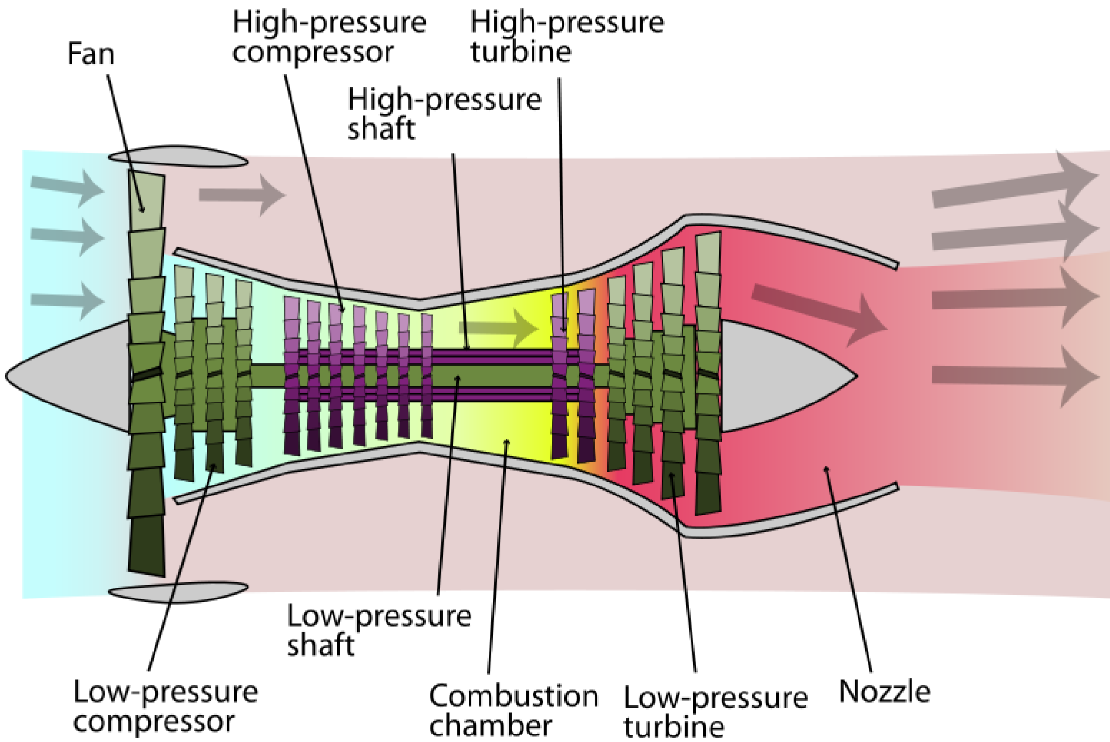
Most modern jet engines are actually turbofans, where the low pressure compressor acts as a fan, supplying supercharged air not only to the engine core, but to a bypass duct. The bypass airflow either passes to a separate 'cold nozzle' or mixes with low pressure turbine exhaust gases, before expanding through a 'mixed flow nozzle'.

Turbofans are used for airliners because they give an exhaust speed that is better matched for subsonic airliners. At airliner flight speeds, conventional turbojet engines generate an exhaust that ends up travelling very fast backwards, and this wastes energy. By emitting the exhaust so that it ends up travelling more slowly, better fuel consumption is achieved as well as higher thrust at low speeds. In addition, the lower exhaust speed gives much lower noise.

In the 1960s there was little difference between civil and military jet engines, apart from the use of afterburning in some (supersonic) applications. Civil turbofans today have a low exhaust speed (low *specific thrust* -net thrust divided by airflow) to keep jet noise to a minimum and to improve fuel efficiency. Consequently the bypass ratio (bypass flow divided by core flow) is relatively high (ratios from 4:1 up to 8:1 are common). Only a single fan stage is required, because a low specific thrust implies a low fan pressure ratio.

Today's military turbofans, however, have a relatively high specific thrust, to maximize the thrust for a given frontal area, jet noise being of less concern in military uses relative to civil uses. Multistage fans are normally needed to reach the relatively high fan pressure ratio needed for high specific thrust. Although high turbine inlet temperatures are often employed, the bypass ratio tends to be low, usually significantly less than 2.0.

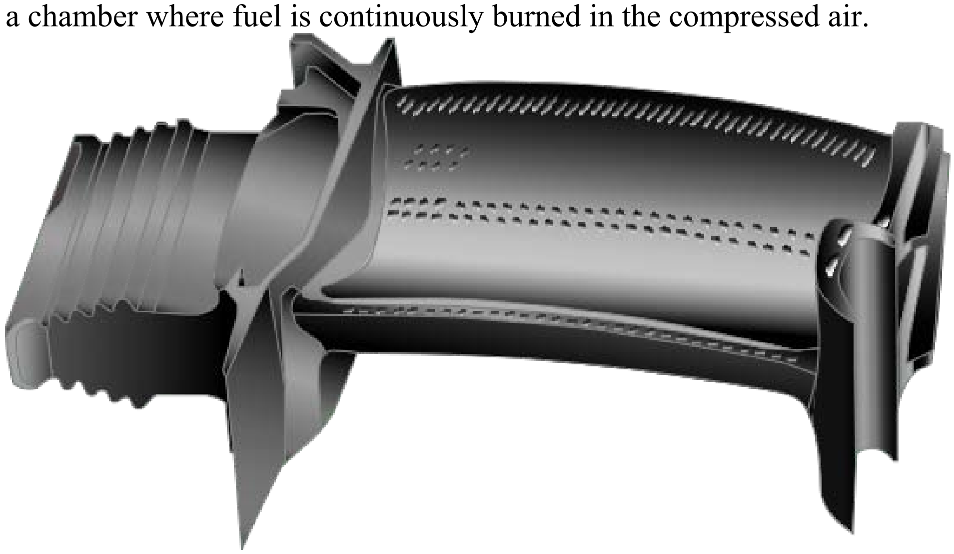
Major components



The major components of a jet engine are similar across the major different types of engines, although not all engine types have all components. The major parts include:

- **Cold Section:**
    - **Air intake (Inlet)**—For subsonic aircraft, the air intake to a jet engine consists essentially of an opening which is designed to minimise drag. The air reaching the compressor of a normal jet engine must be travelling below the speed of sound, even for supersonic aircraft, to allow smooth flow through compressor and turbine blades. At supersonic flight speeds, shockwaves form in the intake system. These help compress the air, but also there is inevitable reduction in the recovered pressure at inlet to the compressor. Some supersonic intakes use devices such as a cone or a ramp to increase pressure recovery.
    - **Compressor** or **Fan**—The compressor is made up of stages. Each stage consists of vanes which rotate, and stators which remain stationary. As air is drawn deeper through the compressor, its heat and pressure increases. Energy is derived from the **turbine** (see below), passed along the **shaft**.

- **Bypass ducts**—Much of the thrust of essentially all modern jet engines comes from air from the front compressor that bypasses the combustion chamber and gas turbine section that leads directly to the nozzle or afterburner (where fitted).

- **Common:**
  - **Shaft**—The shaft connects the **turbine** to the **compressor**, and runs most of the length of the engine. There may be as many as three concentric shafts, rotating at independent speeds, with as many sets of turbines and compressors. Other services, like a bleed of cool air, may also run down the shaft.
- **Diffuser section:** - This section is a divergent duct that utilizes Bernoulli's principle to decrease the velocity of the compressed air to allow for easier ignition. And, at the same time, continuing to increase the air pressure before it enters the combustion chamber.
- **Hot section:**
  - **Combustor** or **Can** or **Flameholders** or **Combustion Chamber**—This is a chamber where fuel is continuously burned in the compressed air.
  - 

    A blade with internal cooling as applied in the high-pressure turbine

    Turbine—The turbine is a series of bladed discs that act like a windmill, gaining energy from the hot gases leaving the **combustor**. Some of this energy is used to drive the **compressor**, and in some turbine engines (i.e. turboprop, turboshaft or turbofan engines), energy is extracted by additional turbine discs and used to drive devices such as propellers, bypass fans or helicopter rotors. One type, a **free turbine**, is configured such that the turbine disc driving the compressor rotates independently of the discs that power the external components. Relatively cool air, bled from the compressor, may be used to cool the turbine blades and vanes, to prevent them from melting.

- **Afterburner** or **reheat** (chiefly UK)—(mainly military) Produces extra thrust by burning extra fuel, usually inefficiently, to significantly raise Nozzle Entry Temperature at the **exhaust**. Owing to a larger volume flow (i.e. lower density) at exit from the afterburner, an increased nozzle flow area is required, to maintain satisfactory engine matching, when the afterburner is alight.
- **Exhaust** or **Nozzle**—Hot gases leaving the engine exhaust expand to atmospheric pressure via a nozzle, the objective being to produce a high velocity jet. In most cases, the nozzle is convergent and of fixed flow area. If the Nozzle Pressure Ratio (Nozzle Entry Pressure/Ambient Pressure) is very high, to maximize thrust it may be worthwhile, despite the additional weight, to fit a convergent-divergent (de Laval) nozzle- a supersonic nozzle. As the name suggests, initially this type of nozzle is convergent, but beyond the throat (smallest flow area), the flow area starts to increase to form the divergent portion. The expansion to atmospheric pressure and supersonic gas velocity continues downstream of the throat, whereas in a convergent nozzle the expansion beyond sonic velocity occurs externally, in the exhaust plume. The former process is more efficient than the latter.

The various components named above have constraints on how they are put together to generate the most efficiency or performance. The performance and efficiency of an engine can never be taken in isolation; for example fuel/distance efficiency of a supersonic jet engine maximises at about Mach 2, whereas the drag for the vehicle carrying it is increasing as a square law and has much extra drag in the transonic region. The highest fuel efficiency for the overall vehicle is thus typically at Mach ~0.85.

For the engine optimisation for its intended use, important here is air intake design, overall size, number of compressor stages (sets of blades), fuel type, number of exhaust stages, metallurgy of components, amount of bypass air used, where the bypass air is introduced, and many other factors. For instance, let us consider design of the air intake.

Operation

Thrust lapse

The nominal net thrust quoted for a jet engine usually refers to the Sea Level Static (SLS) condition, either for the International Standard Atmosphere (ISA) or a hot day condition (e.g. ISA+10 °C). As an example, the GE90-76B has a take-off static thrust of 76,000 lbf (360 kN) at SLS, ISA+15 °C.

Naturally, net thrust will decrease with altitude, because of the lower air density. There is also, however, a flight speed effect.

Initially as the aircraft gains speed down the runway, there will be little increase in nozzle pressure and temperature, because the ram rise in the intake is very small. There will also be little change in mass flow. Consequently, nozzle gross thrust initially only increases marginally with flight speed. However, being an air breathing engine (unlike a conventional rocket) there is a penalty for taking on-board air from the atmosphere. This is known as ram drag. Although the penalty is zero at static conditions, it rapidly increases with flight speed causing the net thrust to be eroded.

As flight speed builds up after take-off, the ram rise in the intake starts to have a significant effect upon nozzle pressure/temperature and intake airflow, causing nozzle gross thrust to climb more rapidly. This term now starts to offset the still increasing ram drag, eventually causing net thrust to start to increase. In some engines, the net thrust at say Mach 1.0, sea level can even be slightly greater than the static thrust. Above Mach 1.0, with a subsonic inlet design, shock losses tend to decrease net thrust, however a suitably designed supersonic inlet can give a lower reduction in intake pressure recovery, allowing net thrust to continue to climb in the supersonic regime.

Safety and reliability

Jet engines are usually very reliable and have a very good safety record. However, failures do sometimes occur.

Engine surge

In some cases in jet engines the conditions in the engine due to airflow entering the engine or other variations can cause the compressor blades to stall. When this occurs the pressure in the engine blows out past the blades, and the stall is maintained until the pressure has decreased, and the engine has lost all thrust. The compressor blades will then usually come out of stall, and re-pressurize the engine. If conditions are not corrected, the cycle will usually repeat. This is called **surge**. Depending on the engine this can be highly damaging to the engine and creates worrying vibrations for the crew.

Compressor blade containment

Due to "foreign object damage"- material being sucked into the engine- the most likely failure is often compressor blade failure, and modern jet engines are designed with structures that can catch these blades and keep them contained within the engine casing. Verification of a jet engine design involves testing that this system works correctly.

Bird strike

Bird strike is an aviation term for a collision between a bird and an aircraft. It is a common threat to aircraft safety and has caused a number of fatal accidents. In 1988 an Ethiopian Airlines Boeing 737 sucked pigeons into both engines during take-off and then crashed in an attempt to return to the Bahir Dar airport; of the 104 people aboard, 35 died and 21 were injured. In another incident in 1995, a Dassault Falcon 20 crashed at a Paris airport during an emergency landing attempt after sucking lapwings into an engine, which caused an engine failure and a fire in the airplane fuselage; all 10 people on board were killed. In 2009, on US Airways Flight 1549, a Airbus A320 aircraft sucked in one bird in each engine. The plane landed in the Hudson River after taking off from LaGuardia International Airport in New York City. There were no fatalities.

Modern jet engines have the capability of surviving an ingestion of a bird. Small fast planes, such as military jet fighters, are at higher risk than big heavy multi-engine ones. This is due to the fact that the fan of a high-bypass turbofan engine, typical on transport aircraft, acts as a centrifugal separator to force ingested materials (birds, ice, etc.) to the outside of the fan's disc. As a result, such materials go through the relatively unobstructed bypass duct, rather than through the core of the engine, which contains the smaller and more delicate compressor blades. Military aircraft designed for high-speed flight typically have pure turbojet, or low-bypass turbofan engines, increasing the risk that ingested materials will get into the core of the engine to cause damage.

The highest risk of the bird strike is during the takeoff and landing, in low altitudes, which is in the vicinity of the airports.

Volcanic ash

If a jet plane is flying through air densely contaminated with volcanic ash, there is risk of ingested ash eroding the front blades, melting in the combustion heat, and re-freezing sticking to the rear blades, affecting performance and perhaps stopping the engine; as well as triggering long-term corrosion.

Uncontained failures

One class of failures that has caused accidents in particular is uncontained failures, where rotary parts of the engine break off and exit through the case. These can cut fuel or control lines, and can penetrate the cabin. Although fuel and control lines are usually duplicated for reliability, the crash of United Airlines Flight 232 was caused when hydraulic fluid lines for all three independent hydraulic systems were simultaneously severed by shrapnel from an uncontained engine failure. Prior to the United 232 crash, the probability of a simultaneous failure of all three hydraulic systems was considered as high as a billion-to-one. However, the statistical models used to come up with this figure did not account for the fact that the number-two engine was mounted at the tail close to all the hydraulic lines, nor the possibility that an engine failure would release many fragments in many directions. Since then, more modern aircraft engine designs have focused on keeping shrapnel from penetrating the cowling or ductwork, and have increasingly utilized high-strength composite materials to achieve the required penetration resistance while keeping the weight low.

Economic considerations

In 2007, the cost of jet fuel, while highly variable from one airline to another, averaged 26.5% of total operating costs, making it the single largest operating expense for most airlines.

Environmental considerations

Jet engines are usually run on fossil fuel propellant, and are thus a source of carbon dioxide in the atmosphere. Jet engines can use biofuels or hydrogen, although the production of the latter is usually made from fossil fuels.

About 7.2% of the oil used in 2004 was consumed by jet engines.

Some scientists believe that jet engines are also a source of global dimming due to the water vapour in the exhaust causing cloud formations.

Nitrogen compounds are also formed from the combustion process from atmospheric nitrogen. At low altitudes this is not thought to be especially harmful, but for supersonic aircraft that fly in the stratosphere some destruction of ozone may occur.

Sulphates are also emitted if the fuel contains sulphur.

Advanced designs

J-58 combined ramjet/turbojet

The SR-71 Blackbird's Pratt & Whitney J58 engines were rather unusual. They could convert in flight from being largely a turbojet to being largely a compressor-assisted ramjet. At high speeds (above Mach 2.4), the engine used variable geometry vanes to direct excess air through 6 bypass pipes from downstream of the fourth compressor stage into the afterburner. 80% of the SR-71's thrust at high speed was generated in this way, giving much higher thrust, improving specific impulse by 10-15%, and permitting continuous operation at Mach 3.2. The name coined for this setup is *turbo-ramjet*.

Hydrogen fuelled air-breathing jet engines

Jet engines can be run on almost any fuel. Hydrogen is a highly desirable fuel, as, although the energy per mole is not unusually high, the molecule is very much lighter than other molecules. The energy per kg of hydrogen is twice that of more common fuels and this gives twice the specific impulse. In addition, jet engines running on hydrogen are quite easy to build—the first ever turbojet was run on hydrogen. Also, although not duct engines, hydrogen-fueled rocket engines have seen extensive use.

However, in almost every other way, hydrogen is problematic. The downside of hydrogen is its density; in gaseous form the tanks are impractical for flight, but even in the form of liquid hydrogen it has a density one fourteenth that of water. It is also deeply cryogenic and requires very significant insulation that precludes it being stored in wings. The overall vehicle would end up being very large, and difficult for most airports to accommodate. Finally, pure hydrogen is not found in nature, and must be manufactured either via steam reforming or expensive electrolysis. Nevertheless, research is ongoing and hydrogen-fueled aircraft designs do exist that may be feasible.

Precooled jet engines

An idea originated by Robert P. Carmichael in 1955 is that hydrogen-fueled engines could theoretically have much higher performance than hydrocarbon-fueled engines if a heat exchanger were used to cool the incoming air. The low temperature allows lighter materials to be used, a higher mass-flow through the engines, and permits combustors to inject more fuel without overheating the engine.

This idea leads to plausible designs like Reaction Engines SABRE, that might permit single-stage-to-orbit launch vehicles, and ATREX, which could permit jet engines to be used up to hypersonic speeds and high altitudes for boosters for launch vehicles. The idea is also being researched by the EU for a concept to achieve non-stop antipodal supersonic passenger travel at Mach 5 (Reaction Engines A2).

Nuclear-powered ramjet

Project Pluto was a nuclear-powered ramjet, intended for use in a cruise missile. Rather than combusting fuel as in regular jet engines, air was heated using a high-temperature, unshielded nuclear reactor. This dramatically increased the engine burn time, and the ramjet was predicted to be able to cover any required distance at supersonic speeds (Mach 3 at tree-top height).

However, there was no obvious way to stop it once it had taken off, which would be a great disadvantage in any non-disposable application. Also, because the reactor was unshielded, it was dangerous to be in or around the flight path of the vehicle (although the exhaust itself wasn't radioactive). These disadvantages limit the application to warhead delivery system for all-out nuclear war, which it was being designed for.

Scramjets

Scramjets are an evolution of ramjets that are able to operate at much higher speeds than any other kind of airbreathing engine. They share a similar structure with ramjets, being a specially shaped tube that compresses air with no moving parts through ram-air compression. Scramjets, however, operate with supersonic airflow through the entire engine. Thus, scramjets do not have the diffuser required by ramjets to slow the incoming airflow to subsonic speeds.

Scramjets start working at speeds of at least Mach 4, and have a maximum useful speed of approximately Mach 17. Due to aerodynamic heating at these high speeds, cooling poses a challenge to engineers.

Turborocket

The **air turborocket** is a form of combined-cycle jet engine. The basic layout includes a gas generator, which produces high pressure gas, that drives a turbine/compressor assembly which compresses atmospheric air into a combustion chamber. This mixture is then combusted before leaving the device through a nozzle and creating thrust.

There are many different types of air turborockets. The various types generally differ in how the gas generator section of the engine functions.

Air turborockets are often referred to as **turboramjets**, **turboramjet rockets**, **turborocket expanders**, and many others. As there is no consensus on which names apply to which specific concepts, various sources may use the same name for two different concepts.

Terminology

To describe the RPM of a jet engine, abbreviations are commonly used:

- For a turboprop engine, N_p refers to the RPM of the propeller shaft. For example, a common N_p would be about 2200 RPM for a constant speed propeller.
- N_1 or N_g refers to the speed of the gas generator (gas producer) section (RPM). Each engine manufacturer will pick between those two abbreviation but N1 is mainly used for turbofan engines whereas Ng is mainly used for turboprop or turboshaft engines. For example, a common N_p would be on the order of 30,000 RPM.
- N_2 or N_f refers to the speed of the power turbine section. Each engine manufacturer will pick between those two abbreviations but N2 is mainly used for turbofan engine where Nf is mainly used for turboprop or turboshaft engines. In many cases, even for free turbine engines, the N_1 and N_2 may be very similar.
- N_s refers to the speed of the reduction gear box (RGB) output shaft for turboshaft engines.

In many cases, instead of expressing N-speeds (N_1, N_2) as a sheer RPM on cockpit displays, pilots are provided with the N-speeds expressed as a percentage of a nominal or maximal value. For example, at full power, the N_1 might be 101.5% or 100%. This user interface decision has been made as a human factors consideration, since pilots are more likely to notice a problem with a two- or 3-digit percentage (where 100% implies a nominal value) than with a large, unbounded scalar number.

Chapter- 6

Afterburner

A U.S. Navy F/A-18 Hornet being launched from the catapult on full afterburner

An **afterburner** (or **reheat**) is an additional component added to some jet engines, primarily those on military supersonic aircraft. Its purpose is to provide a temporary increase in thrust, both for supersonic flight and for takeoff (as the high wing loading typical of supersonic aircraft designs means that take-off speed is very high). On military aircraft the extra thrust is also useful for combat situations. This is achieved by injecting additional fuel into the jet pipe downstream of (i.e. *after*) the turbine. The advantage of afterburning is significantly increased thrust; the disadvantage is its very high fuel consumption and inefficiency, though this is often regarded as acceptable for the short periods during which it is usually used.

Jet engines are referred to as operating *wet* when afterburning is being used and *dry* when the engine is used without afterburning. An engine producing maximum thrust wet is at *maximum power* (this is the maximum power the engine can produce); an engine producing maximum thrust dry is at *military power*.

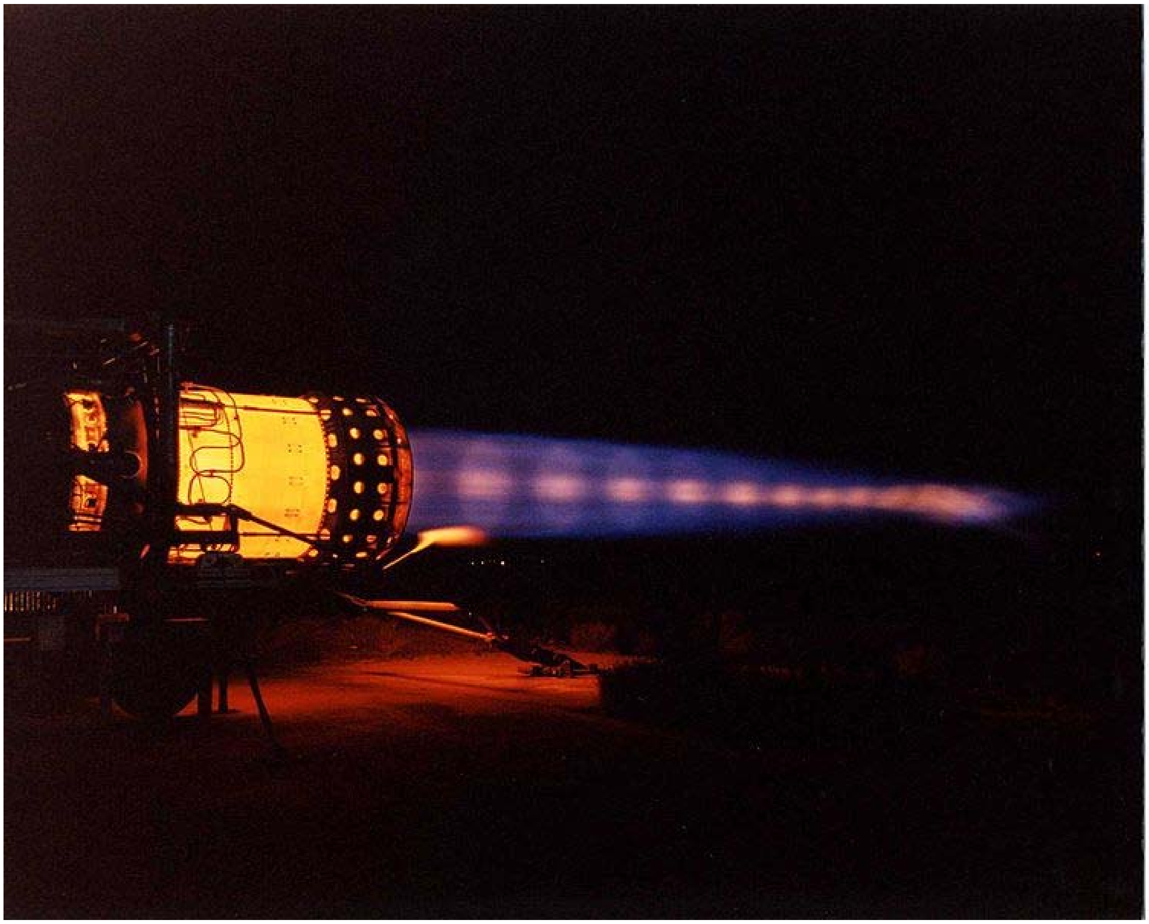
Principle

Jet engine thrust is governed by the general principle of mass flow rate. Simply put, thrust depends on two things: first, the velocity of the exhaust gases; second, the mass of those gases. A jet engine can produce more thrust by either accelerating the gas to a higher velocity or by having a greater mass (quantity) of gas. In the case of a basic turbojet, focusing on the second principle produces the turbofan, which creates slower gas but more of it. Turbofans are efficient and can deliver high thrust for long periods of time but have large sizes for unit power. To create the same power in a compact engine for short periods of time, an engine requires an afterburner. The afterburner increases thrust primarily by the first method. While the mass of the fuel added to the exhaust does contribute to an increase in thrust, this effect is small compared to the increase in exhaust velocity.

The temperature of the gas in the engine is highest just before the turbine, and the ability for the turbine to withstand these temperatures is easily one of the primary restrictions on total dry engine thrust. This temperature is known as the Turbine Entry Temperature (TET), one of the critical engine operating parameters. Being that not all the oxygen has been reacted inside the combustion chamber (any additional energy is dependent on the turbine's ability to withstand the thermal stress), additional fuel could be added to reignite the gases and cause a substantial increase in exhaust velocity and therefore total engine thrust. Thus while operating, the gases pass the turbine, they expand at a near constant entropy, thus losing temperature. The afterburner subsequently injects fuel downstream of the turbine and reheats the gases. (Thus the more correct name from a thermodynamic standpoint is reheat.) In conjunction with the added heat, the pressure rises in the tailpipe and the gases are ejected through the nozzle at a higher velocity while the mass flow is only slightly increased (by the mass flow of the added fuel).

Design

SR-71 Blackbird in flight with J58 engine on full afterburner



A statically mounted Pratt & Whitney J58 engine with full afterburner on disposing of the last of the SR-71 fuel prior to program termination. The bright areas seen in the exhaust are known as shock diamonds.

A jet engine afterburner is an extended exhaust section containing extra fuel injectors, and since the jet engine upstream (i.e., before the turbine) will use little of the oxygen it ingests, the afterburner is, at its simplest, a type of ramjet. When the afterburner is turned on, fuel is injected, which ignites readily, owing to the relatively high temperature of the incoming gases. The resulting combustion process increases the afterburner exit (nozzle entry) temperature significantly, resulting in a steep increase in engine net thrust. In addition to the increase in afterburner exit stagnation temperature, there is also an increase in nozzle mass flow (i.e. afterburner entry mass flow plus the effective afterburner fuel flow), but a decrease in afterburner exit stagnation pressure (owing to a fundamental loss due to heating plus friction and turbulence losses).

The resulting increase in afterburner exit volume flow is accommodated by increasing the throat area of the propulsion nozzle. Otherwise, the upstream turbomachinery rematches (probably causing a compressor stall or fan surge in a turbofan application).

To a first order, the gross thrust ratio (afterburning/dry) is directly proportional to the root of the stagnation temperature ratio across the afterburner (i.e. exit/entry).

Limitations

Due to their high fuel consumption, afterburners are not used for extended periods; a notable exception is the Pratt & Whitney J58 engine used in the SR-71 Blackbird. Afterburners are generally used only when it is important to have as much thrust as possible. This includes takeoffs from short runways (as on an aircraft carrier) and air combat situations.

Efficiency

Since the exhaust gas already has reduced oxygen due to previous combustion, and since the fuel is not burning in a highly compressed air column, the afterburner is generally inefficient compared with the main combustor. Afterburner efficiency also declines significantly if, as is usually the case, the tailpipe pressure decreases with increasing altitude.

However, as a counter-example, the SR-71 had reasonable efficiency at high altitude in afterburning mode ("wet") due to its high speed (mach 3.2) and hence high pressure due to ram intake

Afterburners do produce markedly enhanced thrust as well as (typically) a very large flame at the back of the engine. This exhaust flame may show *shock-diamonds*, which are caused by shock waves being formed due to slight differences between ambient pressure and the exhaust pressure. These imbalances cause oscillations in the exhaust jet diameter over distance and cause the visible banding where the pressure and temperature is highest.

Influence on cycle choice

Afterburning has a significant influence upon engine cycle choice.

Lowering fan pressure ratio decreases specific thrust (both dry and wet afterburning), but results in a lower temperature entering the afterburner. Since the afterburning exit temperature is effectively fixed, the temperature rise across the unit increases, raising the afterburner fuel flow. The total fuel flow tends to increase faster than the net thrust, resulting in a higher specific fuel consumption (SFC). However, the corresponding dry power SFC improves (i.e. lower specific thrust). The high temperature ratio across the afterburner results in a good thrust boost.

If the aircraft burns a large percentage of its fuel with the afterburner alight, it pays to select an engine cycle with a high specific thrust (i.e. high fan pressure ratio/low bypass ratio). The resulting engine is relatively fuel efficient with afterburning (i.e. Combat/Take-off), but thirsty in dry power. If, however, the afterburner is to be hardly used, a low specific thrust (low fan pressure ratio/high bypass ratio) cycle will be favored. Such an engine has a good dry SFC, but a poor afterburning SFC at Combat/Take-off.

Often the engine designer is faced with a compromise between these two extremes.

Usage

MiG-23 afterburner

As early as during the Second World War, the principle was in development for the British Power Jets W.2/700 with what was termed at the time a "a reheat jetpipe" for the Miles M.52 supersonic aircraft project.

Early US research on the concept was done by NACA, in Cleveland, OH, leading to the publication of the paper "Theoretical Investigation of Thrust Augmentation of Turbojet Engines by Tail-pipe Burning" in January 1947.

Post war, the McDonnell F3H Demon and the Douglas F4D Skyray were designed around the Westinghouse J40 turbojet engine, rated at 8,000 lbf (36 kN) thrust without afterburner. The new Pratt & Whitney J48 turbojet, at 8,000 lbf (36 kN) thrust with afterburner, would power the Grumman sweptwing fighter F9F-6, which was about to go into production. Other new Navy fighters with afterburners included the high-speed Chance Vought F7V-3 Cutlass, powered by two 6,000 lbf (27 kN) thrust Westinghouse J46 engines.

In the 1950s several large reheated engines were developed such as the de Havilland Gyron and Orenda Iroquois. In the United Kingdom, the Rolls-Royce Avon was made available with reheat and powered the English Electric Lightning, the first supersonic aircraft in RAF service. The Bristol-Siddeley Rolls-Royce Olympus was also given reheat for the TSR-2 and was fitted to Concorde in such a state (Bristol Siddeley had by then become part of Rolls-Royce and the nozzle and reheat system was developed by Snecma).

Afterburners are generally only used in military aircraft and are considered standard equipment for fighter aircraft. The handful of civilian planes that have used them include some NASA research aircraft, the Tupolev Tu-144 and Concorde, and the White Knight of Scaled Composites. Concorde and the Tu-144 had this capability and flew long distances at supersonic speeds. This would be impossible with the high fuel consumption of reheat, and these aircraft used afterburners at takeoff and to minimise time spent in the high drag transonic flight regime. Supersonic flight without afterburners is referred to as supercruise.

A turbojet engine equipped with an afterburner is called an "afterburning turbojet", whereas a turbofan engine similarly equipped is sometimes called an "augmented turbofan".

A "dump-and-burn" is a fuel dumping procedure where dumped fuel is intentionally ignited using the plane's afterburner. A spectacular flame combined with high speed makes this a popular display for airshows, or as a finale to fireworks, although the procedure itself is intended primarily to safely remove fuel from the aircraft before attempting a crash landing.

Chapter- 7

Propelling Nozzle

A **propelling nozzle** is the component of a jet engine that operates to constrict the flow, to form an exhaust jet and to maximise the velocity of propelling gases from the engine.

Propelling nozzles can be subsonic, sonic, or supersonic. Physically the nozzles can be convergent, or convergent divergent. Convergent-divergent nozzles can give supersonic jet speeds, whereas a convergent nozzle can not exceed the speed of sound in the exhaust fluid.

Propelling nozzles can be fixed geometry, or they can have variable geometry, to give different throat and exit diameters so as to deal with differences in ambient pressure, flow and engine pressure; thus permitting improvement of thrust and efficiency.

Principles of operation

The primary objective of a nozzle is to raise the pressure in the engine by constricting the flow at the narrowest part (the *throat*), and then to expand the exhaust stream to, or near to, atmospheric pressure, and form it into a high speed jet to propel the vehicle.

The energy to accelerate the stream comes from the temperature and pressure of the gas- the gas expands adiabatically, when done against a nozzle, this largely reversibly (and hence efficiently), cools and expands and accelerates the gas. The hotter and higher the pressure the gas entering the nozzle, the faster the exhaust jet can become.

For airbreathing engines, if the fully expanded jet has a higher speed than the aircraft's airspeed, then there is a net rearward momentum gain to the air and there will be a forward thrust on the airframe.

Engines that are required to generate thrust quickly, from idle, use a variable area propelling nozzle in its open configuration to keep thrust to a minimum while maintaining high engine rpm. When thrust is needed, initiating a go-around for example, it is simple and quick to close the nozzle to the high-thrust position.

Convergent nozzles

Almost all nozzles have a convergent section, as this raises the pressure in the rest of the engine and can give more thrust by acting on the forward sections. However, convergent nozzles end at the end of the convergent section.

Simple convergent nozzles are used on many jet engines. If the nozzle pressure ratio is above the critical value (about 1.8:1) a convergent nozzle will choke, resulting in some of the expansion to atmospheric pressure taking place downstream of the throat (i.e. smallest flow area), in the jet wake. Although much of the gross thrust produced will still be from the jet momentum, additional (pressure) thrust will come from the imbalance between the throat static pressure and atmospheric pressure.

In general, narrow convergent nozzles give high speed exhaust, but reduced thrust, whereas wide convergent nozzles give lower speed, but higher thrust.

Afterburners

On non-afterburning engines the nozzle is a fixed size because the differing atmospheric pressure over the operating altitudes makes little difference to the engine aerodynamics and variable nozzle use is expensive. However, the great range of mass flow rates an afterburning engine generates requires the use of variable nozzle diameters and shapes. If it were to have the standard convergent nozzle of a subsonic engine, then it would be choked by the high air flow at supersonic speed. Depending on the amount of afterburning, the variable nozzle may be simple or complex.

Many military combat engines incorporate an afterburner (or reheat) in the engine exhaust system. When the system is lit, the nozzle throat area must be increased, to accommodate the extra exhaust volume flow, so that the turbomachinery is unaware that the afterburner is lit. A variable throat area is achieved by moving a series of overlapping petals, which approximate the circular nozzle cross-section.

Convergent-divergent nozzles

Engines capable of supersonic flight have convergent-divergent duct features that generate supersonic flow. Rockets are an extreme version of this, and the very large area ratio nozzles give rocket engines their distinctive shape.

At high nozzle pressure ratios, the exit pressure is often above ambient and much of the expansion will take place downstream of a convergent nozzle, which is inefficient. Consequently, some jet engines (notably rockets) incorporate a convergent-divergent nozzle, to allow most of the expansion to take place against the inside of a nozzle to maximise thrust. However, unlike the fixed con-di nozzle used on a conventional rocket motor, when such a device is used on a turbojet engine it has to be a complex variable geometry device, to cope with the wide variation in nozzle pressure ratio encountered in flight and engine throttling. This further increases the weight and cost of such an installation.

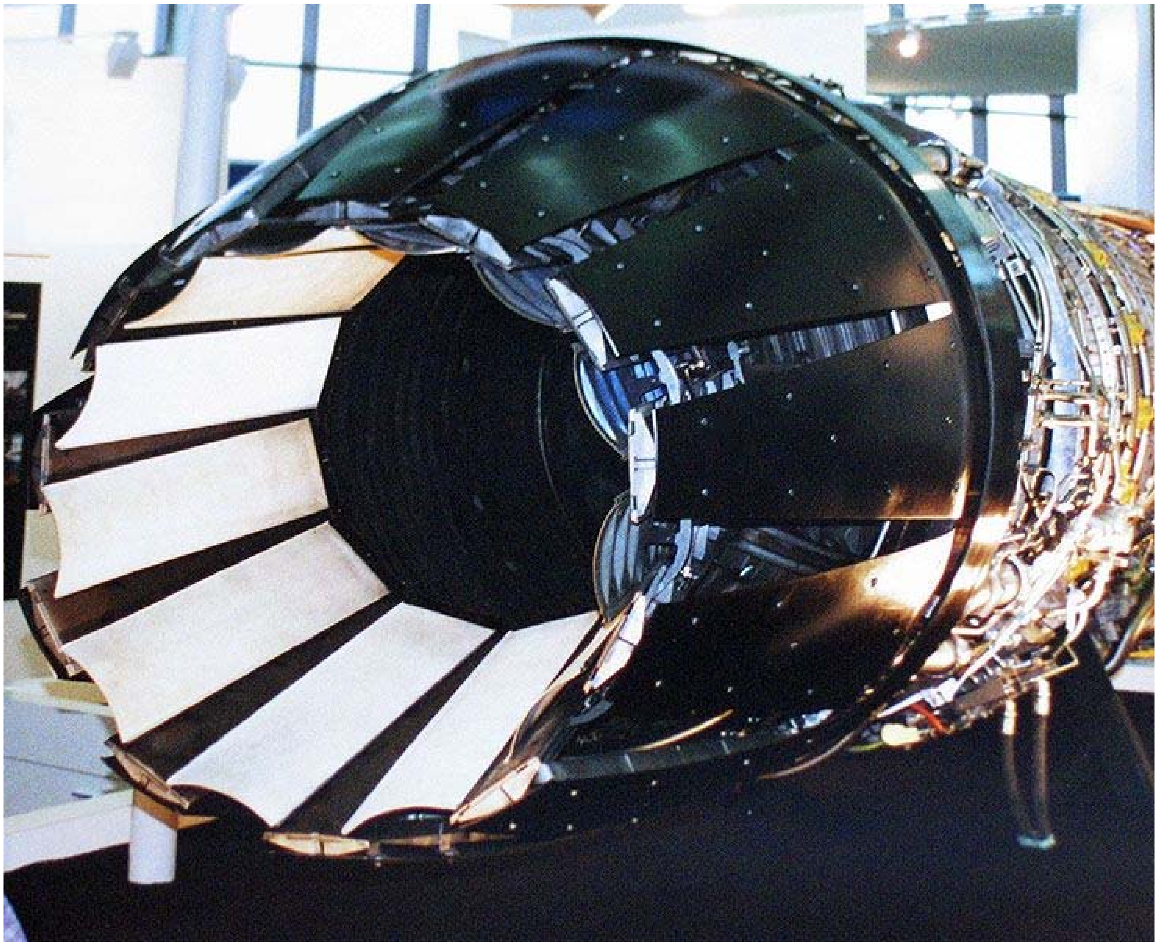
Types of nozzles

Variable Exhaust Nozzle, on the GE F404-400 low-bypass turbofan installed on a Boeing F/A-18 Hornet

Ejector nozzles

The simpler of the two is the **ejector nozzle**, which creates an effective nozzle through a secondary airflow and spring-loaded petals. At subsonic speeds, the airflow constricts the exhaust to a convergent shape. As the aircraft speeds up, the two nozzles dilate, which allows the exhaust to form a convergent-divergent shape, speeding the exhaust gasses past Mach 1. More complex engines can actually use a tertiary airflow to reduce exit area at very low speeds. Advantages of the ejector nozzle are relative simplicity and reliability. Disadvantages are average performance (compared to the other nozzle type) and relatively high drag due to the secondary airflow. Notable aircraft to have utilized this type of nozzle include the SR-71, Concorde, F-111, and Saab Viggen

Iris nozzles



Iris vectored thrust nozzle

For higher performance, it is necessary to use an **iris nozzle**. This type uses overlapping, hydraulically adjustable "petals". Although more complex than the ejector nozzle, it has significantly higher performance and smoother airflow. As such, it is employed primarily on high-performance fighters such as the F-14, F-15, F-16, though is also used in high-speed bombers such as the B-1B. Some modern iris nozzles additionally have the ability to change the angle of the thrust.

Rocket nozzles

Rocket nozzle on V2 showing the classic shape

Rocket motors also employ convergent-divergent nozzles, but these are usually of fixed geometry, to minimize weight. Because of the much higher nozzle pressure ratios experienced, rocket motor con-di nozzles have a much greater area ratio (exit/throat) than those fitted to jet engines. The Convair F-106 Delta Dart has used such a nozzle design, as part of its overall design specification as an aerospace interceptor for high-altitude bomber interception, where conventional nozzle design would prove ineffective.

Low ratio nozzles

At the other extreme, some high bypass ratio civil turbofans use an extremely low area ratio (less than 1.01 area ratio), convergent-divergent, nozzle on the bypass (or mixed exhaust) stream, to control the fan working line. The nozzle acts as if it has variable geometry. At low flight speeds the nozzle is unchoked (less than a Mach number of unity), so the exhaust gas speeds up as it approaches the throat and then slows down slightly as it reaches the divergent section. Consequently, the nozzle exit area controls the fan match and, being larger than the throat, pulls the fan working line slightly away from surge. At higher flight speeds, the ram rise in the intake increases nozzle pressure ratio to the point where the throat becomes choked (M=1.0). Under these circumstances, the throat area dictates the fan match and being smaller than the exit pushes the fan working line slightly towards surge. This is not a problem, since fan surge margin is much better at high flight speeds.

Other Applications

Certain aircraft, like the German Bf-109 and the Macchi C.202/205 were fitted with "ejector-type exhausts". These exhausts converted some of the waste energy of the (internal combustion) engines exhaust-flow into a small amount of forward thrust by accelerating the hot gasses in a rearward direction to a speed greater than that of the aircraft. All exhaust setups do this to some extent, provided that the of exhaust-ejection vector is opposite/dissimilar to the direction of the aircraft movement.