

Handbook of  
**Aircraft Engines**



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## Chapter- 1

# Introduction to Aircraft Engine

An **aircraft engine** is a propulsion system for an aircraft. Aircraft engines are almost always either lightweight piston engines or gas turbines. This is an overview of the basic types of aircraft engines and the design concepts employed in engine development for aircraft.

### ***Engine design considerations***

The process of developing an engine is one of compromises. Engineers design specific attributes into engines to achieve specific goals. Aircraft are one of the most demanding applications for an engine, presenting multiple design requirements, many of which conflict with each other. An aircraft engine must be:

- *reliable*, as losing power in an airplane is a substantially greater problem than in an automobile. Aircraft engines operate at temperature, pressure, and speed extremes, and therefore need to perform reliably and safely under all reasonable conditions.
- *light weight*, as a heavy engine increases the empty weight of the aircraft and reduces its payload.
- *powerful*, to overcome the weight and drag of the aircraft.
- *small and easily streamlined*; large engines with substantial surface area, when installed, create too much drag.
- *field repairable*, to keep the cost of replacement down. Minor repairs should be relatively inexpensive and possible outside of specialized shops.
- *fuel efficient* to give the aircraft the range the design requires.
- capable of operating at sufficient altitude for the aircraft

Unlike automobile engines, aircraft engines are often operated at high power settings for extended periods of time. In general, the engine runs at maximum power for a few minutes during taking off, then power is slightly reduced for climb, and then spends the majority of its time at a cruise setting—typically 65 percent to 75 percent of full power. In contrast, an automobile engine might spend 20 percent of its time at 65 percent power while accelerating, followed by 80 percent of its time at 20 percent power while cruising.

The power of an internal combustion reciprocating or turbine aircraft engine is rated in units of power delivered to the propeller (typically horsepower) which is torque

multiplied by crankshaft revolutions per minute (RPM). The propeller converts the engine power to thrust horsepower or **thp** in which the thrust is a function of the blade pitch of the propeller relative to the velocity of the aircraft. Jet engines are rated in terms of thrust, usually the maximum amount achieved during takeoff.

The design of aircraft engines tends to favor reliability over performance. Long engine operation times and high power settings, combined with the requirement for high-reliability means that engines must be constructed to support this type of operation with ease. Aircraft engines tend to use the simplest parts possible and include two sets of anything needed for reliability. Independence of function lessens the likelihood of a single malfunction causing an entire engine to fail. For example, reciprocating engines have two independent magneto ignition systems, and the engine's mechanical engine-driven fuel pump is always backed-up by an electric pump.

Aircraft spend the vast majority of their time travelling at high speed. This allows an aircraft engine to be air cooled, as opposed to requiring a radiator. With the absence of a radiator, aircraft engines can boast lower weight and less complexity. The amount of air flow an engine receives is usually carefully designed according to expected speed and altitude of the aircraft in order to maintain the engine at the optimal temperature.

Aircraft operate at higher altitudes where the air is less dense than at ground level. As engines need oxygen to burn fuel, a forced induction system such as turbocharger or supercharger is especially appropriate for aircraft use. This does bring along the usual drawbacks of additional cost, weight and complexity.

## ***History of aircraft engines***

- 1633: Lagari Hasan Çelebi took off with what was described to be a cone shaped rocket and then glided with wings into a successful landing (although this account is considered legend)
- 1848: John Stringfellow made a steam engine capable of powering a model, albeit with negligible payload
- 1903: Karl Jatho He tested his plane on August 18, 1903 and managed to make hops of up to 3 m (10 ft) in height for a distance of 60 m (200 ft).
- 1903: The Wright brothers commissioned Charlie Taylor to build an inline aeroengine (12 horsepower) for the Wright Flyer
- 1906: Traian Vuia flew his first airplane "Vuia I" at Montesson on 18 March. He made a hop of 20 Meters at an altitude of 1 Meter using compressed carbonic acid as a power source.
- 1908: René Lorin patents a design for the ramjet engine
- 1909: Roger Ravaud' Gnôme rotary engine in Henry Farman's aircraft won the Grand Prix for the greatest non-stop distance flown - 180 kilometres (110 mi) - and created a world record for endurance flight
- 1910: Henri Coanda an unsuccessful ducted fan powered aircraft
- 1911: Adams-Farwell's rotary engines powered fixed-wing aircraft in the US

- 1916: Auguste Rateau suggests using exhaust-powered compressors to improve high-altitude performance, the first example of the turbocharger.
- 1930: Frank Whittle submitted his first patent
- 1938: The German Heinkel HeS 3 turbojet propels the Heinkel He 178 into the air
- 1939-1942: The world's first turboprop - the Jendrassik Cs-1 - is designed by the Hungarian mechanical engineer György Jendrassik
- 1944: Messerschmitt Me 163 Komet, the world's first rocket propelled aircraft deployed
- 1947: Bell X-1 rocket propelled aircraft exceeds the speed of sound
- 1948: the first turboshaft engine, the 100 shp 782. In 1950 this work was used to develop the larger 280 shp (210 kW) Artouste
- 1949: The Leduc 010 the world's first ramjet powered aircraft flies
- 1950(late): Rolls-Royce Conway, the world's first production turbofan, enters service
- 1960s: TF39 high bypass turbofan enters service delivering greater thrust and much better efficiency
- 1960s: X-15 rocket plane flies at more than 50 miles (80 km) altitude at more than 3,000 mph (4,800 km/h).
- 2002: HyShot scramjet flew in dive
- 2004: Hyper-X first scramjet to maintain altitude

## ***Fuel***

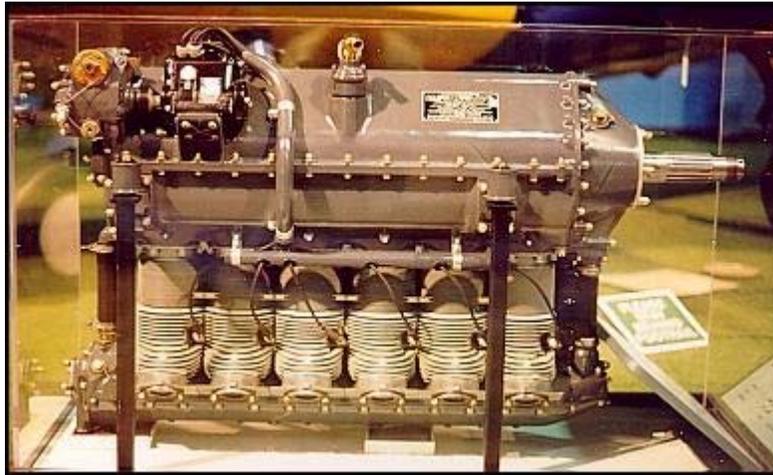
All aviation fuel is produced to stringent quality standards to avoid fuel-related engine failures. Aviation standards are much more strict than those for road vehicle fuel because an aircraft engine must meet a strictly defined level of performance under known conditions. These high standards mean that aviation fuel costs much more than fuel used for road vehicles.

Aircraft reciprocating (piston) engines are typically designed to run on aviation gasoline. Avgas has a higher octane rating as compared to automotive gasoline, allowing the use of higher compression ratios, increasing power output and efficiency at higher altitudes. Currently the most common Avgas is 100LL, which refers to the octane rating (100 octane) and the lead content (LL = low lead).

Avgas is blended with tetra-ethyl lead (TEL) to achieve these high octane ratings, a practice no longer permitted with road vehicle gasoline. The shrinking supply of TEL, and the possibility of environmental legislation banning its use, has made a search for replacement fuels for general aviation aircraft a priority for pilot's organizations.

Turbine engines burn various grades of jet fuel, a relatively heavy and less volatile petroleum derivative similar to diesel fuel.

## ***Shaft engines***



Ranger L-440 air-cooled, six-cylinder, inverted, in-line engine used in Fairchild PT-19

## **In-line engine**

This type of engine has cylinders lined up in one row. It typically has an even number of cylinders, but there are instances of three- and five- cylinder engines. The biggest advantage of an inline engine is that it allows the aircraft to be designed with a narrow frontal area for low drag. If the engine crankshaft is located above the cylinders, it is called an inverted inline engine, which allows the propeller to be mounted up high for ground clearance even with short landing gear. The disadvantages of an inline engine include a poor power-to-weight ratio, because the crankcase and crankshaft are long and thus heavy. An in-line engine may be either air cooled or liquid cooled, but liquid-cooling is more common because it is difficult to get enough air-flow to cool the rear cylinders directly. Inline engines were common in early aircraft, including the Wright Flyer, the aircraft that made the first controlled powered flight. However, the inherent disadvantages of the design soon became apparent, and the inline design was abandoned, becoming a rarity in modern aviation.

## ***New designs***

### **Economics of new designs**

Throughout most of the history of aircraft engine design, they tended to be more advanced than their automobile counterparts. High-strength aluminum alloys were used in these engines decades before they became common in cars. Likewise, those engines adopted fuel injection instead of carburetion quite early. Similarly, overhead cams and multiple valves per cylinder were introduced, while automobile engines continued to use pushrods and didn't widely use more than two valves per cylinder until the 1990s.

Today the piston-engine aviation market is so small that there is essentially no commercial money for new design work. Most aviation engines flying are based on a

design from the 1960s, or before, using original materials, tooling and parts. Meanwhile the financial power of the automobile industry has continued improvement. A new car design is likely to use an engine designed no more than a few years ago, built with the latest alloys and advanced electronic engine controls. Modern car engines require very little maintenance apart from oil changes, aircraft engines are now, in comparison and paradoxically, rather heavy, dirty and unreliable.

Much of the innovation (and most newly constructed planes flying) in the past two decades in private aviation has been in ultralights and homebuilt aircraft, and so has innovation in powerplants. Rotax, amongst others, has introduced a number of new small production engine designs for this type of craft. The smallest of these mostly use two-stroke designs, but the larger models are four-strokes. For the reasons discussed above, some hobbyists and experimenters prefer to adapt automotive engines for their home-built aircraft, instead of using certified aircraft engines.

Over the history of the development of aircraft engines, the Otto cycle, that is, conventional gasoline powered, reciprocating-piston engines have been by far the most common type. That is not because they are the best but simply because they were there first and type-certification of new designs is an expensive, time-consuming process.

## **Diesel engine**

The diesel engine is another engine design that has been examined for aviation use. In general diesel engines are more reliable and much better suited to running for long periods of time at medium power settings—this is why they are widely used in trucks for instance. Several attempts to produce diesel aircraft engines were made in the 1930s but, at the time, the alloys were not up to the task of handling the much higher compression ratios used in these designs. They generally had poor power-to-weight ratios and were uncommon for that reason but, for example, the Clerget 14F diesel radial engine (1939) has the same power to weight as a gasoline radial. Improvements in diesel technology in automobiles (leading to much better power-weight ratios), the diesel's much better fuel efficiency (particularly compared to the old gasoline designs currently being used in light aircraft) and the high relative taxation of AVGAS compared to Jet A1 in Europe have all seen a revival of interest in the concept. Thielert Aircraft Engines converted Mercedes diesel automotive engines, certified them for aircraft use and became an OEM provider to Diamond Aviation for their light twin. Financial problems have plagued Thielert, so Diamond's affiliate—Austro Engine—developed the new AE300 turbodiesel, also based on a Mercedes engine. Competing new diesel engines may bring fuel efficiency and lead-free emissions to small aircraft, representing the biggest change in light aircraft engines in decades. Wilksch Airmotive build 2 stroke diesel engine (same power to weight as a gasoline engine) for experimental aircraft: WAM 100 (100 hp), WAM 120 (120 hp) and WAM 160 (160 hp)

## **Precooled jet engines**

For very high supersonic/low hypersonic flight speeds inserting a cooling system into the air duct of a hydrogen jet engine permits greater fuel injection at high speed and obviates the need for the duct to be made of refractory or actively cooled materials. This greatly improves the thrust/weight ratio of the engine at high speed.

It is thought that this design of engine could permit sufficient performance for antipodal flight at Mach 5, or even permit a single stage to orbit vehicle to be practical.

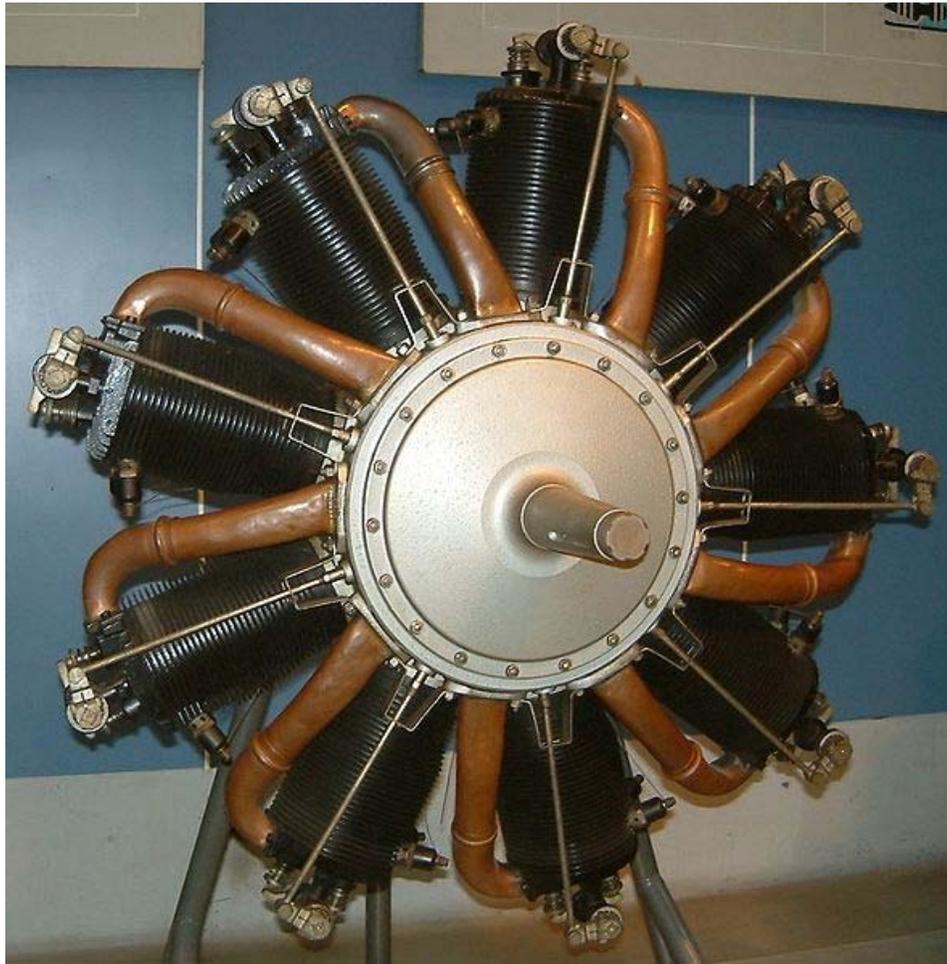
## **Electric**

About 60 electrically powered aircraft, such as the QinetiQ Zephyr, have been designed since the 1960s, Some are used as military drones. In France in late 2007, a conventional light aircraft powered by an 18 kW electric motor using lithium polymer batteries was flown, covering more than 50 kilometers (31 miles), the first electric airplane to receive a certificate of airworthiness.

Limited experiments with solar electric propulsion have been performed, notably the manned Solar Challenger and Solar Impulse and the unmanned NASA Pathfinder aircraft.

## Chapter- 2

# Rotary Engine



An 80 horsepower rated Le Rhône 9C, a typical rotary engine of WWI. The copper pipes carry the fuel-air mixture from the crankcase to the cylinder heads.

The **rotary engine** was an early type of internal-combustion engine, usually designed with an odd number of cylinders per row in a radial configuration, in which the crankshaft remained stationary and the entire cylinder block rotated around it. Its main application was in aviation.

This type of engine was widely used as an alternative to conventional in-line or V engines during World War I and the years immediately preceding that conflict, and has been described as "a very efficient solution to the problems of power output, weight, and reliability".

By the early 1920s, however, the inherent limitations of this type of engine had rendered it obsolete, with the power output increasingly going into overcoming the air-resistance of the spinning engine itself. Another factor in its demise was the fundamentally inefficient use of fuel and lubricating oil caused in part by the need for the fuel/air mixture to be aspirated through the hollow crankshaft and crankcase.

## ***Description***

A rotary engine is essentially a standard Otto cycle engine, but instead of having a fixed cylinder block with rotating crankshaft as with a conventional radial engine, the crankshaft remains stationary and the entire cylinder block rotates around it. In the most common form, the crankshaft was fixed solidly to an aircraft frame, and the propeller simply bolted onto the front of the crankcase.

Three key factors contributed to the rotary engines success at the time:

- Smooth running: Rotaries delivered power very smoothly because (relative to the engine mounting point) there are no reciprocating parts, and the relatively large rotating mass of the cylinders acted as a flywheel.
- Weight advantage: many conventional engines had to have heavy flywheels added to smooth out power impulses and reduce vibration. Rotary engines gained a substantial power-to-weight ratio advantage by having no need for an added flywheel.
- Improved cooling: when the engine was running the rotating cylinder block created its own fast-moving cooling airflow, even with the aircraft at rest.

Most rotary engines were arranged with the cylinders pointing outwards from a single crankshaft, in the same general form as a radial, but there were also rotary boxer engines and even one-cylinder rotaries.

Like radial engines, rotaries were generally built with an odd number of cylinders (usually either 7 or 9), so that a consistent every-other-piston firing order could be maintained, to provide smooth running. Rotary engines with an even number of cylinders were mostly of the "two row" type.

## **Distinction between "Rotary" and "Radial" engines**

Rotary and radial engines look strikingly similar when they are not running and can easily be confused, since both have cylinders arranged radially around a central crankshaft. Unlike the rotary engine, however, radial engines use a conventional rotating crankshaft in a fixed engine block.

## ***Rotary engine control***

It is often asserted that rotary engines had no carburetor and hence power could only be reduced by intermittently cutting the ignition using a "blip" or *coupe* momentary push-button switch, operating in a manner directly opposite that of a kill switch for other types of internal combustion engines, which grounded the magneto when pressed, shutting off power to the spark plugs and stopping ignition. However, rotaries did have a simple carburetor which combined a gasoline jet and a flap valve, or "bloctube" style throttling device, for throttling the air supply. Unlike modern carburetors, it could not keep the fuel/air ratio constant over a range of throttle openings; in use, a pilot would set the throttle to the desired setting (usually full open) then adjust the fuel/air mixture to suit using a separate "fine adjustment" lever that controlled the fuel valve.

Due to the rotary engine's large rotational inertia, it was possible to adjust the appropriate fuel/air mixture by trial and error without stalling it. After starting the engine with a known setting that allowed it to idle, the air valve was opened until maximum engine speed was obtained. Since the reverse process was more difficult, "throttling", especially when landing, was often accomplished by temporarily cutting the ignition using the blip switch.

By the middle stages of World War I, some throttling capability was found necessary to allow pilots to fly in formation, and the improved carburetors which entered use allowed a power reduction of up to 25%. The pilot would close off the air valve to the required position, then re-adjust the fuel/air mixture to suit. Experienced pilots would gently back off the fuel lever at frequent intervals to make sure that the mixture was not too rich: a too-lean mixture was preferable, since power recovery would be instant when the fuel supply was increased, whereas a too-rich mixture could take up to seven seconds to recover and could also cause fouling of spark plugs and the cylinders to cut out.

The Gnôme Monosoupape was an exception to this, since most of its air supply was taken in through the exhaust valve, and so could not be controlled via the crankcase intake. Monosoupapes therefore had a single petrol regulating control used for a limited degree of speed regulation. Early models also featured a pioneering form of variable valve timing to give greater control, but this caused the valves to burn and therefore it was abandoned.

Later rotaries still used blipping the ignition for landing, and some engines were equipped with a switch that cut out only some rather than all of the cylinders to ensure that the engine kept running and did not oil up. A few 9 cylinder rotaries had this capability, typically allowing 1, 3, or 6 cylinders to be kept running. Some 9 cylinder Monosoupapes had a selector switch which allowed the pilot to cut out six cylinders so that each cylinder fired only once per three engine revolutions but the engine remained in perfect balance. Some documentation regarding the Fokker Eindecker shows a rotary selector switch to cut out a selected number of cylinders suggesting that German rotaries did as well.

By 1918 a Clerget handbook advised that all necessary control was to be effected using the throttle, and the engine was to be stopped and started by turning the fuel on and off. Pilots were advised to avoid use of the cut out switch as it would eventually damage the engine.

The blip switch is, however, still recommended for use during landing rotary-engined aircraft in modern times as it allows pilots a more reliable, quick source of power that lends itself to modern airfields. The landing procedure using a blip switch involved shutting off the fuel using the fuel lever, while leaving the blip switch on. The windmilling propeller allowed the engine to continue to spin without delivering any power as the aircraft descended. It was important to leave the blip switch on while the fuel was shut off to allow the spark plugs to continue to spark and keep them from oiling up, while the engine could easily be restarted simply by re-opening the fuel valve. If a pilot shut the engine off by holding the blip switch down without cutting off the fuel, fuel would continue to pass through the engine without combusting and raw fuel/air mix would collect in the cowling. This could cause a serious fire when the switch was released, or alternatively could cause the spark plugs to oil up and prevent the engine from restarting.

## **History**

### **Hargrave**

Lawrence Hargrave first developed a rotary engine in 1889 using compressed air, intending it to be used in powered flight. Weight of materials and lack of quality machining prevented it becoming an effective power unit.

### **Balzer**

Stephen Balzer of New York, a former watchmaker, constructed rotary engines in the 1890s. He was interested in the rotary layout for two main reasons:

- In order to generate 100 hp (75 kW) at the low rpm at which the engines of the day ran, the pulse resulting from each combustion stroke was quite large. To damp out these pulses, engines needed a large flywheel, which added weight. In the rotary design the engine acted as its own flywheel, thus rotaries could be lighter than similarly sized conventional engines.
- The cylinders had good cooling airflow over them, even when the aircraft in which they were mounted were at rest, which was important, as the low airspeed attainable by aircraft of the time provided limited cooling airflow, and alloys of the day were less advanced than they are now. Balzer's early designs even dispensed with cooling fins, although subsequent rotaries did have this common feature of air-cooled engines.

Balzer produced a 3-cylinder, rotary engined car in 1894, then later became involved in Langley's *Aerodrome* attempts, which bankrupted him while he tried to make much larger

versions of his engines. Balzer's rotary engines were later converted to static radial operation by Langley's assistant, Charles Manly.

## De Dion-Bouton

The famous De Dion-Bouton company produced an experimental 4-cylinder rotary engine in 1899. Though intended for aviation use, it was not fitted to any aircraft.

## Adams-Farwell

The Adams-Farwell was another early US rotary engine which was being manufactured for use in automobiles by 1901. Emil Berliner sponsored its development as a lightweight power unit for his unsuccessful helicopter experiments. Adams-Farwell engines later powered fixed-wing aircraft in the US after 1910. It has also been asserted that the Gnome design was derived from the Adams-Farwell, since an Adams-Farwell car is reported to have been demonstrated to the French Army in 1904. In contrast to the later Gnome engines, the Adams-Farwell rotaries had conventional exhaust and inlet valves mounted in the cylinder heads.

## Gnome

The Gnome engine was the work of the three Seguin brothers, Louis, Laurent and Augustin. They were gifted engineers and the grandsons of famous French engineer Marc Seguin. In 1906 the eldest brother, Louis, had formed the Société des Moteurs Gnome to build stationary engines for industrial use, having licensed production of the **Gnom** single-cylinder stationary engine from Motorenfabrik Oberursel, who would themselves build similar rotary aviation engines for the German aircraft of the *Luftstreitkräfte* during World War I.

Louis was joined by his brother Laurent who designed a rotary engine specifically for aircraft use, using **Gnom** engine cylinders. The brothers' first experimental engine was a 5-cylinder model which developed 34 hp (25 kW), and which was a radial rather than a rotary. They then turned to rotary engines in the interests of better cooling, and the first production engine, the 7-cylinder, 50 hp (37 kW) "Omega" was shown at the 1908 Paris automobile show. (The Gnome Omega No.1 still exists, having been acquired and preserved by the late USMS retired Rear Admiral Lauren S. McCready, its last private owner, and is now in the collection of the Smithsonian's National Air and Space Museum.) The Seguins used the highest strength material available - recently developed nickel steel alloy - and kept the weight down by machining components from solid metal, using the best American and German machine tools to create the engine's components; the cylinder wall of a 50 hp Gnome was only 1.5 mm thick, while the connecting rods were milled with deep central channels to reduce weight. While somewhat low powered in terms of horsepower per litre, its power to weight ratio was an outstanding 1 hp (0.75 kW) per kg.

The following year, 1909, the inventor Roger Ravaud fitted one to his *Aéroscaphe*, a combination hydrofoil/aircraft, which he entered in the motor boat and aviation contests at Monaco. However, it was Henry Farman's use of the Gnome at the famous Rheims aircraft meet that year which brought it to prominence, when he won the Grand Prix for the greatest non-stop distance flown - 180 kilometres (110 mi) - and also created a world record for endurance flight.

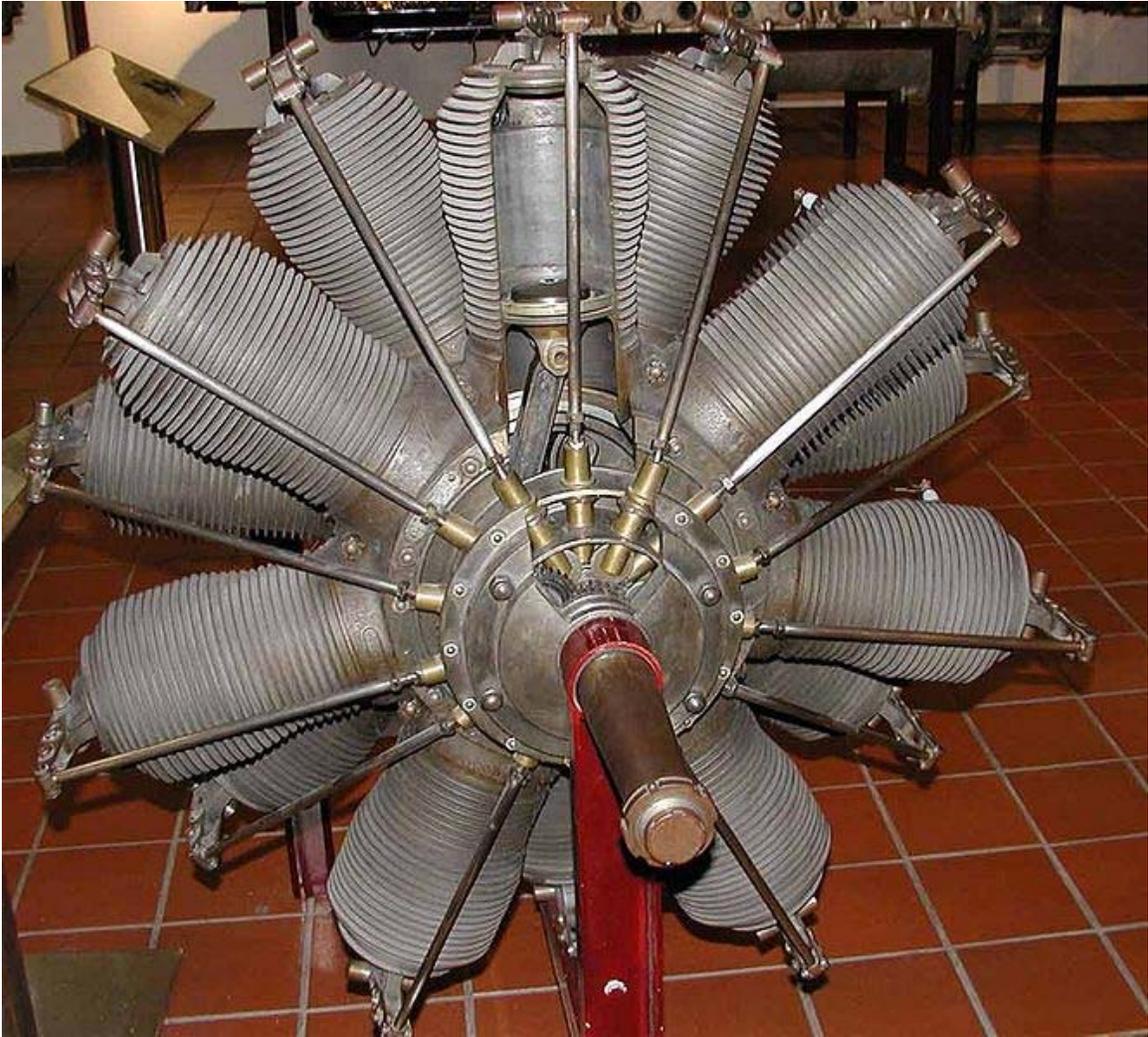
The very first successful seaplane flight, of Henri Fabre's *Le Canard*, was powered by a Gnome Omega on March 28, 1910 near Marseille.

Production of Gnome rotaries increased rapidly, with some 4,000 being produced before World War I, and the Omega's power output was increased to 80 hp (60 kW), and eventually to 110 hp (82 kW). By the standards of other engines of the period, the Gnome was considered not particularly temperamental, and was considered reliable, being credited as the first engine able to run for ten hours between overhauls.

In 1913 the Seguin brothers introduced the new Monosoupape ("single valve") series, which eliminated the cylinder inlet valves, and had a single exhaust valve in each cylinder head which doubled as an air intake. Each cylinder had transfer ports of the type used on two-stroke engines at its bottom which connected with the crankcase. The engine speed was controlled by varying the opening time and extent of the exhaust valves using levers acting on the valve tappet rollers, a system which was later abandoned due to causing burning of the valves. The weight of the Monosoupape was slightly less than the earlier two-valve engines and it used less lubricating oil. The 100 hp Monosoupape was built with 9 cylinders, and developed its rated power at 1,200 rpm.

Rotary engines produced by the Clerget and Le Rhône companies used conventional pushrod-operated valves in the cylinder head, but used the same principle of drawing the fuel mixture through the crankshaft, with the Le Rhône's having prominent copper intake tubes running from the crankcase to the top of each cylinder to admit the intake charge.

The 80 hp (60 kW) seven-cylinder Gnome was the standard at the outbreak of World War I, as the Gnome Lambda, and it quickly found itself being used in a large number of aircraft designs. It was so good that it was licensed by a number of companies, including the German Motorenfabrik Oberursel firm who designed the original Gnom engine. Oberursel was later purchased by Fokker, whose 80 hp Gnome Lambda copy was known as the Oberursel U.0. It was not at all uncommon for French Gnomes, as used in the earliest examples of the Bristol Scout biplane, to meet German versions, powering Fokker E.I Eindeckers, in combat, from the latter half of 1915 on.



A German Oberursel U.III engine on museum display

The only attempts to produce twin-row rotary engines in any volume were undertaken by Gnome, with their Double Lambda fourteen-cylinder 160 hp design, and with the German Oberursel firm's early World War I clone of the Double Lambda design, the U.III of the same power rating. While an example of the Double Lambda went on to power one of the Deperdussin Monocoque racing aircraft to a world-record speed of nearly 204 km/h (126 mph) in September 1913, the Oberursel U.III is only known to have been fitted into a few German production military aircraft, the Fokker E.IV fighter monoplane and Fokker D.III fighter biplane, both of whose failures to become successful combat types were partially due to the poor quality of the German powerplant, which was prone to wearing out after only a few hours of combat flight.

## **World War I**

The favourable power-to-weight ratio of the rotaries was their greatest advantage. While larger, heavier aircraft relied almost exclusively on conventional in-line engines, many fighter aircraft designers preferred rotaries right up to the end of the war.

Rotaries had a number of disadvantages, notably very high fuel consumption, partially because the engine was typically run at full throttle, and also because the valve timing was often less than ideal. The rotating mass of the engine also made it, in effect, a large gyroscope. During level flight the effect was not especially apparent, however under turning it was far more pronounced. Due to the direction of the force left-turns required some degree of effort and happened relatively slowly, combined with a tendency to nose-up, while right-turns were almost instantaneous, with a tendency for the nose to drop. In some aircraft this could be advantageous in situations such as dogfights, while the Sopwith Camel suffered to such an extent that it required left rudder for both left and right turns and could be extremely hazardous if full power was used over the top of a loop at low airspeeds. Trainee Camel pilots were warned to attempt their first hard right turns only at altitudes above 1,000 ft (300 m).

Even before the First World War attempts were made to overcome the inertia problem of rotary engines. As early as 1906 Charles Benjamin Redrup had demonstrated to the Royal Flying Corps at Hendon a 'Reactionless' engine in which the crankshaft rotated in one direction and the cylinder block in the opposite direction, each one driving a propeller. A later development of this was the 1914 reactionless 'Hart' engine designed by Redrup in which there was only one propeller connected to the crankshaft, but it rotated in the opposite direction to the cylinder block, thereby largely cancelling out rotational inertia. This proved too complicated for the Air Ministry and Redrup changed the design to a static radial engine which later flew in Vickers F.B.12b and F.B.16 aircraft.

As the war progressed, aircraft designers demanded ever increasing amounts of power. Inline engines were able to meet this demand by improving their upper rev limits, which meant more power. Improvements in valve timing, ignition systems, and lightweight materials made these higher revs possible, and by the end of the war the average engine had increased from 1,200 rpm to 2,000. The rotary was not able to do the same due to the drag of the rotating cylinders through the air. For instance, if an early-war model of 1,200 rpm increased its revs to only 1,400, the drag on the cylinders increased 36%, as air drag increases with the square of velocity. At lower rpm, drag could simply be ignored, but as the rev count rose, the rotary was putting more and more power into spinning the engine, with less remaining to provide useful thrust through the propeller.

One clever attempt to rescue the design, in a similar manner to Redrup's British "reactionless" engine concept, was made by Siemens AG. The crankcase (with the propeller still fastened directly to the front of it) and cylinders spun counterclockwise at 900 rpm, as seen externally from a "nose on" viewpoint, while the crankshaft and other internal parts spun clockwise at the same speed. This was achieved by the use of bevel gearing at the rear of the crankcase, resulting in the eleven-cylindered Siemens-Halske

Sh.III, running at 1800 rpm with little net torque. It was also apparently the only rotary engine to use a normal carburetor, which could be controlled by a conventional throttle, just as in an in-line engine. Used on the Siemens-Schuckert D.IV fighter, the new engine created what is considered by many to be the best fighter aircraft design of the war.

One new rotary powered aircraft, Fokker's own D.VIII, was designed at least in part to provide some use for the Oberursel factory's backlog of otherwise redundant 110 hp (82 kW) Ur.II engines, themselves clones of the Le Rhône 9J rotary.

## ***Postwar***

By the time the war ended, the rotary engine had become obsolete, and it disappeared from use quite quickly. The British Royal Air Force probably used rotary engines for longer than most other operators - the RAF's standard post-war fighter, the Sopwith Snipe, used the Bentley BR2 rotary, and the standard trainer, the Avro 504K, had a universal mounting to allow the use of several different types of low powered rotary, of which there was a large surplus supply. However, the cheapness of war-surplus engines had to be balanced against their poor fuel efficiency and the operating expense of their total loss lubrication system.

By the mid-1920s, rotaries had been more or less completely displaced even in British service, largely by the new generation of air-cooled "stationary" radials.

## ***Use in cars and motorcycles***

Although rotary engines were mostly used in aircraft, a few cars and motorcycles were built with rotary engines. A famous motorcycle, winning many races, was the Megola, which had a rotary engine inside the front wheel. Another motorcycle with a rotary engine was Charles Redrup's 1912 Redrup Radial, which was a three-cylinder 303cc rotary engine fitted to a number of motorcycles by Redrup.

In 1904 the Barry engine, also designed by Redrup, was built in Wales: a rotating 2-cylinder boxer engine weighing 6.5 kg was mounted inside a motorcycle frame.

In the 1940s Cyril Pullin developed the Powerwheel, a wheel with a rotating one-cylinder engine, clutch and drum brake inside the hub, but it never entered production.

Cars with rotary engines were built by American companies Adams-Farwell, Bailey, Balzer and Intrepid, amongst others.

## ***Other rotary engines***

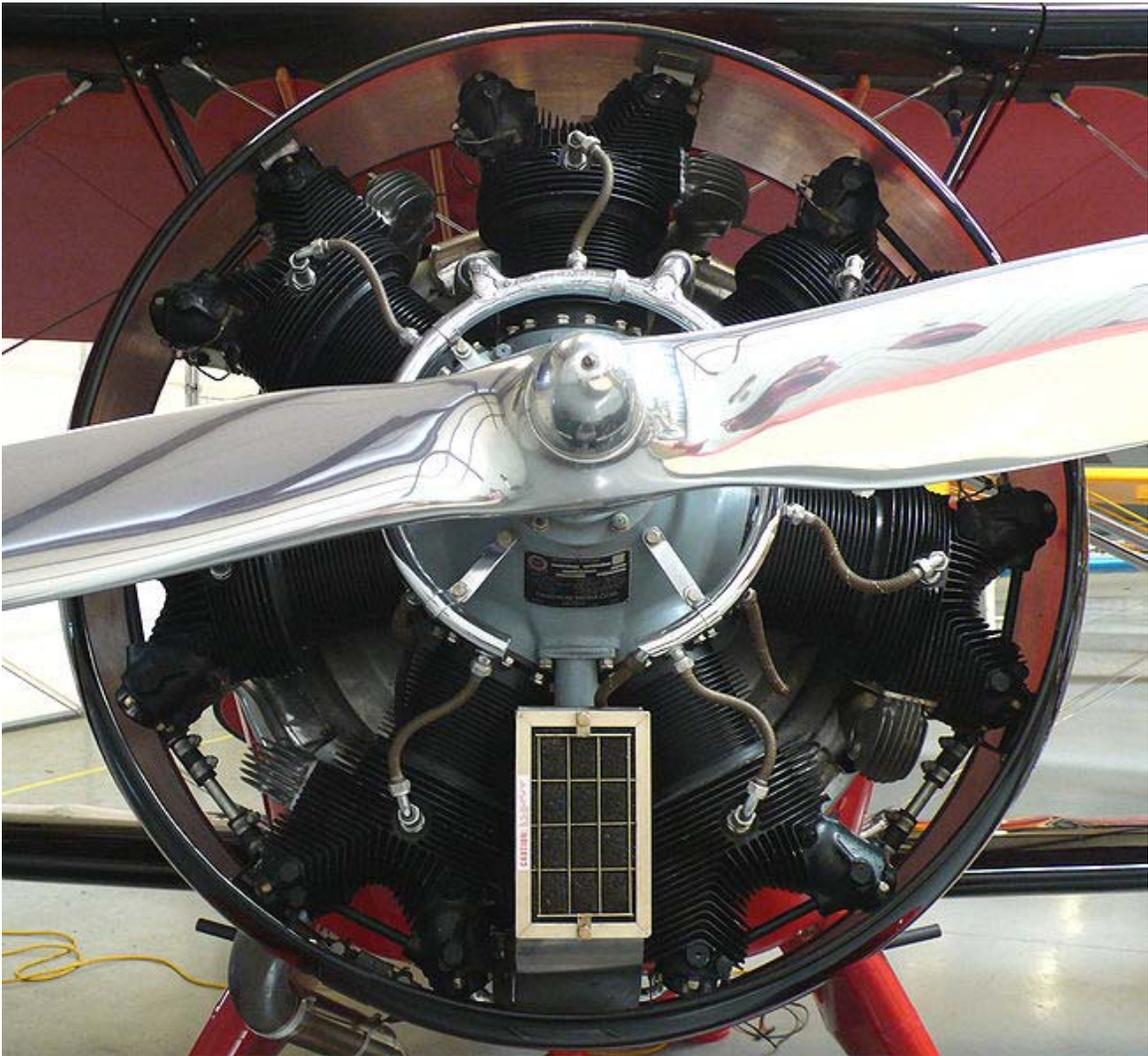
Besides the configuration described here with cylinders moving around a fixed crankshaft, several other very different engine designs are also called rotary engines. The most notable pistonless rotary engine, the Wankel rotary engine has also been used in cars (notably by NSU in the Ro80 and by Mazda in a variety of cars such as the RX-

series which includes the popular RX-7 and RX-8), as well as in some experimental aviation applications.

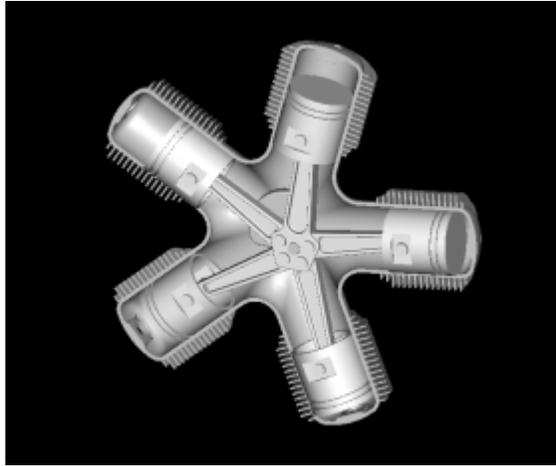
In the late 1970s a concept engine called the Bricklin-Turner Rotary Vee was being tested. The Rotary Vee is similar in configuration to the elbow steam engine. The Rotary Vee uses piston pairs connected as solid V shaped members with each end floating in a pair of rotating cylinders clusters. The rotating cylinder cluster pair are set with their axes at a wide V angle. The pistons in each cylinder cluster move parallel to each other instead of a radial direction, This engine design has not yet gone into production. The Rotary Vee was intended to power the Bricklin SV-1.

## Chapter- 3

# Radial Engine



Radial engine of a biplane



Radial engine in a cut-away view

The **radial engine** is a reciprocating type internal combustion engine configuration in which the cylinders point outward from a central crankshaft like the spokes on a wheel. This configuration was very commonly used in large aircraft engines before most large aircraft started using turbine engines.

In a radial engine, the pistons are connected to the crankshaft with a master-and-articulating-rod assembly. One piston, the uppermost one in the image a master rod with a direct attachment to the crankshaft. The remaining pistons pin their connecting rods' attachments to rings around the edge of the master rod. Four-stroke radials always have an odd number of cylinders per row, so that a consistent every-other-piston firing order can be maintained, providing smooth operation. This is achieved by the engine taking two revolutions of the crankshaft to complete the four strokes, (intake, compression, power, exhaust), which means the firing order is 1,3,5,2,4 and back to cylinder 1 again. This means that there is always a two-piston gap between the piston on its power stroke and the next piston to fire (i.e., the piston on compression). If an even number of cylinders was used, the firing order would be something similar to 1,3,5,2,4,6, which leaves a three-piston gap between firing pistons on the first crank shaft revolution, and only a one-piston gap on the second crank shaft revolution. This leads to an uneven firing order within the engine, and is not ideal.

Most radial engines use overhead poppet valves driven by pushrods and lifters on a cam plate which is concentric with the crankshaft, with a few smaller radials, like the five-cylinder Kinner B-5, using individual camshafts within the crankcase for each cylinder. A few engines utilize sleeve valves instead, like the very reliable 14 cylinder Bristol Hercules (built up to 1970' under license in France by SNECMA) and the powerful 18 cylinder Bristol Centaurus.

## History



A Continental radial engine, 1944



Pratt & Whitney R-1340 radial engine mounted in Sikorsky H-19 helicopter

Charles Manly constructed a water-cooled 5-cylinder radial engine in 1901, a conversion of one of Stephen Balzer's rotary engines, for Langley's *Aerodrome* aircraft. Manly's engine produced 52 hp (39 kW) at 950 rpm.

In 1903-04 Jacob Ellehammer used his experience constructing motorcycles to build the world's first air-cooled radial engine, a 3-cylinder engine which he used as the basis for a more powerful 5-cylinder model in 1907. This was installed in his triplane and made a number of short free-flight hops. During 1908-9, Ellehammer developed another engine, which had six cylinders arranged in two rows of three. His engines had a very good power-to-weight ratio, but his aircraft designs suffered from his lack of understanding of control. If he had concentrated on his engines, he might have become a successful manufacturer.

Another early radial engine was the 3-cylinder Anzani, originally built as a "semi-radial" W3 configuration design, one of which powered Louis Blériot's Blériot XI in his July 25, 1909 crossing of the English Channel. By 1914 Anzani had developed their range, their largest radial being a 20-cylinder engine of 200 hp (150 kW), with its cylinders arranged in four groups of five. One of the three-cylinder "fully radial", 120° cylinder angle Anzani powerplants still exists today, in fully running condition, in the nose of Old

Rhinebeck Aerodrome's restored and flyable 1909 vintage Blériot XI. There is also another running Anzani at Brodhead airfield to go on a replica Blériot XI.

Radial engines are regarded as being air-cooled almost by definition - so that it is interesting that one of the most successful of the early radial engines was the Salmson 9Z series of 9 cylinder water-cooled radial engines that were produced in large numbers during the First World War. Georges Canton and Pierre Unné patented the original engine design in 1909, offering it to the Salmson company - and the engine was often known as the Canton-Unné.

The radial engine was not developed at this time in Germany: two radial engines were made there before World War I, but the Germans seemed to lose faith in the type under war conditions, or it may have been that insistence on standardization ruled out any but proven engine types.

During the decade 1910-1920 the radial engine was largely overshadowed by its close relative, the rotary engine - which differed from the so called "stationary" radial in that the whole engine revolved with the propeller. In WWI, many French and other Allied aircraft flew with Bentley, Clerget, Gnome and Le Rhone rotary engines, the ultimate examples of which produced about 240 hp (180 kW), with the Germans either making close copies of the Gnome and Le Rhone powerplants built by the Oberursel firm, or, late in the war, using the unique Siemens eleven-cylinder rotary engine. By the end of the war the rotary engine was already essentially obsolete, being superseded as a type by rapid development of true radials.

## ***Radial versus inline debate***



1935 Monaco-Trossi, a rare example of automobile use

By 1918, the potential advantages of air-cooled radials over the water-cooled inline engine and air-cooled rotary engine that had powered World War I aircraft were well appreciated. While British designers had produced the ABC radial in 1917, they were unable to resolve its cooling problems, and it was not until the 1920s that the Bristol Aircraft Company produced reliable British radials.

In the US, NACA noted in 1920 that air-cooled radials could offer ship-based aircraft an increase in the power to weight ratio and reliability, and by 1921 the US Navy had announced it would only order aircraft fitted with air-cooled radials. Charles Lawrance's J-1 engine, developed in 1922 with Navy funding, and using aluminium cylinders with steel liners, ran for an unprecedented 300 hours, at a time when 50 hours endurance was acceptable for liquid-cooled engines. At the urging of the Army and Navy the Wright Aeronautical Corporation bought Lawrance's company, and subsequent engines were known as Wright Radials. The radial engines gave confidence to Navy pilots performing long-range overwater flights, and their increased performance meant that carrier-based aircraft could hold their own against land-based aircraft in combat.

Wright's 225 hp (168 kW) J-5 Whirlwind radial engine of 1925 was widely acknowledged as "the first truly reliable aircraft engine". Wright employed Giuseppe Mario Bellanca to design an aircraft to showcase it, and the result was the Wright-Bellanca 1, or WB-1, which was first flown in the latter part of that year. The J-5 was

used on many advanced aircraft of the day, including Charles Lindbergh's Ryan NYP with which he made the first solo Atlantic flight.

In 1925, the American rival firm to Wright's radial engine production efforts, Pratt & Whitney was founded, with the P & W firm's initial offering, the Pratt & Whitney Wasp, being test run later in that year, the start of production for the many models of Pratt & Whitney radial engines that were to appear during the second quarter of the 20th century, among them the 14-cylinder, twin row Pratt & Whitney R-1830 Twin Wasp, possibly the most-produced aviation engine of any single design, with a total production quantity of nearly 175,000 engines.

By 1929, it was considered by some that inline engines would completely displace air-cooled radials, and the Bristol Aeroplane Company was considered to be falling behind in engine production, as they had not produced an inline engine, concentrating instead on radials. At that time inline engines were mostly air-cooled, and presented some cooling problems.

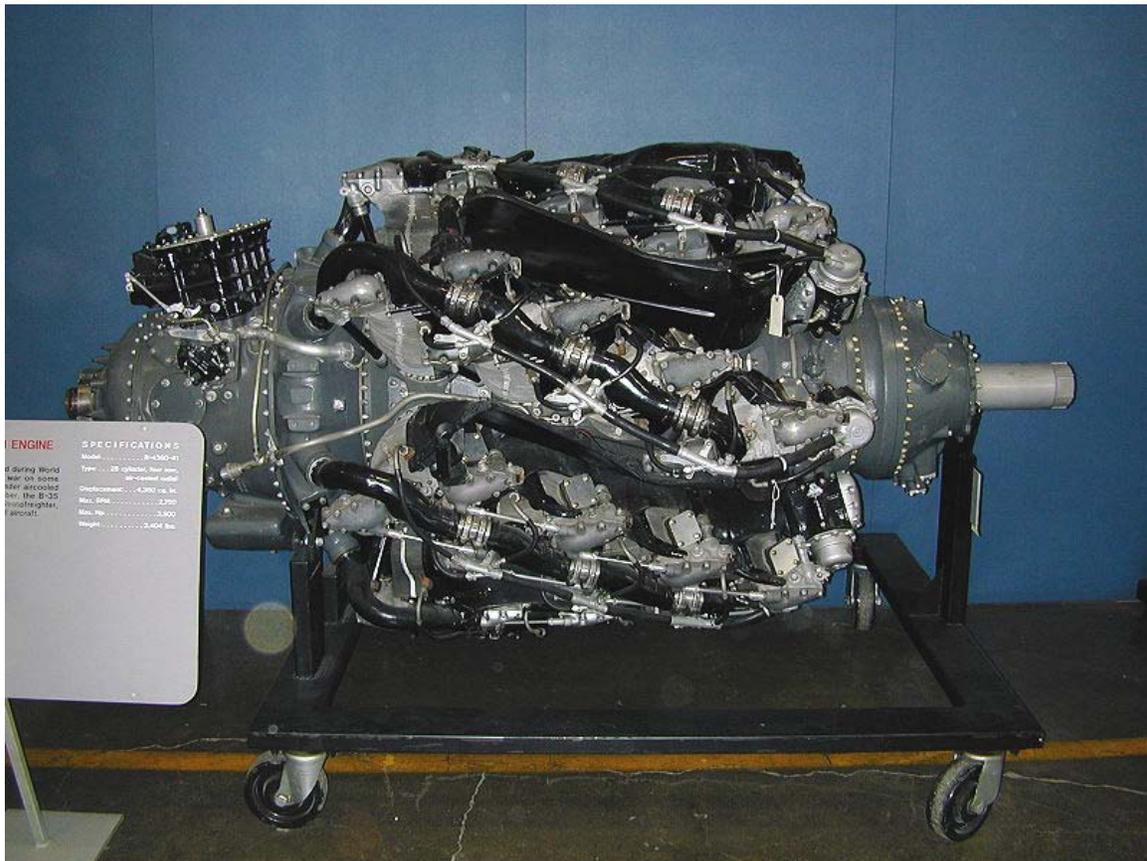
Rolls Royce introduced the Merlin engine in 1933, which eventually powered the Spitfire and Hurricane fighters and the Lancaster heavy bomber, amongst others; the Merlin was also built in the US as the Packard V-1650. By 1938 liquid-cooled inline aircraft engines had been successfully developed in the US by the automobile industry, with the backing of the US Army. Many notable fighter aircraft of World War II were powered by inline engines, including the Supermarine Spitfire, P-51 Mustang, P-38 Lightning and Messerschmitt Bf 109, but radial engines also saw service in the successful Mitsubishi Zero, P-47 Thunderbolt, F4U Corsair, F6F Hellcat, and Focke-Wulf Fw 190, while the late-war Hawker Sea Fury, one of the fastest production single piston-engined aircraft ever built, used a radial engine. Until the development of the jet engine, bombers, transport aircraft, and airliners commonly used radial engines. Factors influencing the choice of radial over inline were the larger radial engine displacements available, the reliability of the engine, and the maintenance simplicity. Additionally, the larger total frontal area of these aircraft meant the radial engine's large frontal profile was less detrimental in proportion to smaller aircraft designs.

The radial was popular largely due to its simplicity, and most navy air arms had dedicated themselves to it because of its improved reliability for over-water flights and better power/weight ratio for aircraft carrier takeoffs. Being liquid-cooled, inline engines require the added weight and complexity of cooling systems and are generally more vulnerable to battle damage. Damage to an inline engine could result in a loss of coolant and consequent engine seizure, while an air-cooled radial could take damage but continue to operate. Additionally, radials offered higher mechanical efficiency than inline engines, as they had shorter and stiffer crankshafts, a five-cylinder radial needing only two crankshaft bearings as opposed to the seven required for a six-cylinder inline engine. The shorter crankshaft also produced less vibration and hence higher reliability. Another advantage of the air-cooled radial is that all cylinders receive equal cooling airflow, and most radial-engined aircraft designed since the 1930s were fitted with NACA cowlings to

further improve cooling and reduce drag. Also, by being flat, radial engines resulted in shorter aircraft with better landing visibility (very important for carrier landings).

The inline engine's major advantage was a smaller frontal area compared to radial engines. This made it possible to build more streamlined designs and, for single-engine aircraft, could improve the pilot's forward visibility. In addition, being liquid-cooled offered greater options for both engine and radiator placement. For example, the P-39 Airacobra mounted the engine behind the pilot to allow the large M4 cannon to be mounted in the front of the aircraft, while the Spitfire incorporated an underwing radiator design which offset cooling drag by using the cooling air to generate thrust.

### ***Multi-row radials***



The Wasp Major, a four-row radial

Originally radial engines had one row of cylinders, but as engine sizes increased it became necessary to add extra rows. The first known radial-configuration engine to ever use a twin-row design was the 160 hp Gnôme "Double Lambda" rotary engine of 1912, designed as a 14 cylinder twin-row version of the firm's 80 hp Lambda single-row seven cylinder rotary, with only the German Oberursel U.III clone of the Double Lambda reproducing the Gnome Double Lambda's twin-row design before the end of World War I. Most stationary radial engines did not exceed two rows, but the largest displacement radial engine ever built in quantity, the Pratt & Whitney R-4360 Wasp Major, nicknamed

*corncob*, was a 28-cylinder 4-row radial engine used in many large aircraft designs in the post-World War II period. The Lycoming R-7755 was the largest piston-driven aircraft engine ever produced; with 36 cylinders totaling about 7,750 in<sup>3</sup> (127 L) of displacement and a power output of 5,000 horsepower (3,700 kW). It was originally intended to be used in the "European bomber" that eventually emerged as the Convair B-36. Only two examples were built before the project was terminated in 1946. The USSR also built a limited number of 'Zvezda' engines with up to 56 cylinders, which were even larger in displacement than the Lycoming R-7755. The 112-cylinder diesel boat engines featuring 16 rows with 7 banks of cylinders, bore of 160 mm (6.3 in), stroke of 170 mm (6.7 in), and total displacement of 383 liters (23,931 in<sup>3</sup>). The engine produced 10,000 hp (7,500 kW) at 2,000 rpm. They were used on fast attack craft, such as Osa class missile boats.

### ***Modern radials***

At least five companies build radials today. Vedeneyev engines produces the M-14P model, 360 hp (270 kW) (up to 450 hp (340 kW)) radial used on Yakovlevs, and Sukhoi Su-26 and Su-29 aerobatic aircraft. The M-14P has also found great favor among builders of experimental aircraft, such as the Culp's Special, and Culp's Sopwith Pup, Pitts S12 "Monster" and the Murphy "Moose". 110 hp (82 kW) 7-cylinder and 150 hp (110 kW) 9-cylinder engines are available from Australia's Rotec Engineering. HCI Aviation offers the R180 5-cylinder (75 hp (56 kW)) and R220 7-cylinder (110 hp (82 kW)), available "ready to fly" and as a build-it-yourself kit. Verner Motor, from the Czech Republic, now builds several radial engines. Models range in power from 71 hp (53 kW) to 172 hp (128 kW). Miniature radial engines for model airplane use are also available from Seidel in Germany, OS and Saito Seisakusho of Japan, and Technopower in the USA. The Saito firm is known for making three different sizes of 3-cylinder radials, as well as a 5-cylinder example, as the Saito firm is a specialist in making a large line of miniature four-stroke engines for model use in both methanol-burning glow plug and gasoline-fueled spark plug ignition engine formats.

### ***Diesel radials***

While most radial engines have been produced for gasoline fuels, there have been instances of diesel fueled engines. The Bristol Phoenix of 1928-1932 was successfully tested in aircraft and the Nordberg Manufacturing Company of the US developed and produced a series of large radial diesel engines from the 1940s.

To reduce the danger of engine fires, in 1932 the French company Clerget developed the 14D, a 14-cylinder 2-stroke diesel radial engine. After a series of improvements, in 1938 the 14F2 model produced 520 hp (390 kW) at 1910 rpm cruise power, with a power-to-weight ratio near that of contemporary gasoline engines and a specific fuel consumption of 166 g/hp/hour. During WWII the research continued, but no engines were mass-produced because of the Nazi occupation, and by 1943 the engine had grown to produce over 1,000 hp (750 kW) with a turbocharger. After the war, the Clerget company was integrated in the SNECMA company and had plans for a 32-cylinder diesel engine of

4,000 hp (3,000 kW), but in 1947 the company abandoned piston engine development in favor of work on the emerging turbine engines.

The Nordberg engines were initially designed for electricity production in aluminium smelters. They differed from the norm of radial design by using two opposite cylinders as a double master instead of the more usual single master rod, and managed to run perfectly circular. The engine design also permitted even numbers of cylinders in a single row with the cylinders being fired in consecutive order. The engines were a two-stroke design and were also available in a dual-fuel gas/diesel model. A number of powerhouse installations utilising large numbers of these engines were made in the US.

Packard designed and built a diesel radial aircraft engine, the DR-980, in 1928. It was a 9 cylinder radial engine displacing 980 cubic inches and rated to produce 225 horsepower (168 kW). On 28 May 1931, a Bellanca CH-300 fitted with a DR-980, piloted by Walter Edwin Lees and Frederick Brossy, set a record for staying aloft for 84 hours and 32 minutes without being refueled. This record was not broken until 55 years later by the Rutan Voyager.

### ***Use in tanks***

In the years leading up to WWII, as the need for armored vehicles was realized, designers were faced with the problem of how to power the vehicles, and turned to using aircraft engines, among them radial types. The radial aircraft engines provided greater power to weight ratios and were more reliable than conventional inline vehicle engines available at the time. This reliance had a downside though: if the engines were mounted vertically as in the M3 Lee and M4 Sherman, their comparatively large diameter gave the tank a higher silhouette than designs using inline engines.

The Continental R-670, a 7-cylinder radial aero engine which first flew in 1931, became a widely-used tank powerplant, being installed in the M1 Combat Car, M2 Light Tank, M3 Stuart, M3 Lee, LVT-2 Water Buffalo.

The Guiberson T-1020, a 9-cylinder radial diesel aero engine, was used in the M1A1E1, M2, and M3, while the Continental R975 saw service in the M4 Sherman, M7 Priest, M18 Hellcat tank destroyer, and the M44 self-propelled howitzer.

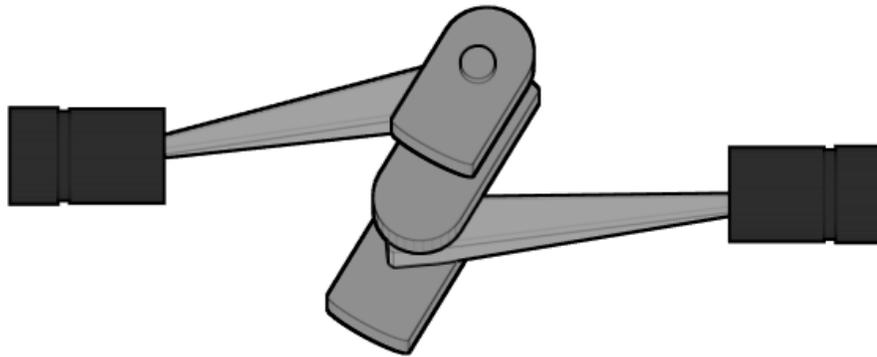
### ***Model radial engines***

A number of multi-cylinder 4-stroke model engines have been commercially available in a radial configuration, beginning with the Japanese O.S. Max firm's FR5-300 five-cylinder, 3.0 cu.in. (50 cm<sup>3</sup>) displacement "Sirius" radial in 1986. The American 'Technopower' firm had made smaller displacement five and seven cylinder model radial engines as early as 1976, but the OS firm's engine was the first mass-produced radial engine design in aeromodeling history. The rival Saito Seisakusho firm in Japan has since produced a similiary-sized five cylinder radial four stroke model engine of their own as a direct rival to the OS design, with Saito also creating a trio of three-cylinder radial

engines ranging from 0.90 cu.in. (15 cm<sup>3</sup>) to 4.50 cu.in. (75 cm<sup>3</sup>) in displacement. The German Seidel firm has made both seven and nine cylinder "large" (starting at 70 cm<sup>3</sup> displacement) radio control model radial engines, mostly for glow plug ignition, with an experimental fourteen cylinder twin-row radial being tried out.

## Chapter- 4

# Flat Engine



The Boxer engine was first patented by German engineer Karl Benz

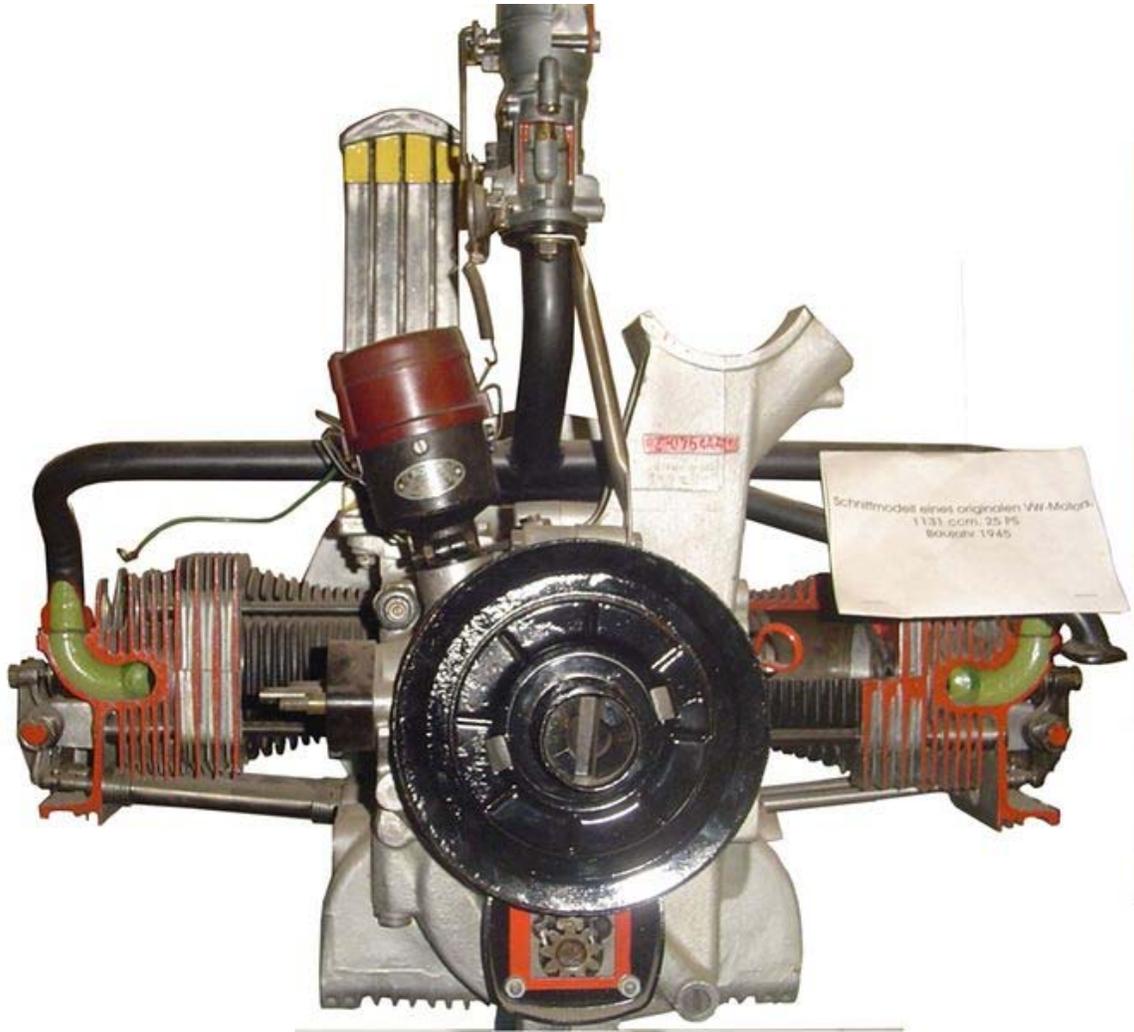
A **flat engine** is an internal combustion engine with multiple pistons that move in a horizontal plane. Typically, layout has cylinders arranged in two banks on either side of a single crankshaft and is generally known as the **boxer**, or horizontally-opposed engine—not to be confused with opposed-piston engines, which are mechanically different. This is the concept patented in 1896 by engineer Karl Benz, eight years after he started producing the world's first successful automobiles.

Another widely-used form of flat engine consists of a straight engine with two, three, four or more cylinders canted 90 degrees into the horizontal plane, however this is not generally considered significantly different from other straight engines.

## ***Configuration***



1954 BMW "Boxer" motorcycle engine. The two cylinders cannot be directly opposite each other.



The Flat-4 Volkswagen air cooled engine



UL260i Flat-4 aircraft engine

Flat engines offer a low centre of gravity and thereby may offer a drive configuration with better stability and control. They are also wider than other engines configurations, presenting complications with the fitment of the engine within the engine bay of a front-engined car. With motorcycles, the flat engine's width may restrict cornering. Flat engines lend themselves well to aircraft engines.

Front-mounted air-cooled flat-twin engines were used in Tatra 11 and Tatra 30, by Citroën in their model 2CV and its derivatives, while the GS and GSA. Olcit used a flat-four and a flat-six was proposed for the Citroën DS but rejected. BMW Motorrad used an air-cooled flat-twin in almost all of its motorcycles from 1921 until 1980 and still depends heavily on this layout, using it in many models to the present day. Cars such as the Porsche 911 use a flat-engine (in that particular case a six-cylinder) at the rear of the car, where its extra width does not interfere with the steering of the front wheels and there is a weight-saving since no prop-shaft is required.

All versions of the Subaru Impreza, Forester, Tribeca, Legacy, Outback and SVX use either a flat-4 or flat-6 engine.

True boxers have each crankpin controlling only one piston/cylinder while 180° engines, which superficially appear very similar, share crankpins.

- The boxer engine (the true horizontally opposed engine) has corresponding pistons reaching top dead centre (TDC) simultaneously.
- The 180° V engine has corresponding pistons sharing a crankpin on the crankshaft and reaching TDC half a crankshaft revolution apart. They may use regular connecting rods side by side, or use a master/slave system, or a fork-and-blade system. Flat engines with more than eight cylinders are most commonly V engines.

Boxer engines must not be confused with opposed-piston engines, which are based on a quite different concept using two crankshafts. These can be used in vehicles such as tanks.

## Boxer engines



1969 Hino Motors DS140 12 cylinder boxer diesel engine

Boxer engines got their name because each pair of pistons moves simultaneously in and out rather than alternately, like boxers showing they are ready by clashing their gloved fists against each other before a fight. Boxer engines of up to eight cylinders have proved highly successful in automobiles and up to six cylinders in motorcycles and continue to be popular for light aircraft engines.

Boxers are one of only three cylinder layouts that have a natural dynamic balance; the others being the straight-6 and the V12. These engines can run very smoothly and free of

unbalanced forces with a four-stroke cycle and do not require a balance shaft or counterweights on the crankshaft to balance the weight of the reciprocating parts, which are required in other engine configurations. Note that this is generally true of boxer engines regardless of the number of cylinders (assumed to be even), but not true for all V or inline engines. However, in the case of boxer engines with fewer than six cylinders, unbalanced moments (a reciprocating torque also known as a "rocking couple") are unavoidable due to the "opposite" cylinders being slightly out of line with each other.

Boxer engines (and flat engines in general) tend to be noisier than other common engines for both intrinsic and other reasons, e.g., in cars, valve clatter from under the hood is not damped by large air filters and other components. Boxers need no balance weights on the crankshaft, which should be lighter and fast-accelerating - but, in practice (e.g. in cars), they need a flywheel to run smoothly at low speeds and this negates the advantage. They have a characteristic smoothness throughout the rev range and offer a low centre of gravity. When combined with a mounting position immediately ahead of the rear axle (e.g. Porsche Boxster and Cayman but not Porsche 911 nor Volkswagen Beetle), they have largely neutral handling.

### ***Notable flat engines***



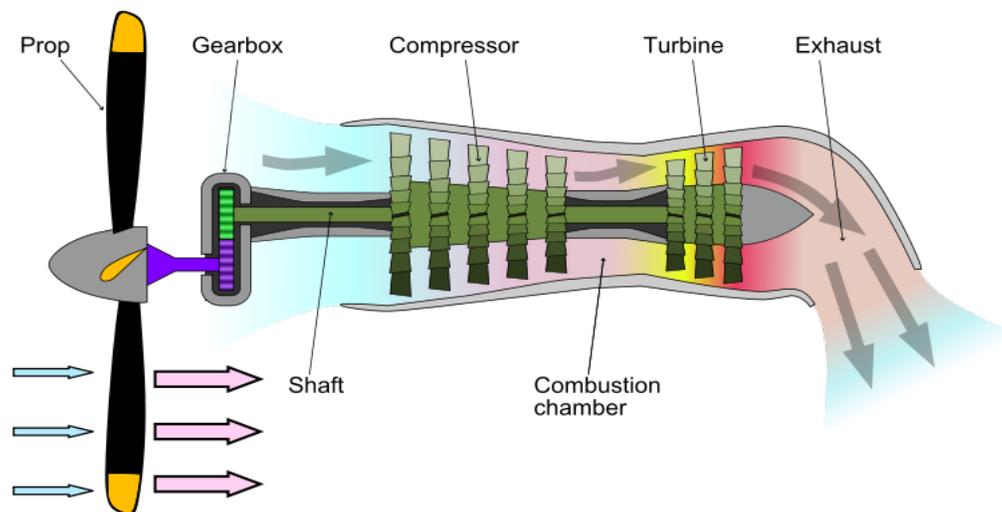
Subaru Boxer Turbodiesel engine cutaway display

- In 1896, Karl Benz invented the first internal combustion engine with horizontally opposed pistons.
- In 1923 Max Friz designed the first BMW motorcycles, choosing a 500 cc boxer engine and unit transmission with shaft drive. This engine type is still in production today. The BMW 247 engine, known as an airhead due to its air cooling, was produced until 1995. BMW replaced it with the oilhead engine with partial oil cooling and four valves per cylinder, but still retaining the same boxer twin configuration.
- In 1948 Preston Tucker modified a helicopter flat-6 to be rear mounted in his Tucker Torpedo
- The Volkswagen air-cooled flat-4 engine used in the Volkswagen Beetle, SP2 and Karmann Ghia, and later developed further for the Volkswagen Type 2 (Bus) transporters and Volkswagen Type 3 cars. VW was rumoured to have worked on a Diesel version of the aircooled boxer but abandoned this engine due to noise and heat issues. The latest version of the VW boxer was watercooled and thus dubbed the 'Wasserboxer' or waterboxer by enthusiasts. This engine included many developments of the earlier engines. It was offered in capacities of 1.9 and 2.1 litres was used to power T3 buses and transporters.
- The Citroën 2CV and Panhard air-cooled flat-2 engines, both influenced by the flat-2s of BMW
- The air-cooled Chevrolet Corvair OHV flat-6
- In 1960 Lancia's flat-4 water-cooled engine debuted for the Lancia Flavia model, first Italian front-wheel drive car, like 1500 cc 90 PS (66 kW) coupé version and during the years become a 2000 cc with 142 bhp (106 kW) when was mounted the first electronic Injection by Bosch in 1970 in a flat four engine, Lancia also rebuild a new big flat-4 engine in 1976, 2484 cc, for his upper size model Lancia Gamma. It was produced until 1984 and was Lancia's last flat-4 engine.
- The flat-4 engines in Alfa Romeo's Alfasud, Sprint, 33 and early versions of the 145. The last of the line was a 1712 cc flat-4, 16 valves, producing up to 137 PS (101 kW).
- The water-cooled front-mounted flat-4 and flat-6 engines used by Subaru in all of its mid-sized cars. Subaru refers to these as boxer engines in publicity commentary, and include a variety of naturally aspirated and turbo driven engines from 1966, when the Subaru 1000 was introduced to current; both closed and semi-closed short blocks have been used. A print add for the 1973 Subaru GL coupe referred to the engine as "quadrozontal" The EJ series of 4 cylinder engines released first in 1990 has been the focus for the development of the Boxer engine in the late 20th century. Ranging from 1.6-2.5 litres, this engine in its 2 litre turbo arrangement has been the power behind World Rally Championship winning cars. Subaru also offers a boxer turbodiesel, called the Subaru EE series, the world's first to be fitted into a passenger car.
- Since its introduction in 1975, the Honda Goldwing has utilized a boxer engine, a 4-cylinder until 1987, and 6-cylinders since. The water-cooled SOHC 1832 cc flat-6 is fitted to the Honda Goldwing from 2001 on.
- The air-cooled flat-4, flat-6 and flat-8 engines were used for many years in early Porsches. The flat-12 in the 917 model is a 180° V-engine and not a boxer.

- The water-cooled flat-6 engines in the Porsche Boxster, Cayman and later 911 models
- General aviation aircraft often use air-cooled flat-4 and flat-6 engines made by companies such as Lycoming, Continental. Ultralight and microlight aircraft often use engines such as the Rotax 912 or Jabiru 2200.
- Ferrari made use of a flat-12 design in several models, including the Berlinetta Boxer, the Testarossa and its derivatives, such as the 512TR and the F512 M, although this engine design is technically a V12 that has been flattened down to a 180° configuration, and therefore cannot be regarded as a true boxer engine.

## Chapter- 5

# Turboprop



Schematic diagram showing the operation of a turboprop engine

**Turboprop** engines are a type of aircraft powerplant that use a gas turbine to drive a propeller. The gas turbine is designed specifically for this application, with almost all of its output being used to drive the propeller. The engine's exhaust gases contain little energy compared to a jet engine and play a minor role in the propulsion of the aircraft.

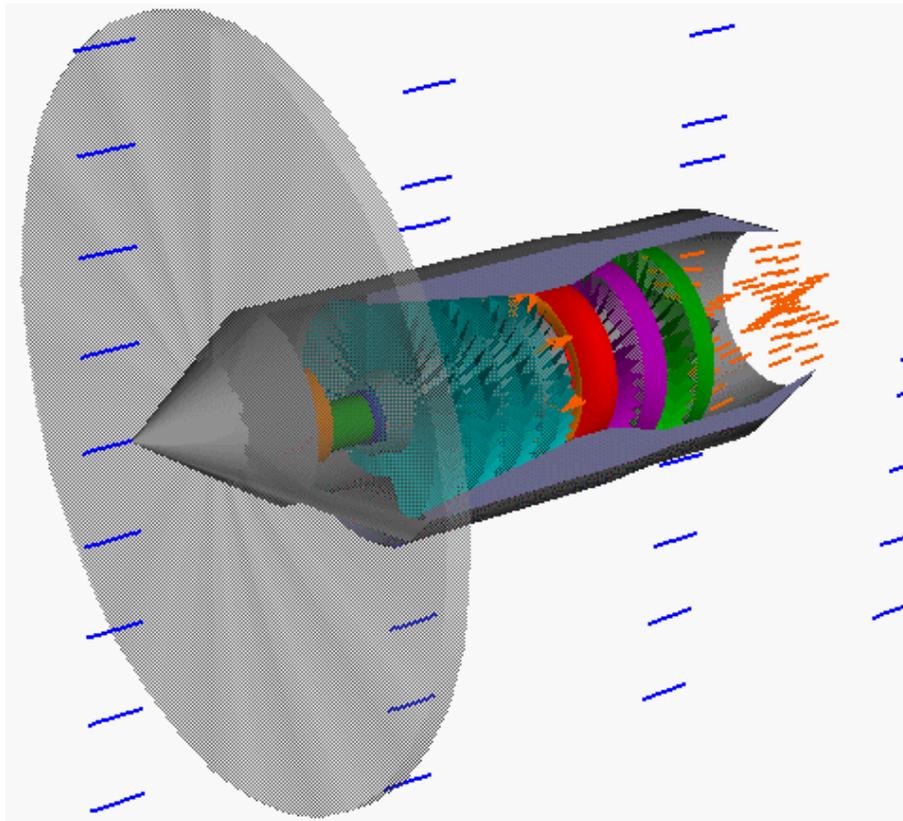
The propeller is coupled to the turbine through a reduction gear that converts the high RPM, low torque output to low RPM, high torque. The propeller itself is normally a constant speed (variable pitch) type similar to that used with larger reciprocating aircraft engines.

Turboprop engines are generally used on small subsonic aircraft, but some aircraft outfitted with turboprops have cruising speeds in excess of 500 kt (926 km/h, 575 mph). Large military and civil aircraft, such as the Lockheed L-188 Electra and the Tupolev Tu-95, have also used turboprop power. The Airbus A400M is powered by four Europrop TP400 engines, which are the third most powerful turboprop engines ever produced, after the Kuznetsov NK-12 and Progress D-27.

In its simplest form a turboprop consists of an intake, compressor, combustor, turbine, and a propelling nozzle. Air is drawn into the intake and compressed by the compressor. Fuel is then added to the compressed air in the combustor, where the fuel-air mixture then combusts. The hot combustion gases expand through the turbine. Some of the power generated by the turbine is used to drive the compressor. The rest is transmitted through the reduction gearing to the propeller. Further expansion of the gases occurs in the propelling nozzle, where the gases exhaust to atmospheric pressure. The propelling nozzle provides a relatively small proportion of the thrust generated by a turboprop.

Turboprops are very efficient at flight speeds (below 450 mph) because the jet velocity of the propeller (and exhaust) is relatively low. Due to the high price of turboprop engines, they are mostly used where high-performance short-takeoff and landing (STOL) capability and efficiency at modest flight speeds are required. The most common application of turboprop engines in civilian aviation is in small commuter aircraft, where their greater reliability than reciprocating engines offsets their higher initial cost. Turboprop airliners now operate at near the same speed as small turbofan powered aircraft and burn two thirds of the fuel per passenger. Turboprop powered aircraft have become popular for bush airplanes such as the Cessna Caravan and Quest Kodiak as jet fuel is easier to obtain in remote areas than is aviation grade gasoline (avgas).

### ***Technological aspects***



Flow past a turboprop engine in operation

Much of the jet thrust in a turboprop is sacrificed in favor of shaft power, which is obtained by extracting additional power (up to that necessary to drive the compressor) from turbine expansion. While the power turbine may be integral with the gas generator section, many turboprops today feature a free power turbine on a separate coaxial shaft. This enables the propeller to rotate freely, independent of compressor speed. Owing to the additional expansion in the turbine system, the residual energy in the exhaust jet is low. Consequently, the exhaust jet produces (typically) less than 10% of the total thrust.

Propellers are not efficient when the tips reach or exceed supersonic speeds. For this reason, a reduction gearbox is placed in the drive line between the power turbine and the propeller to allow the turbine to operate at its most efficient speed while the propeller operates at its most efficient speed. The gearbox is part of the engine and contains the parts necessary to operate a constant speed propeller. This differs from the turboshaft engines used in helicopters, where the gearbox is remote from the engine.

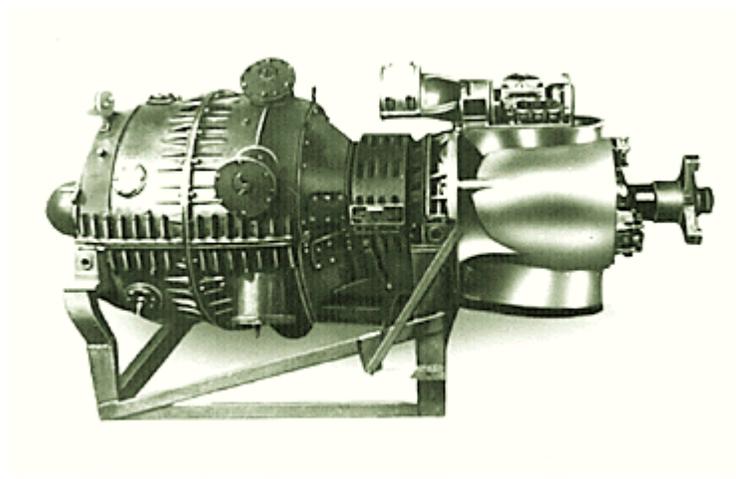
Residual thrust on a turboshaft is avoided by further expansion in the turbine system and/or truncating and turning the exhaust 180 degrees, to produce two opposing jets. Apart from the above, there is very little difference between a turboprop and a turboshaft.

While most modern turbojet and turbofan engines use axial-flow compressors, turboprop engines usually contain at least one stage of centrifugal compression. Centrifugal compressors have the advantage of being simple and lightweight, at the expense of a streamlined shape.

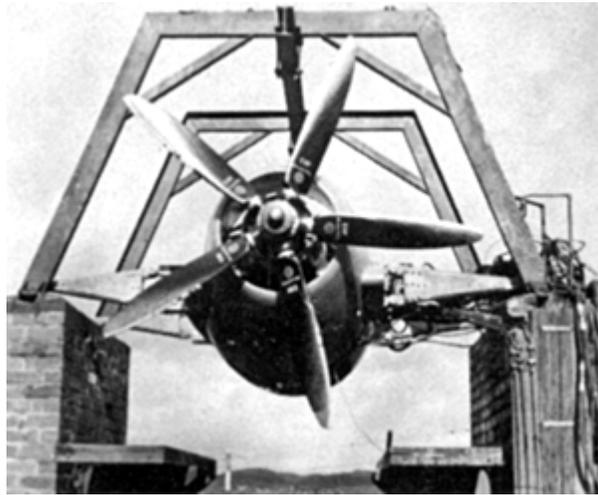
Propellers lose efficiency as aircraft speed increases, so turboprops are normally not used on high-speed aircraft. However, propfan engines, which are very similar to turboprop engines, can cruise at flight speeds approaching Mach 0.75. To increase the efficiency of the propellers, a mechanism can be used to alter the pitch, thus adjusting the pitch to the airspeed. A variable pitch propeller, also called a controllable pitch propeller, can also be used to generate negative thrust while decelerating on the runway. Additionally, in the event of an engine outage, the pitch can be adjusted to a vaning pitch (called feathering), thus minimizing the drag of the non-functioning propeller.

Some commercial aircraft with turboprop engines include the Bombardier Dash 8, ATR 42, ATR 72, BAe Jetstream 31, Embraer EMB 120 Brasilia, Fairchild Swearingen Metroliner, Saab 340 and 2000, Xian MA60, Xian MA600, and Xian MA700.

## *History*



Jendrassik Cs-1, built in Budapest, Hungary in 1938



A Rolls-Royce RB.50 *Trent* on a test rig at Hucknall, in March 1945



Kuznetsov NK-12M Turboprop, on a Tu-95

Alan Arnold Griffith had published a paper on turbine design in 1926. Subsequent work at the Royal Aircraft Establishment investigated axial turbine designs that could be used to supply power to a shaft and thence a propeller. From 1929, Frank Whittle began work on centrifugal turbine designs that would deliver pure jet thrust.

The world's first turboprop was the Jendrassik Cs-1, designed by the Hungarian mechanical engineer György Jendrassik. It was produced and tested in the Ganz factory in Budapest between 1939 and 1942. It was planned to fit to the Varga RMI-1 X/H twin-engined reconnaissance bomber in 1940, but the program was cancelled.

The first British turboprop engine was the Rolls-Royce RB.50 Trent, a converted Derwent II fitted with reduction gear and a Rotol 7-ft, 11-in five-bladed propeller. Two Trents were fitted to Gloster Meteor *EE227* — the sole "Trent-Meteor" — which thus became the world's first turboprop powered aircraft, albeit a test-bed not intended for production. It first flew on 20 September 1945. From their experience with the Trent, Rolls-Royce developed the Dart, which became one of the most reliable turboprop engines ever built. Dart production continued for more than fifty years. The Dart-powered Vickers Viscount was the first turboprop aircraft of any kind to go into production and sold in large numbers. It was also the first four-engined turboprop. Its first flight was on 16 July 1948. The world's first single engined turboprop aircraft was the Armstrong Siddeley Mamba-powered Boulton Paul Balliol, which first flew on 24 March 1948.

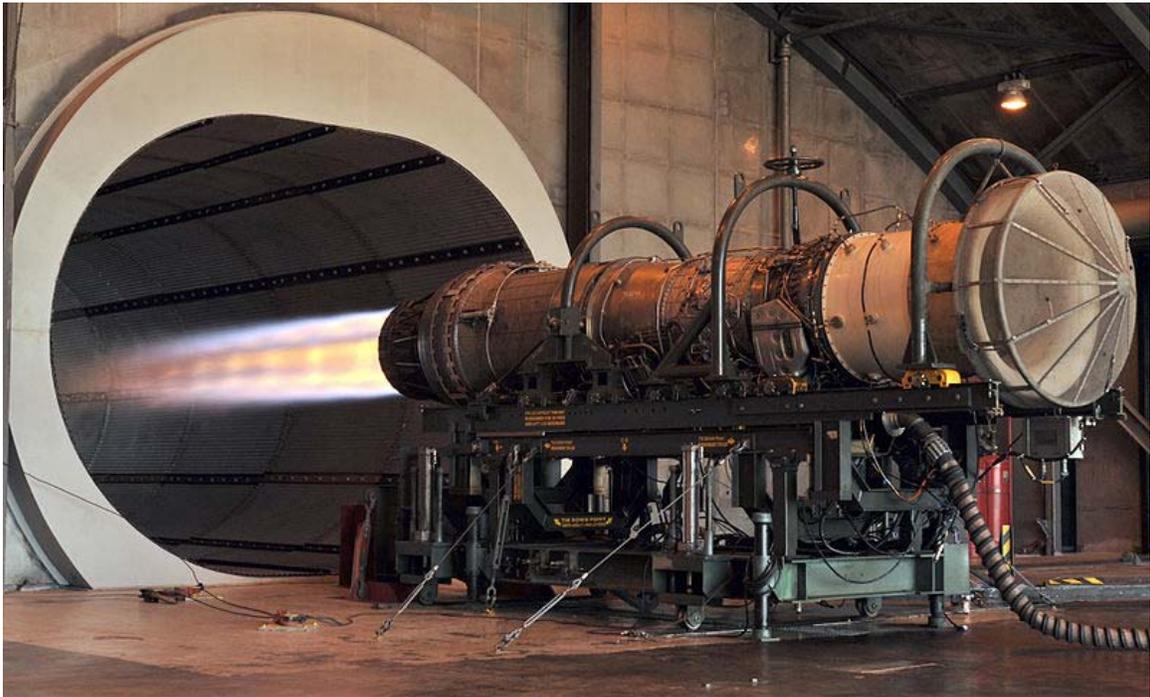
The Soviet Union built on German World War II development by Junkers (BMW and Hirth/Daimler-Benz also developed and partially tested designs). While the Soviet Union had the technology to create a jet-powered strategic bomber comparable to Boeing's B-52 Stratofortress, they instead produced the Tupolev Tu-95, powered with four Kuznetsov NK-12 turboprops, mated to eight contra-rotating propellers (two per nacelle) with supersonic tip speeds to achieve maximum cruise speeds in excess of 575 mph, faster than many of the first jet aircraft and comparable to jet cruising speeds for most missions. The Bear would serve as their most successful long-range combat and surveillance aircraft and symbol of Soviet power projection throughout the end of the 20th century. The USA would incorporate contra-rotating turboprop engines, such as the ill-fated Allison T40, into a series of experimental aircraft during the 1950s, but none would be adopted into service.

The first American turboprop engine was the General Electric XT31, first used in the experimental Consolidated Vultee XP-81. The XP-81 first flew in December 1945, the first aircraft to use a combination of turboprop and turbojet power. The technology of the Lockheed Electra airliner was also used in military aircraft, such as the P-3 Orion and the C-130 Hercules. One of the most produced turboprop engines is the Pratt & Whitney Canada PT6 engine.

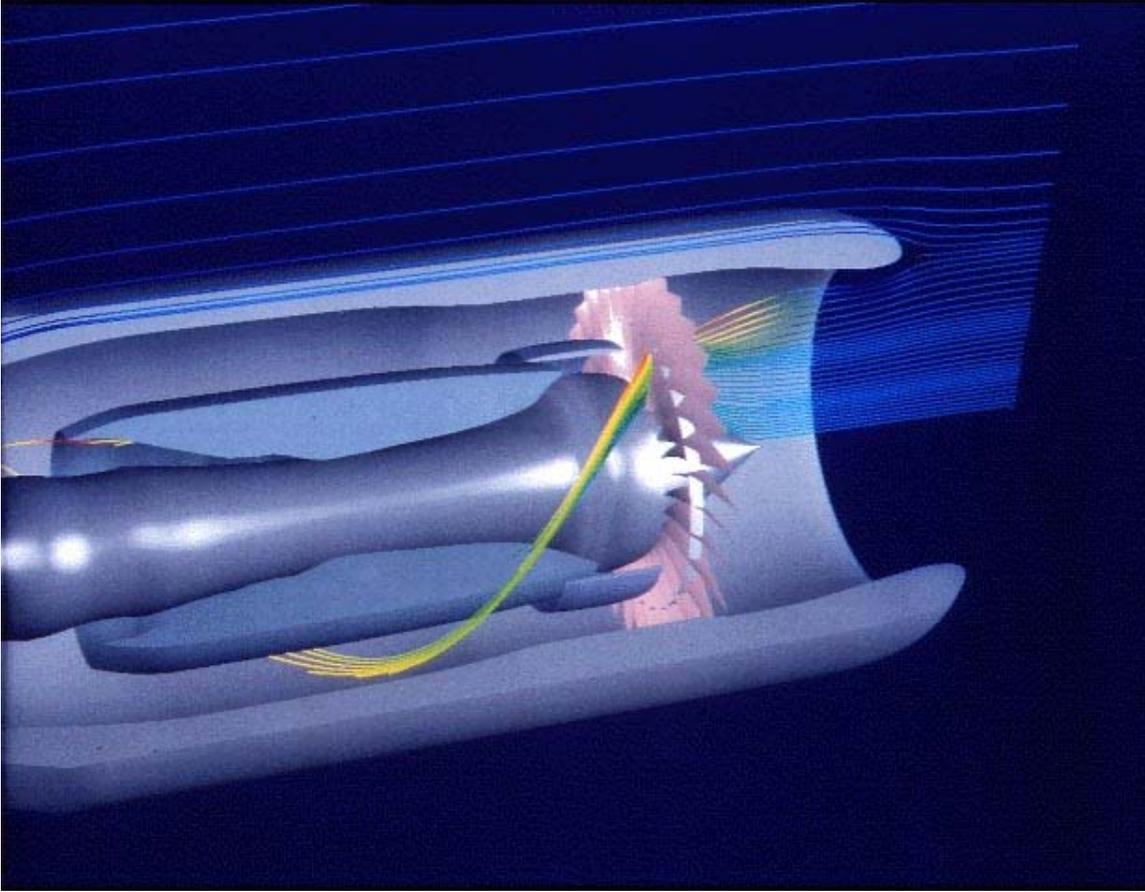
The first turbine powered, shaft driven helicopter was the Bell XH-13F, a version of the Bell 47 powered by Continental XT-51-T-3 (Turbomeca Artouste) engine.

## Chapter- 6

# 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.

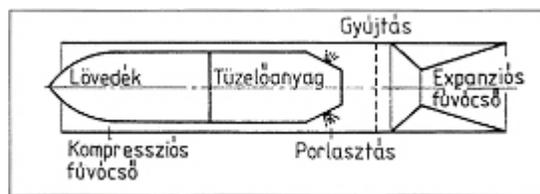
### ***History***

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.

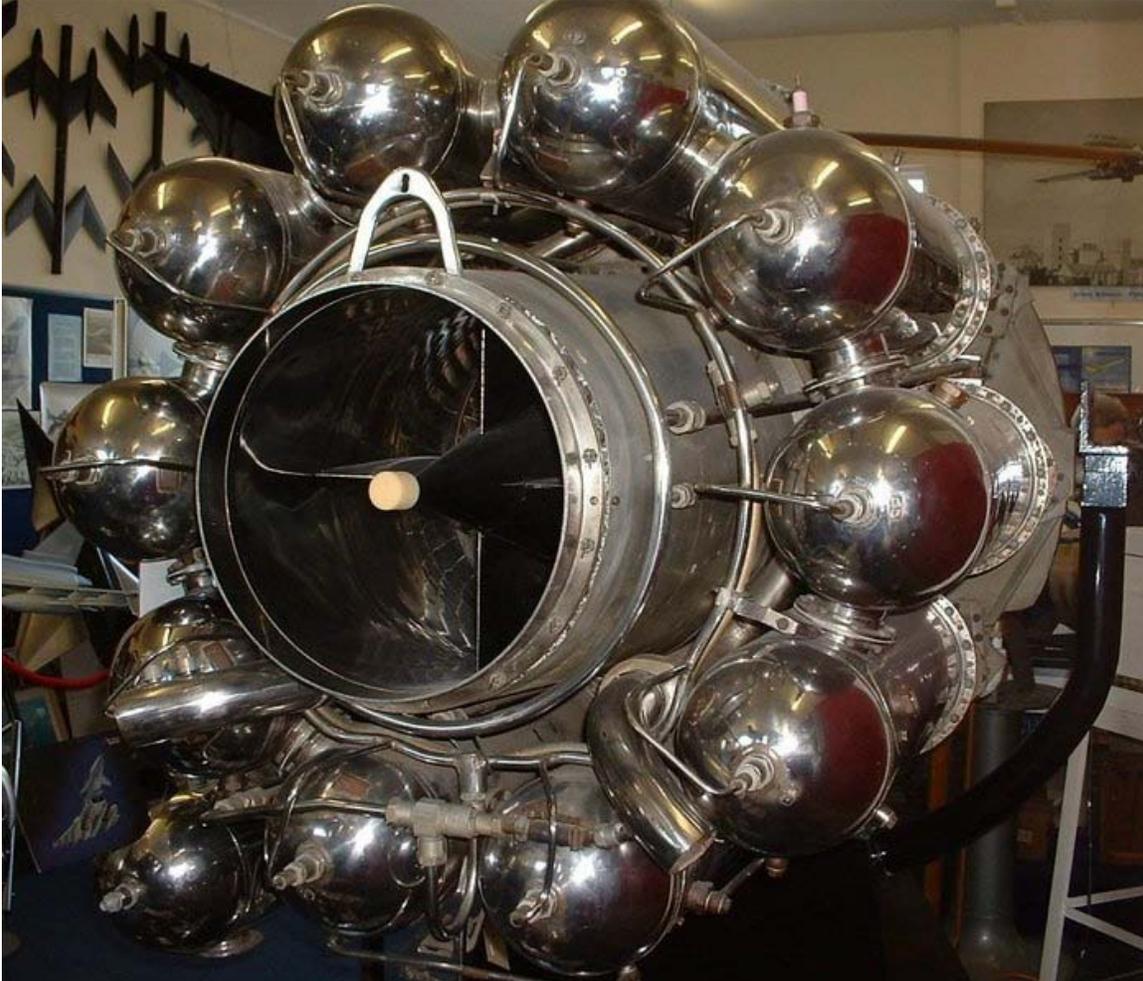


Albert Fonó's ramjet-cannonball from 1915

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.

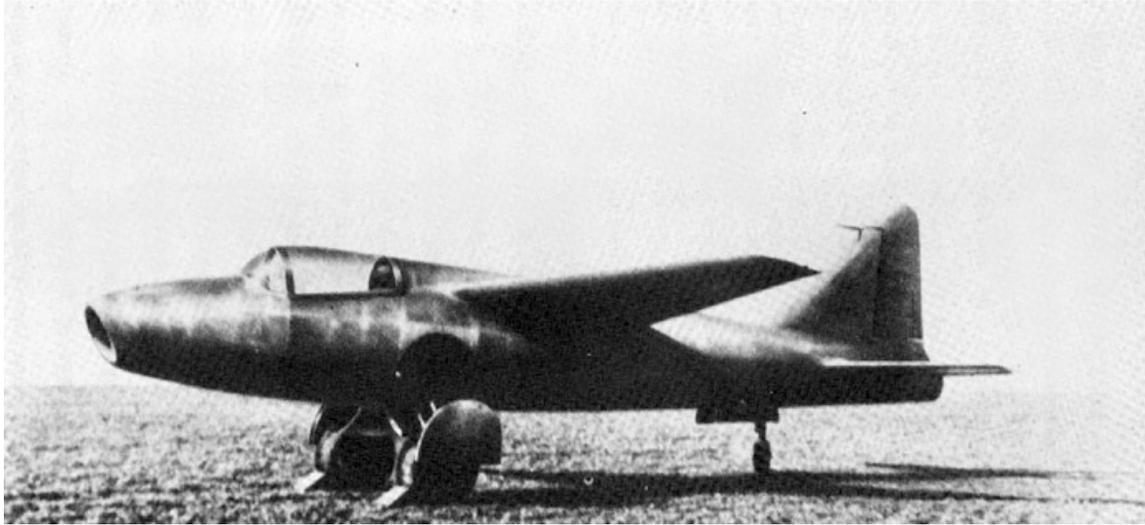
The first patent for using a gas turbine to power an aircraft was filed in 1921 by Frenchman Maxime Guillaume. His engine was an axial-flow turbojet. Alan Arnold Griffith published *An Aerodynamic Theory of Turbine Design* in 1926 leading to experimental work at the RAE.



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-fueled, 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.

## **Types**

There are a large number of different types of jet engines, all of which achieve forward thrust from the principle of *jet propulsion*.

### **Airbreathing**

Nearly all aircraft are propelled by airbreathing jet engines, and most of the airbreathing jet engines that are in use are turbofan jet engines which give good efficiency at speeds just below the speed of sound.

### **Turbine powered**

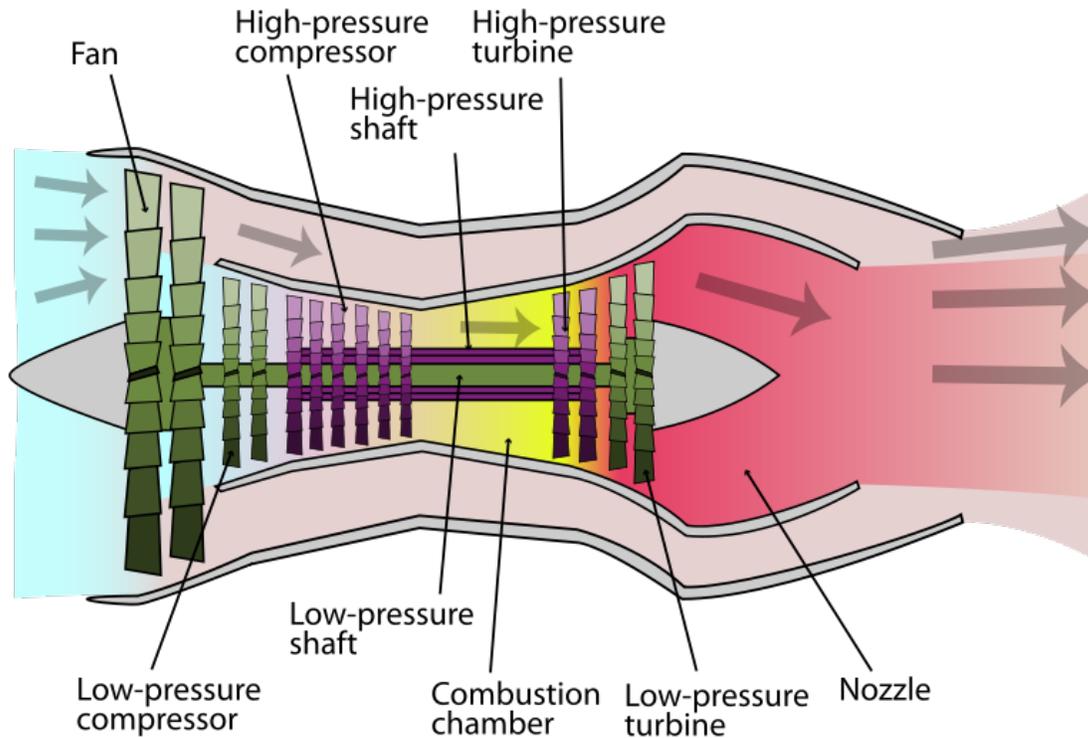
Gas turbines are rotary engines that extract energy from a flow of combustion gas. They have an upstream compressor coupled to a downstream turbine with a combustion chamber in-between. In aircraft engines, those three core components are often called the "gas generator." There are many different variations of gas turbines, but they all use a gas generator system of some type.

### **Turbojet**

A turbojet engine is a gas turbine engine that works by compressing air with an inlet and a compressor (axial, centrifugal, or both), mixing fuel with the compressed air, burning the mixture in the combustor, and then passing the hot, high pressure air through a turbine and a nozzle. The compressor is powered by the turbine, which extracts energy from the expanding gas passing through it. The engine converts internal energy in the fuel to kinetic energy in the exhaust, producing thrust. All the air ingested by the inlet is

passed through the compressor, combustor, and turbine, unlike the turbofan engine described below.

### Turbofan



Schematic diagram illustrating the operation of a low-bypass turbofan engine

A turbofan engine is a gas turbine engine that is very similar to a turbojet. Like a turbojet, it uses the gas generator core (compressor, combustor, turbine) to convert internal energy in fuel to kinetic energy in the exhaust. Turbofans differ from turbojets in that they have an additional component, a fan. Like the compressor, the fan is powered by the turbine section of the engine. Unlike the turbojet, some of the flow accelerated by the fan bypasses the gas generator core of the engine and is exhausted through a nozzle. The bypassed flow is at lower velocities, but a higher mass, making thrust produced by the fan more efficient than thrust produced by the core. Turbofans are generally more efficient than turbojets at subsonic speeds, but they have a larger frontal area which generates more drag.

There are two general types of turbofan engines, low bypass and high bypass. Low bypass turbofans have a bypass ratio of around 2:1 or less, meaning that for each kilogram of air that passes through the core of the engine, two kilograms or less of air bypass the core. Low bypass turbofans often used a mixed exhaust nozzle meaning that the bypassed flow and the core flow exit from the same nozzle. High bypass turbofans have larger bypass ratios, sometimes on the order of 5:1 or 6:1. These turbofans can produce much more thrust than low bypass turbofans or turbojets because of the large

mass of air that the fan can accelerate, and are often more fuel efficient than low bypass turbofans or turbojets.

### **Turboprop and turboshaft**

Turboprop engines are jet engine derivatives that extract work from the hot-exhaust jet to turn a rotating shaft, which is then used to produce thrust by some other means. While not strictly jet engines in that they rely on an auxiliary mechanism to produce thrust, turboprops are very similar to other turbine-based jet engines, and are often described as such.

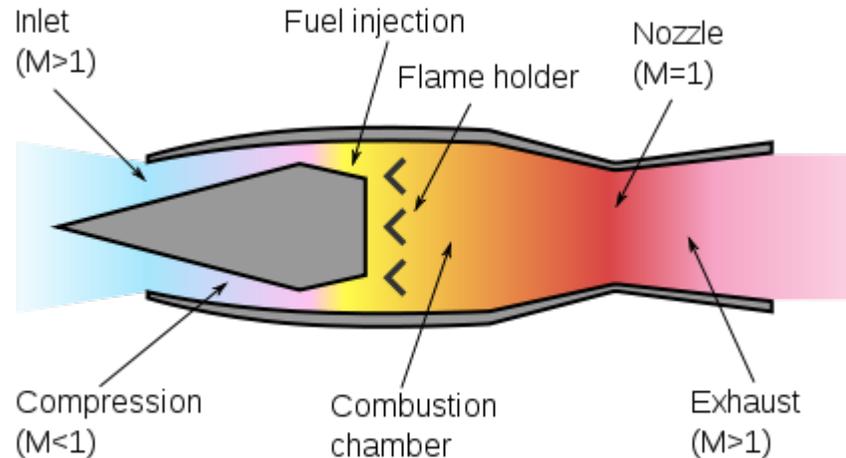
In turboprop engines, a portion of the engines' thrust is produced by spinning a propeller, rather than relying solely on high-speed jet exhaust. As their jet thrust is augmented by a propeller, turboprops are occasionally referred to as a type of hybrid jet engine. While many turboprops generate the majority of their thrust with the propeller, the hot-jet exhaust is an important design point, and maximum thrust is obtained by matching thrust contributions of the propeller to the hot jet. Turboprops generally have better performance than turbojets or turbofans at low speeds where propeller efficiency is high, but become increasingly noisy and inefficient at high speeds.

Turboshaft engines are very similar to turboprops, differing in that nearly all energy in the exhaust is extracted to spin the rotating shaft. They therefore generate little to no jet thrust. Turboshaft engines are often used to power helicopters.

### **Propfan**

A propfan engine (also called "unducted fan", "open rotor", or "ultra-high bypass") is a jet engine that uses its gas generator to power an exposed fan, similar to turboprop engines. Like turboprop engines, propfans generate most of their thrust from the propeller and not the exhaust jet. The primary difference between turboprop and propfan design is that the propeller blades on a propfan are highly swept to allow them to operate at speeds around Mach 0.8, which is competitive with modern commercial turbofans. These engines have the fuel efficiency advantages of turboprops with the performance capability of commercial turbofans. While significant research and testing (including flight testing) has been conducted on propfans, no propfan engines have entered production.

## Ram powered



A schematic of a ramjet engine, where "M" is the Mach number of the airflow

Ram powered jet engines are airbreathing engines similar to gas turbine engines and they both follow the Brayton cycle. Gas turbine and ram powered engines differ, however, in how they compress the incoming airflow. Whereas gas turbine engines use axial or centrifugal compressors to compress incoming air, ram engines rely only on air compressed through the inlet or diffuser. Ram powered engines are considered the most simple type of air breathing jet engine because they can contain no moving parts.

### Ramjet

Ramjets are the most basic type of ram powered jet engines. They consist of three sections; an inlet to compressed oncoming air, a combustor to inject and combust fuel, and a nozzle expel the hot gases and produce thrust. Ramjets require a relatively high speed to efficiently compress the oncoming air, so ramjets cannot operate at a standstill and they are most efficient at supersonic speeds. A key trait of ramjet engines is that combustion is done at subsonic speeds. The supersonic oncoming air is dramatically slowed through the inlet, where it is then combusted at the much slower, subsonic, speeds. The faster the oncoming air is, however, the less efficient it becomes to slow it to subsonic speeds. Therefore ramjet engines are limited to approximately Mach 5.

### Scramjet

Scramjets are mechanically very similar to ramjets. Like a ramjet, they consist of an inlet, a combustor, and a nozzle. The primary difference between ramjets and scramjets is that scramjets do not slow the oncoming airflow to subsonic speeds for combustion, they use supersonic combustion instead. The name "scramjet" comes from "supersonic combusting ramjet." Since scramjets use supersonic combustion they can operate at speeds above Mach 6 where traditional ramjets are too inefficient. Another difference

between ramjets and scramjets comes from how each type of engine compresses the oncoming air flow: while the inlet provides most of the compression for ramjets, the high speeds at which scramjets operate allow them to take advantage of the compression generated by shock waves, primarily oblique shocks.

Very few scramjet engines have ever been built and flown. In May 2010 the Boeing X-51 set the endurance record for the longest scramjet burn at over 200 seconds.

### Non-continuous combustion

Type	Description	Advantages	Disadvantages
<b>Motorjet</b>	Obsolete type that worked like a turbojet but instead of a turbine driving the compressor a piston engine drives it.	Higher exhaust velocity than a propeller, offering better thrust at high speed	Heavy, inefficient and underpowered. Example: Caproni Campini N.1.
<b>Pulsejet</b>	Air is compressed and combusted intermittently instead of continuously. Some designs use valves.	Very simple design, commonly used on model aircraft	Noisy, inefficient (low compression ratio), works poorly on a large scale, valves on valved designs wear out quickly
<b>Pulse detonation engine</b>	Similar to a pulsejet, but combustion occurs as a detonation instead of a deflagration, may or may not need valves	Maximum theoretical engine efficiency	Extremely noisy, parts subject to extreme mechanical fatigue, hard to start detonation, not practical for current use

### Rocket

The rocket engine uses the same basic physical principles as the jet engine for propulsion via thrust, but is distinct in that it does not require atmospheric air to provide oxygen; the rocket carries all components of the propellant.

This type of engine is used for launching satellites, space exploration and manned access, and permitted landing on the moon in 1969.

Rocket engines are used for high altitude flights as they have a lack of reliance on atmospheric oxygen and this allows them to operate at arbitrary altitudes, or anywhere where very high accelerations are needed since rocket engines themselves have a very high thrust-to-weight ratio.

However, the high exhaust speed and the heavier, oxidiser-rich propellant results in far more propellant use than turbfans although, even so, at high speeds they become energy-efficient.

An approximate equation for the net thrust of a rocket engine is:

$$F = \dot{m}g_0 I_{sp-vac} - A_e P$$

Where  $F$  is the thrust,  $I_{sp(vac)}$  is the specific impulse,  $g_0$  is a standard gravity,  $\dot{m}$  is the propellant flow in kg/s,  $A_e$  is the area of the exhaust bell at the exit, and  $P$  is the atmospheric pressure.

Type	Description	Advantages	Disadvantages
<b>Rocket</b>	Carries all propellants and oxidants on-board, emits jet for propulsion	Very few moving parts, Mach 0 to Mach 25+, efficient at very high speed (> Mach 5.0 or so), thrust/weight ratio over 100, no complex air inlet, high compression ratio, very high speed (hypersonic) exhaust, good cost/thrust ratio, fairly easy to test, works in a vacuum-indeed works best exoatmospheric which is kinder on vehicle structure at high speed, fairly small surface area to keep cool, and no turbine in hot exhaust stream. Very high temperature combustion and high expansion ratio nozzle gives very high efficiency- at very high speeds.	Needs lots of propellant—very low specific impulse—typically 100–450 seconds. Extreme thermal stresses of combustion chamber can make reuse harder. Typically requires carrying oxidiser on-board which increases risks. Extraordinarily noisy.

## Hybrid

Combined cycle engines simultaneously use 2 or more different jet engine operating principles.

Type	Description	Advantages	Disadvantages
<b>Turborocket</b>	A turbojet 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	Airspeed limited to same range as turbojet engine, carrying oxidizer like LOX can be dangerous. Much heavier than simple rockets.
<b>Air-augmented rocket</b>	Essentially a ramjet where intake air is compressed and	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

burnt with the exhaust from a rocket

undeveloped and unexplored type, cooling difficulties, very noisy, thrust/weight ratio is similar to ramjets.

### Precooled jets / LACE

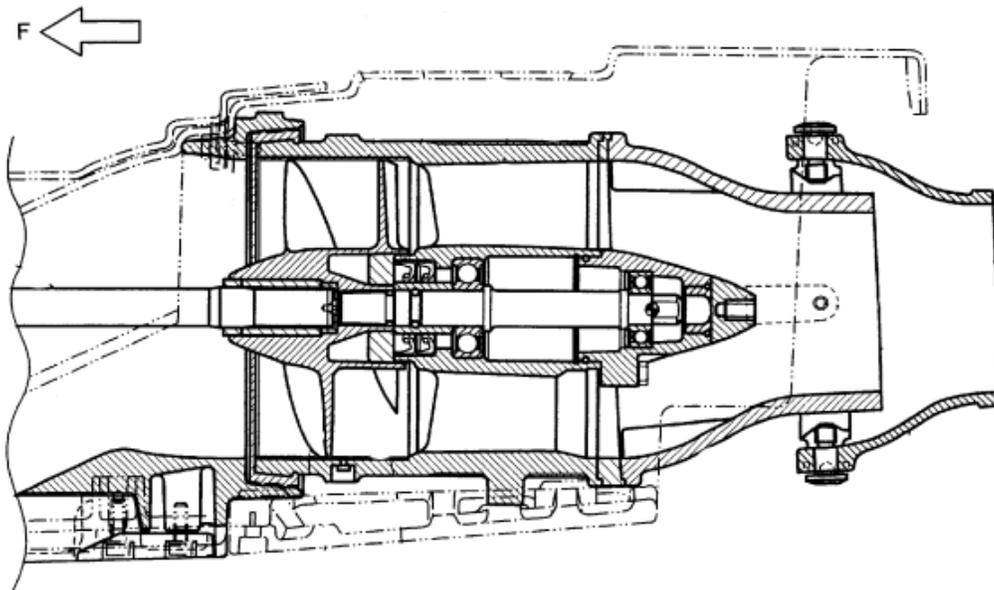
Intake air is chilled to very low temperatures at inlet in a heat exchanger before passing through a ramjet and/or turbojet and/or rocket engine.

Easily tested on ground. Very 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, very long distance intercontinental travel.

Exists only at the lab prototyping stage. Examples include RB545, Reaction Engines SABRE, ATREX. Requires liquid hydrogen fuel which has very low density and requires heavily insulated tankage.

### Water jet

A water jet, or pump jet, is a marine propulsion system that utilizes a jet of water. The mechanical arrangement may be a ducted propeller with nozzle, or a centrifugal compressor and nozzle.



A pump jet schematic

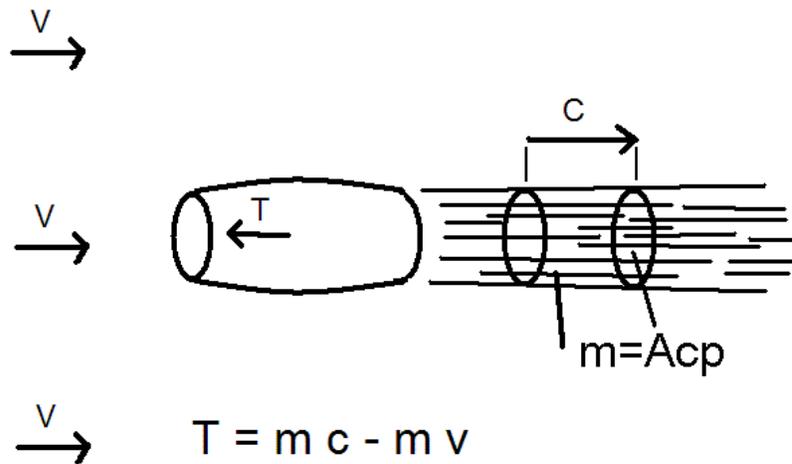
Type	Description	Advantages	Disadvantages
<b>Water jet</b>	For propelling water rockets and jetboats; squirts water out the back through a nozzle	In boats, can run in shallow water, high acceleration, no risk of engine overload (unlike propellers), less noise and vibration, highly maneuverable at all boat speeds, high speed efficiency, less vulnerable to damage from debris, very reliable, more load flexibility, less harmful to wildlife	Can be less efficient than a propeller at low speed, more expensive, higher weight in boat due to entrained water, will not perform well if boat is heavier than the jet is sized for

### 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:

$$mv$$

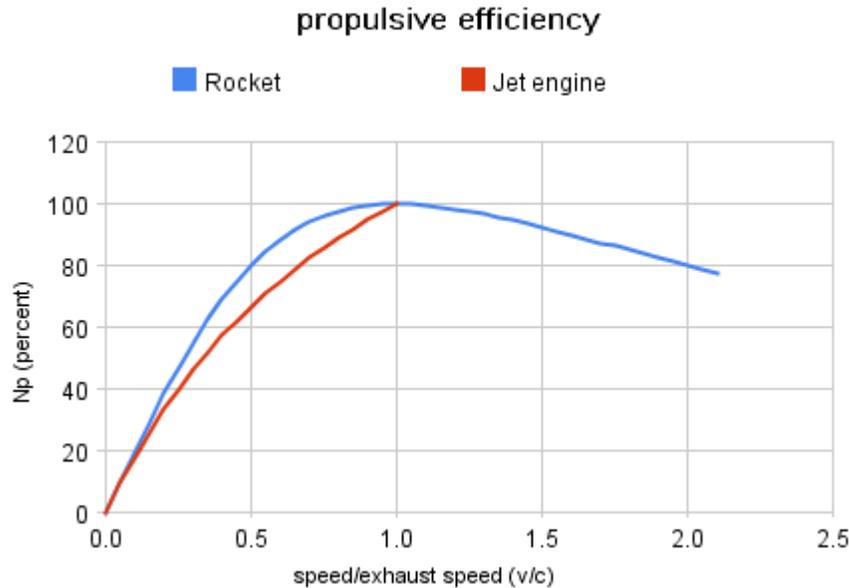
Most types of jet engine have an intake, which provides the bulk of the fluid exiting the exhaust. Conventional rocket motors, however, do not have an intake, the oxidizer and fuel both being carried within the vehicle. Therefore, rocket motors do not have ram drag; the gross thrust of the nozzle is 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 ( $\eta$ ) upon the vehicle speed/exhaust speed ratio ( $v/c$ ) for air-breathing jet and rocket engines

Energy efficiency ( $\eta$ ) of jet engines installed in vehicles has two main components, *cycle efficiency* ( $\eta_c$ )- how efficiently the engine can accelerate the jet, and *propulsive efficiency* ( $\eta_p$ )-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  $\eta$  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

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

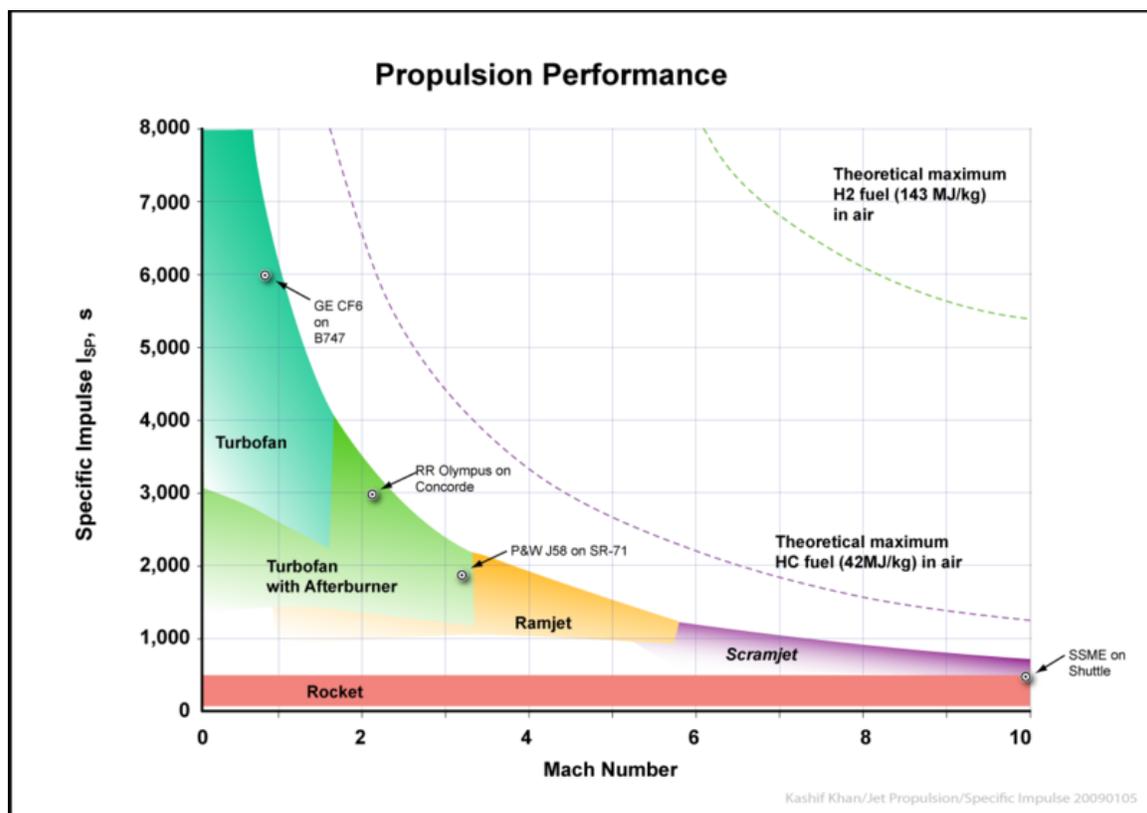
And for a rocket:

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

## 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 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.

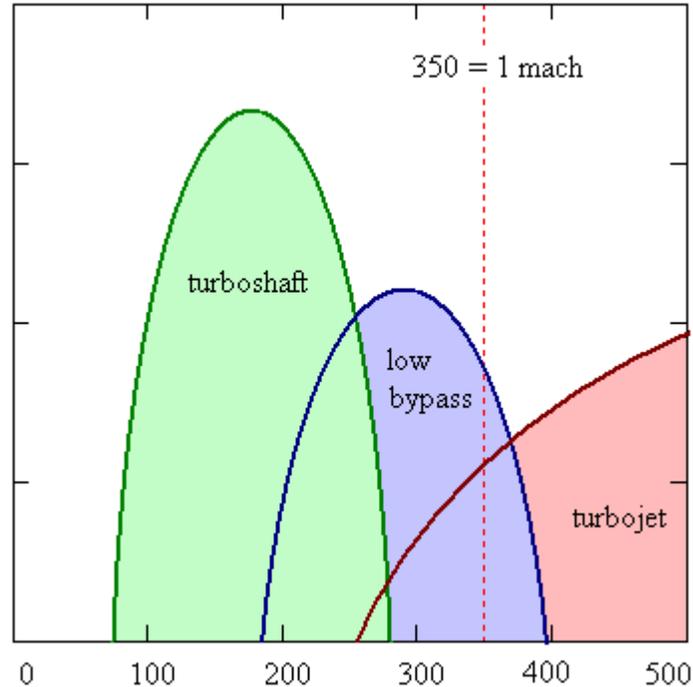
### Thrust-to-weight ratio

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.

<b>Jet or Rocket engine</b>	<b>Mass, kg</b>	<b>Jet or rocket thrust, kN</b>	<b>Thrust-to-weight ratio</b>
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
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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 ( $c_1$  and  $c_2$ ). The thrust of such engine is

$$S = m_1 (c_1 - v) + m_2 (c_2 - v)$$

where  $m_1$  and  $m_2$  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.

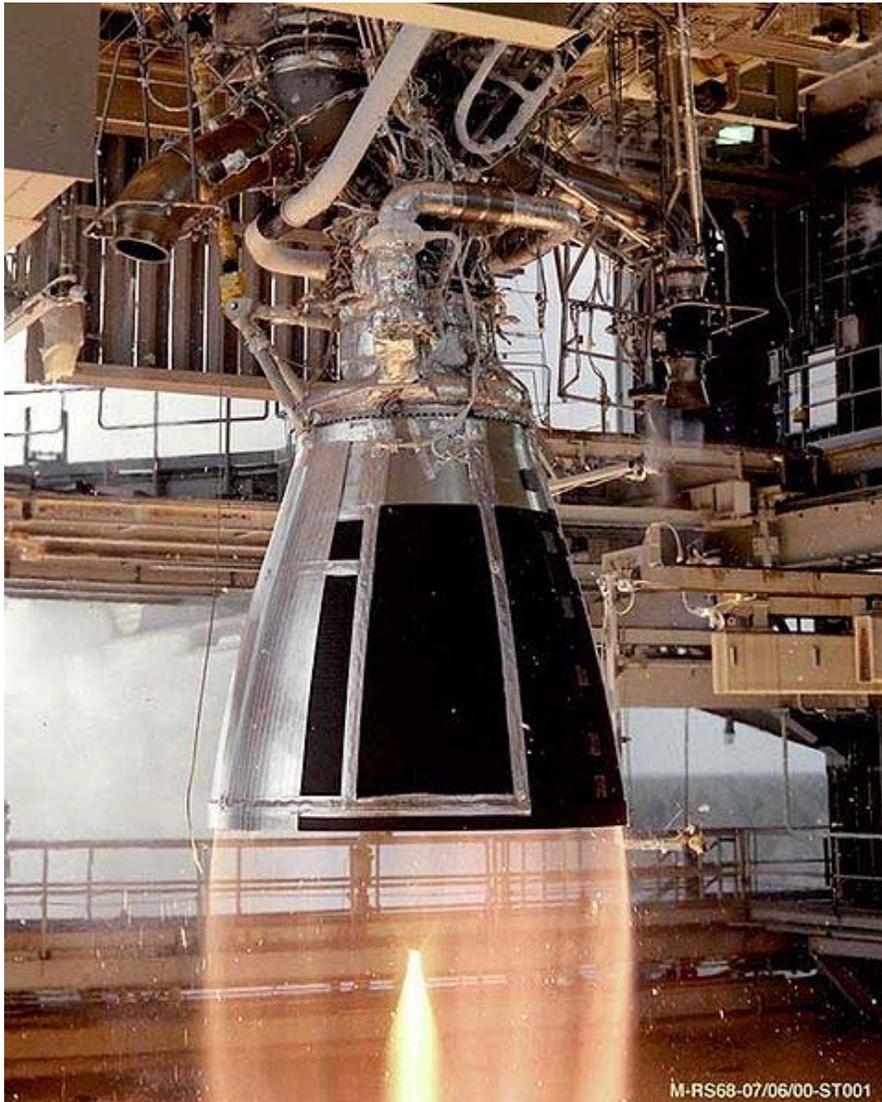
## **Noise**

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- 7

# 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.

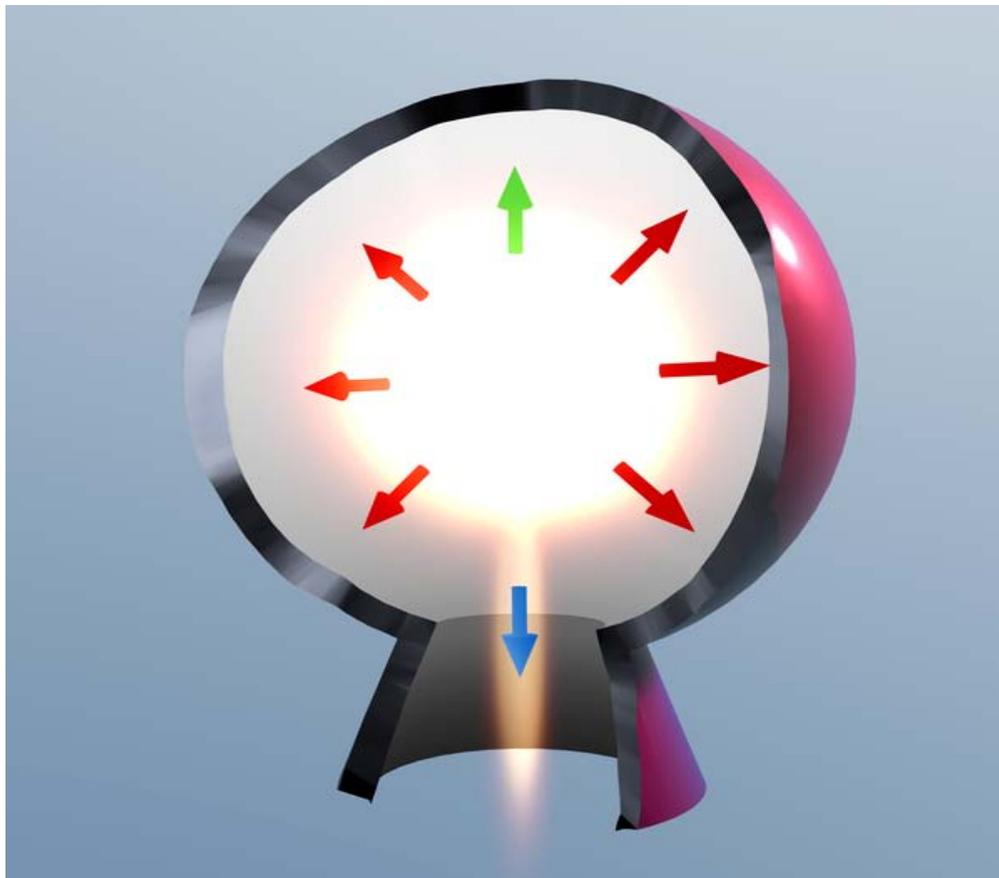
**Rocket motor** (or **solid-propellant rocket motor**) is a synonymous term with rocket engine that usually refers to solid rocket engines.

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

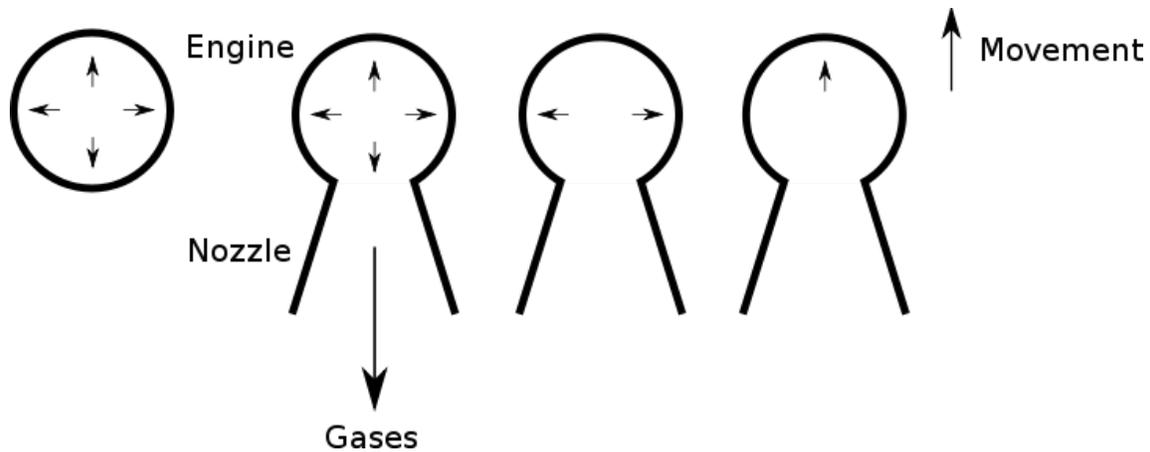
**Hybrid rockets** have a solid propellant in the combustion chamber and a second liquid or gas propellant is added to permit it to burn.

**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***



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



How rocket engines work

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.

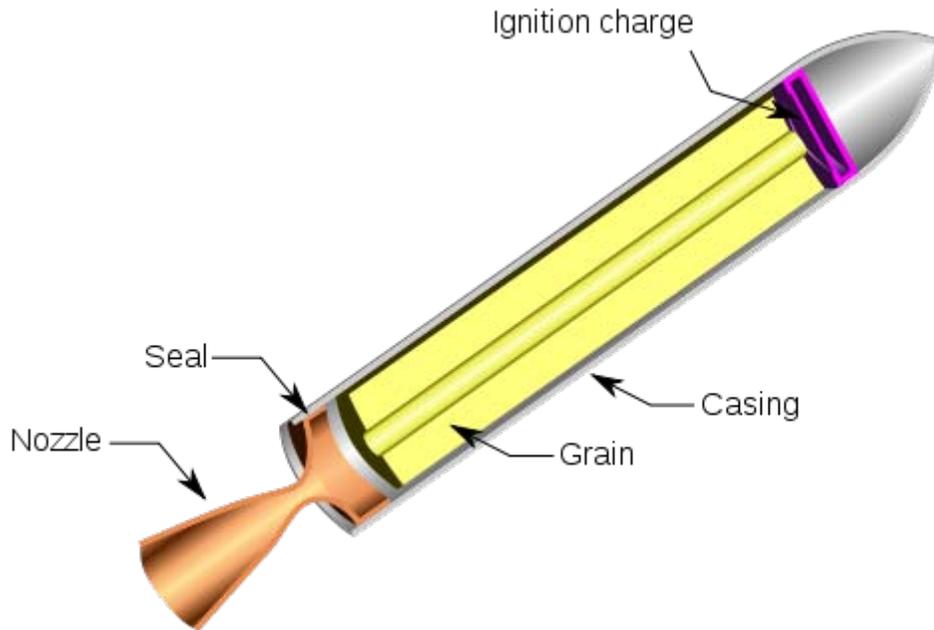
The fluid exhaust is then passed through a propelling nozzle which typically uses the heat energy of the gas to accelerate the exhaust to very high speed, and the reaction to this pushes the engine in the opposite direction.

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  $L^*$  :

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

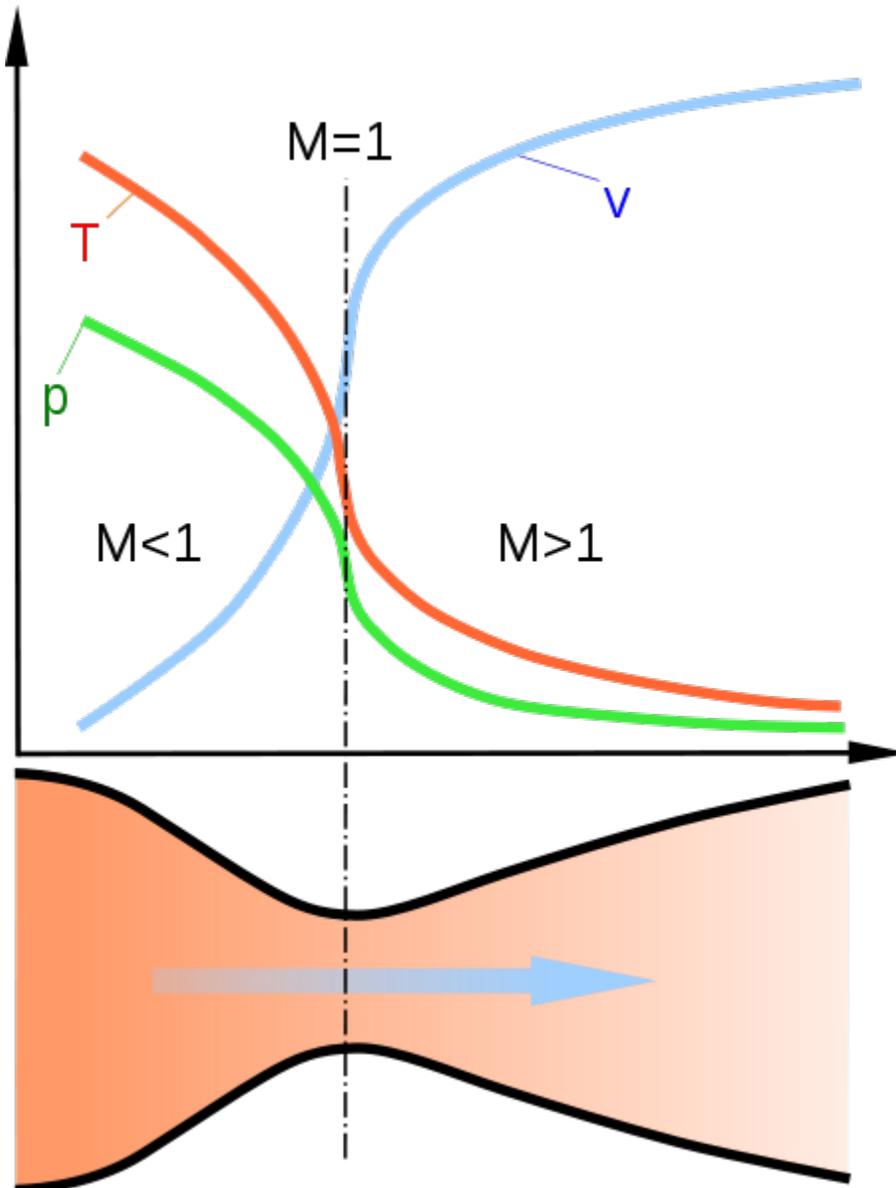
where:

- $V_c$  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



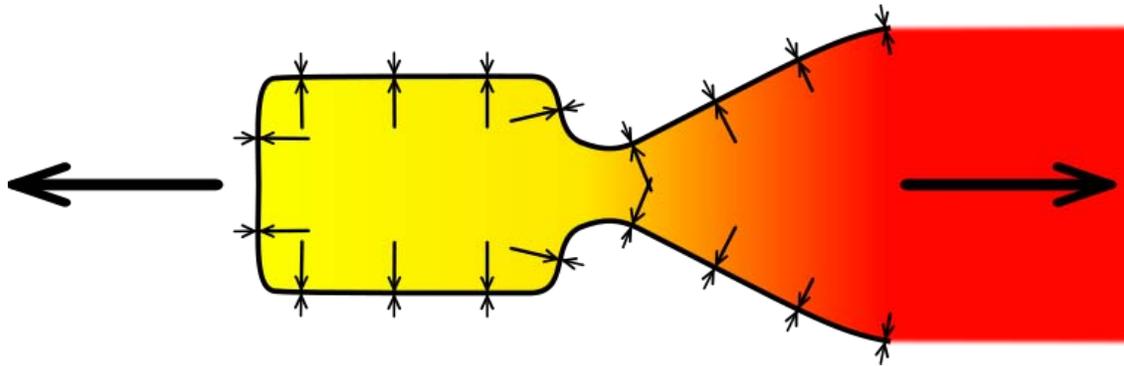
Typical temperatures (T) and pressures (p) and speeds (v) in a De Laval Nozzle

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)

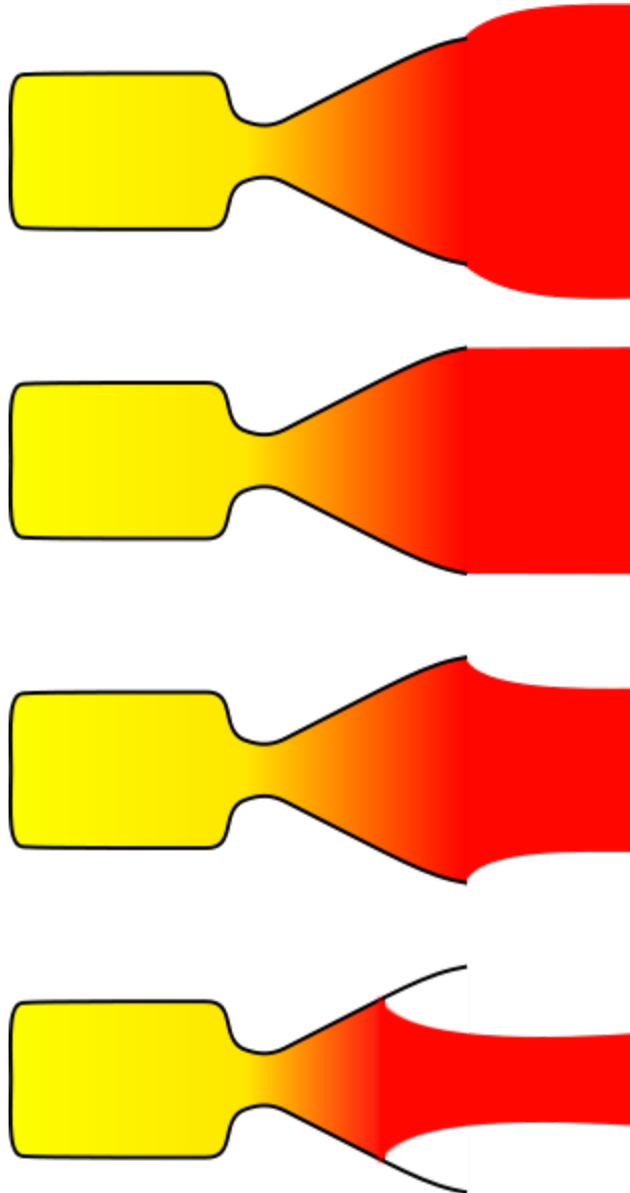
$P_e$  = static pressure at nozzle exit plane

$P_{amb}$  = 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:

$$\begin{aligned} c^* &= \text{the speed of sound constant at the throat} \\ C_f &= \text{the thrust coefficient constant of the nozzle (typically about 2)} \end{aligned}$$

And hence:

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

## Throttling

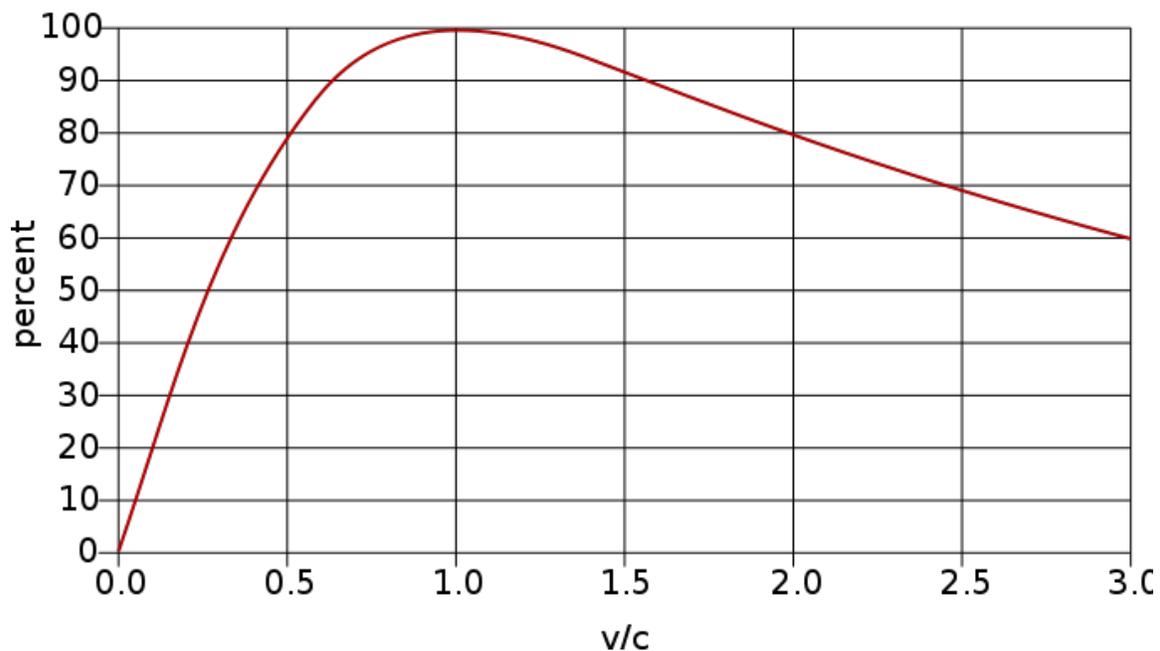
Rockets can be throttled by controlling the propellant combustion rate  $\dot{m}$  (usually measured in kg/s or lb/s). In liquid and hybrid rockets, the propellant flow entering the chamber is controlled using valves, in solid rockets it is controlled by changing the area of propellant that is burning 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

## Propulsive 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.

<b>Jet or Rocket engine</b>	<b>Mass, kg</b>	<b>Jet or rocket thrust, kN</b>	<b>Thrust-to-weight ratio</b>
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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<sup>2</sup>. 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  $\pm 200$  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 (LH<sub>2</sub>) and oxygen (LOX, or LO<sub>2</sub>), 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
<b>water rocket</b>	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)
<b>cold gas thruster</b>	A non combusting form, used for vernier thrusters	Non contaminating exhaust	Extremely low performance
<b>hot water rocket</b>	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
<b>Solid rocket</b>	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.
<b>Hybrid rocket</b>	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.

<b>Monopropellant rocket</b>	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
<b>Liquid Bipropellant rocket</b>	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.
<b>Dual mode propulsion rocket</b>	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
<b>Tripopellant rocket</b>	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
<b>Air-augmented rocket</b>	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.
<b>Turborocket</b>	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.
<b>Precooled jet engine / LACE (combined cycle with rocket)</b>	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
<b>Resistojet rocket (electric heating)</b>	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
<b>Arcjet rocket (chemical burning aided by electrical discharge)</b>	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.
<b>Pulsed plasma thruster (electric arc heating; emits plasma)</b>	Plasma is used to erode a solid propellant	High $I_{sp}$ , can be pulsed on and off for attitude control	Low energetic efficiency
<b>Variable specific impulse magnetoplasma</b>	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
<b>Solar thermal rocket</b>	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
<b>light beam powered rocket</b>	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
<b>microwave beam powered</b>	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

<b>rocket</b>	vehicle from a distance	~900 seconds exhaust speeds might be achievable	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.
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## 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:

<b>Type</b>	<b>Description</b>	<b>Advantages</b>	<b>Disadvantages</b>
<b>Radioisotope rocket/"Poodle thruster" (radioactive decay energy)</b>	Heat from radioactive decay is used to heat hydrogen	about 700–800 seconds, almost no moving parts	low thrust/weight ratio.
<b>Nuclear thermal rocket (nuclear fission energy)</b>	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.
<b>Gas core reactor rocket (nuclear fission energy)</b>	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.
<b>Fission-fragment rocket (nuclear fission energy)</b>	Fission products are directly exhausted to		Theoretical only at this point.

	give thrust		
<b>Fission sail (nuclear fission energy)</b>	A sail material is coated with fissionable material on one side	No moving parts, works in deep space	Theoretical only at this point.
<b>Nuclear salt-water rocket (nuclear fission energy)</b>	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.
<b>Nuclear pulse propulsion (exploding fission/fusion bombs)</b>	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.
<b>Antimatter catalyzed nuclear pulse propulsion (fission and/or fusion energy)</b>	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.
<b>Fusion rocket (nuclear fusion energy)</b>	Fusion is used to heat propellant	Very high exhaust velocity	Largely beyond current state of the art.
<b>Antimatter rocket (annihilation energy)</b>	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- 8

# Aircraft Engine Controls

**Aircraft engine controls** provide a means for the pilot to control and monitor the operation of the aircraft's powerplant. Here we describes controls used with a basic internal-combustion engine driving a propeller. Some optional or more advanced configurations are described at the end. Jet turbine engines use different operating principles and have their own sets of controls and sensors.

### ***Basic Controls and Indicators***

- **Master Switch** - Most often actually two separate switches, the Battery Master and the Alternator Master. The Battery Master activates a relay (sometimes called the battery contactor) which connects the battery to the aircraft's main electrical bus. The alternator master activates the alternator by applying power to the alternator field circuit. These two switches provide electrical power to all the systems in the aircraft.
- **Throttle** - Sets the desired power level. The throttle controls the mass flow-rate of air (in fuel-injected engines) or air/fuel mixture (in carburetted engines) delivered to the cylinders.
- **Pitch Control** - Adjusts the Constant Speed Unit, which in turn adjusts the propeller pitch & regulates the engine load as necessary to maintain the set R.P.M.
- **Mixture Control** - Sets the amount of fuel added to the intake airflow. At higher altitudes the air pressure (and therefore the oxygen level) declines so the fuel volume must also be reduced to give the correct air/fuel mixture. This process is known as "leaning".
- **Ignition Switch** - Activates the magnetos by opening the grounding or 'p-lead' circuit; with the p-lead ungrounded the magneto is free to send its high-voltage output to the spark plugs. In most aircraft the ignition switch also applies power to the starter motor during engine start. In piston aircraft engines, the battery does not generate the spark for combustion. This is accomplished using devices called magnetos. Magnetos are connected to the engine by gearing. When the crankshaft turns, it turns the magnetos which mechanically generate voltage for spark. In the event of an electrical failure, the engine will continue to run. The Ignition Switch has the following positions:
  1. Off - Both magneto p-leads are connected to electrical ground. This disables both magnetos, no spark is produced.

2. Right - The left magneto p-lead is grounded, and the right is open. This disables the left magneto and enables the right magneto only.
  3. Left - The right magneto p-lead is grounded, and the left is open. This disables the right magneto and enables the left magneto only.
  4. Both - This is the normal operating configuration, both p-leads are open enabling both magnetos.
  5. Start - The pinion gear on the starter motor is engaged with the flywheel and the starter motor runs to turn the engine over. In most cases, only the left magneto is active (the right p-lead is grounded) due to timing differences between the magnetos at low PRMs.
- **Tachometer** - A gauge to indicate engine speed in revolutions per minute (RPM) or percentage of maximum.
  - **Manifold Pressure (MP) Gauge** - Indicates the pressure in the intake manifold.
  - **Oil Temperature Gauge** - Indicates the engine oil temperature.
  - **Oil Pressure Gauge** - Indicates the supply pressure of the engine lubricant.
  - **Exhaust Gas Temperature (EGT) Gauge** - Indicates the temperature of the exhaust gas just after combustion. Used to set the fuel/air mixture (leaning) correctly.
  - **Cylinder Head Temperature (CHT) Gauge** - Indicates the temperature of at least one of the cylinder heads. Used to set the fuel/air mixture.
  - **Carburetor Heat Control** - Controls the application of heat to the carburetor venturi area to remove or prevent the formation of ice in the throat of the carburetor as well as bypassing the air filter in case of impact icing.
  - **Alternate Air** - Bypasses the air filter on a fuel-injected engine.

## **Fuel**

- **Fuel Primer Pump** - A manual pump to add a small amount of fuel at the cylinder intakes to assist in starting a cold engine. Fuel injected engines do not have this control. For fuel injected engines, a fuel boost pump is used to prime the engine prior to start.
- **Fuel Quantity Gauge** - Indicates the amount of fuel remaining in the identified tank. One per fuel tank.
- **Fuel Select Valve** - Connects the fuel flow from the selected tank to the engine.

If the aircraft is equipped with a fuel pump:

- **Fuel Pressure Gauge** - Indicates the supply pressure of fuel to the carburetor (or in the case of a fuel injected engine, to the fuel controller.)
- **Fuel Boost Pump Switch** - Controls the operation of the auxiliary electric fuel pump to provide fuel to the engine before it starts or in case of failure of the engine powered fuel pump. Some large airplanes have a fuel system that allows the flight crew to jettison or dump the fuel. When operated, the boost pumps in the fuel tanks pump the fuel to the dump chutes or jettison nozzles and overboard to atmosphere.

## Propeller

If the aircraft is equipped with adjustable-pitch or constant-speed propeller(s):

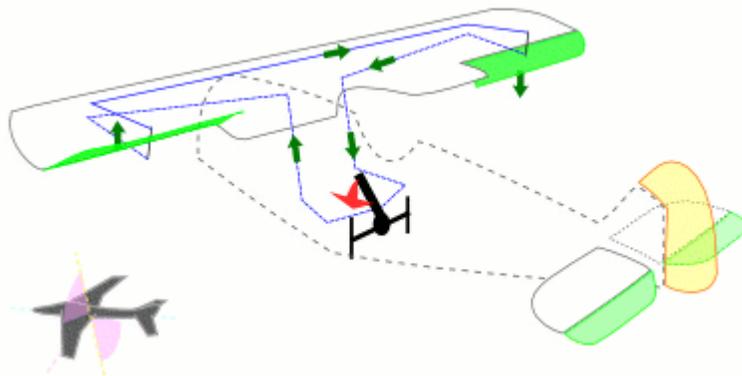
- **Propeller Control** - Used to set the desired propeller speed. Once the pilot has set the desired propeller speed, the propeller governor maintains that propeller speed by adjusting the pitch of the propeller blades, using the engine's oil pressure to move a hydraulic piston in the propeller hub.
- **Manifold Pressure Gauge** - Indicates the (absolute) pressure in the engine's intake manifold. When the engine is running normally, there is a good correlation between the intake manifold pressure and the torque the engine is developing.

## Cowl

If the aircraft is equipped with adjustable Cowl Flaps:

- **Cowl Flap Position Control** - Cowl Flaps are opened during high power/low airspeed operations like takeoff to maximize the volume of cooling airflow over the engine's cooling fins.
- **Cylinder Head Temperature Gauge** - Indicates the temperature of all cylinder heads or on a single CHT system, the hottest head. A Cylinder Head Temperature Gauge has a much shorter response time than the oil temperature gauge, so it can alert the pilot to a developing cooling issue more quickly. Engine overheating may be caused by:
  1. Running too long at a high power setting.
  2. Poor leaning technique.
  3. Restricting the volume of cooling airflow too much.
  4. Insufficient delivery of lubricating oil to the engine's moving parts.

## Aircraft flight control system



A typical aircraft's primary flight controls in motion

A conventional fixed-wing **aircraft flight control system** consists of flight control surfaces, the respective cockpit controls, connecting linkages, and the necessary operating mechanisms to control an aircraft's direction in flight. Aircraft engine controls are also considered as flight controls as they change speed.

The fundamentals of aircraft controls are explained in flight dynamics.

## ***Cockpit controls***

### **Primary controls**

Generally the primary cockpit controls are arranged as follows:

- A control column or a control yoke attached to a column—for roll and pitch, which moves the ailerons when turned or deflected left and right, and moves the elevators when moved backwards or forwards
- Rudder pedals to control yaw, which move the rudder; left foot forward will move the rudder left for instance.
- Throttle controls to control engine speed or thrust for powered aircraft.

Even when an aircraft uses different kinds of surfaces, such as a V-tail/ruddervator, flaperons, or elevons, to avoid pilot confusion the aircraft will still normally be designed so that the yoke or stick controls pitch and roll in the conventional way, as will the rudder pedals for yaw.

### **Secondary controls**

In addition to the primary flight controls for roll, pitch, and yaw, there are often secondary controls available to give the pilot finer control over flight or to ease the workload. The most commonly-available control is a wheel or other device to control elevator trim, so that the pilot does not have to maintain constant backward or forward pressure to hold a specific pitch attitude (other types of trim, for rudder and ailerons, are common on larger aircraft but may also appear on smaller ones). Many aircraft have wing flaps, controlled by a switch or a mechanical lever or in some cases are fully automatic by computer control, which alter the shape of the wing for improved control at the slower speeds used for takeoff and landing. Other secondary flight control systems may be available, including slats, spoilers, air brakes and variable-sweep wings.

## ***Basic flight control systems***

### **Mechanical**



de Havilland Tiger Moth elevator and rudder cables

Mechanical or manually-operated flight control systems are the most basic method of controlling an aircraft. They were used in early aircraft and are currently used in small aircraft where the aerodynamic forces are not excessive. Very early aircraft used a system of wing warping where no movable control surfaces were used, except for the rudder. A manual flight control system uses a collection of mechanical parts such as rods, tension cables, pulleys, counterweights, and sometimes chains to transmit the forces applied to the cockpit controls directly to the control surfaces. Turnbuckles are often used to adjust control cable tension. The Cessna Skyhawk is a typical example of an aircraft that uses this type of system. Gust locks are often used on parked aircraft with mechanical systems to protect the control surfaces and linkages from damage from wind. Some aircraft have gust locks fitted as part of the control system.

Increases in the control surface area required by large aircraft or higher loads caused by high airspeeds in small aircraft lead to a large increase in the forces needed to move them, consequently complicated mechanical gearing arrangements were developed to extract maximum mechanical advantage in order to reduce the forces required from the

pilots. This arrangement can be found on bigger or higher performance propeller aircraft such as the Fokker 50.

Some mechanical flight control systems use servo tabs that provide aerodynamic assistance. Servo tabs are small surfaces hinged to the control surfaces. The flight control mechanisms move these tabs, aerodynamic forces in turn move, or assist the movement of the control surfaces reducing the amount of mechanical forces needed. This arrangement was used in early piston-engined transport aircraft and in early jet transports. The Boeing 737 incorporates a system, whereby in the unlikely event of total hydraulic system failure, it automatically and seamlessly reverts to being controlled via servo-tab.

## Hydro-mechanical

The complexity and weight of mechanical flight control systems increase considerably with the size and performance of the aircraft. Hydraulically powered control surfaces help to overcome these limitations. With hydraulic flight control systems, the aircraft's size and performance are limited by economics rather than a pilot's muscular strength. At first, only-partially boosted systems were used in which the pilot could still feel some of the aerodynamic loads on the control surfaces (feedback).

A hydro-mechanical flight control system has two parts:

- The *mechanical circuit*, which links the cockpit controls with the hydraulic circuits. Like the mechanical flight control system, it consists of rods, cables, pulleys, and sometimes chains.
- The *hydraulic circuit*, which has hydraulic pumps, reservoirs, filters, pipes, valves and actuators. The actuators are powered by the hydraulic pressure generated by the pumps in the hydraulic circuit. The actuators convert hydraulic pressure into control surface movements. The electro-hydraulic servo valves control the movement of the actuators.

The pilot's movement of a control causes the mechanical circuit to open the matching servo valve in the hydraulic circuit. The hydraulic circuit powers the actuators which then move the control surfaces. As the actuator moves, the servo valve is closed by a mechanical feedback linkage - one that stops movement of the control surface at the desired position.

This arrangement was found in the older-designed jet transports and in some high-performance aircraft. Examples include the Antonov An-225 and the Lockheed SR-71.

## Artificial feel devices

With purely mechanical flight control systems, the aerodynamic forces on the control surfaces are transmitted through the mechanisms and are felt directly by the pilot. This gives tactile feedback of airspeed and aids flight safety.

With hydromechanical flight control systems however, the load on the surfaces cannot be felt and there is a risk of overstressing the aircraft through excessive control surface movement. To overcome this problem artificial feel systems are used. For example, for the controls of the RAF's Avro Vulcan jet bomber and the RCAF's Avro Canada CF-105 Arrow supersonic interceptor, both 1950's-era designs, the required force feedback was achieved by a spring device. The fulcrum of this device was moved in proportion to the square of the air speed (for the elevators) to give increased resistance at higher speeds. For the controls of the American Vought F-8 Crusader and the LTV A-7 Corsair II warplanes, a "bob-weight" was used in the pitch axis of the control stick, giving force feedback that was proportional to the airplane's normal acceleration.

### **Stick shaker**

A stick shaker is a device (available in some hydraulic aircraft) which is fitted into the control column which shakes the control column when the aircraft is about to stall. Also in some aircraft like the McDonnell Douglas DC-10 there is/was a back-up electrical power supply which the pilot can turn on to re-activate the stick shaker in case the hydraulic connection to the stick shaker is lost.

### ***Fly-by-wire control systems***

A fly-by-wire (FBW) system replaces manual flight control of an aircraft with an electronic interface. The movements of flight controls are converted to electronic signals transmitted by wires (hence the fly-by-wire term), and flight control computers determine how to move the actuators at each control surface to provide the expected response. Commands from the computers are also input without the pilot's knowledge to stabilize the aircraft and perform other tasks.

### ***Fluidic flight controls***

Conventional mechanical flight control surfaces may also be replaced completely, by a fluidic flight control system, provided by differential streams of blown air, such as with the Demon (UAV), aircraft which flew for the first time, in the UK, in September 2010.