AIRCRAFT ENGINES

A Brief Study - K C Avatar

Contents

Chapter 1

Turbojet

The **turbojet** is a jet engine, usually used in aircraft. It consists of a gas turbine with a propelling nozzle. The gas turbine has an air inlet, a compressor, a combustion chamber, and a turbine (that drives the compressor). The compressed air from the compressor is heated by the fuel in the combustion chamber and then allowed to expand through the turbine. The turbine exhaust is then expanded in the propelling nozzle where it is accelerated to high speed to provide thrust.[1] Two engineers, Frank Whittle in the United Kingdom and Hans von Ohain in Germany, developed the concept independently into practical engines during the late 1930s.

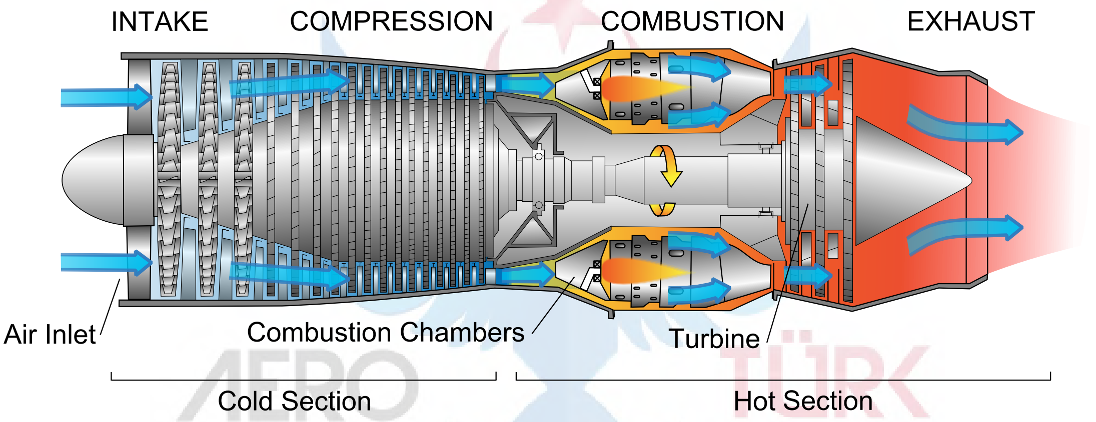


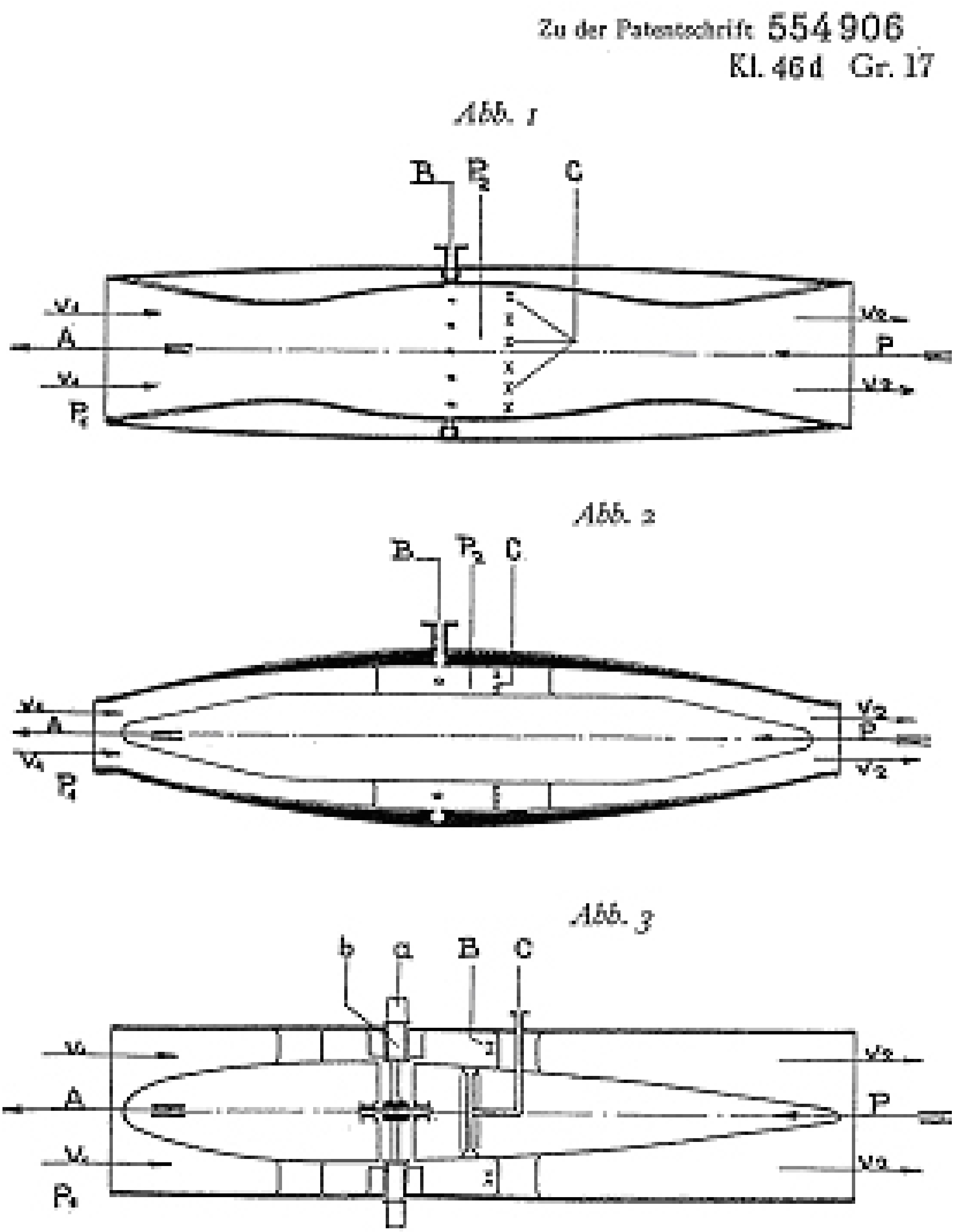
Diagram of a typical gas turbine jet engine

Turbojets have been replaced in slower aircraft by turboprops which use less fuel. At higher speeds, where the propeller is no longer efficient, they have been replaced by turbofans. The turbofan is quieter and uses less fuel than the turbojet. Turbojets are still common in medium range cruise missiles, due to their high exhaust speed, small frontal area, and relative simplicity.

The jet engine is only efficient at high vehicle speeds, which limits their usefulness apart from aircraft. Turbojet engines have been used in isolated cases to power vehicles other than aircraft, typically for attempts on land speed records. Where vehicles are 'turbine powered' this is more commonly by use of a turboshaft engine, a development of the gas turbine engine where an additional turbine is used to drive a rotating output shaft. These are common in helicopters and hovercraft. Turbojets have also been used experimentally to clear snow from switches in railyards.

1.1 History

The first patent for using a gas turbine to power an aircraft was filed in 1921 by Frenchman Maxime Guillaume.[2] His engine was to be an axial-flow turbojet, but was never constructed, as it would have required considerable advances over the state of the art in compressors.



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

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

The centrifugal-flow turbojet was first patented in 1930 by Frank Whittle of the Royal Air Force, and in Germany, Hans von Ohain patented a similar engine in 1935.[3]

The first turbojet to run was the Power Jets WU which ran on 12 April 1937.

On 27 August 1939 the Heinkel He 178 became the world's first aircraft to fly under turbojet power with test-pilot Erich Warsitz at the controls,[4] thus becoming the first practical jet plane. The first two operational turbojet aircraft,

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

the Messerschmitt Me 262 and then the Gloster Meteor entered service towards the end of World War II in 1944.

Air is drawn into the rotating compressor via the intake and is compressed to a higher pressure before entering the combustion chamber. Fuel is mixed with the compressed air and burns in the combustor. The combustion products leave the combustor and expand through the turbine where power is extracted to drive the compressor. The turbine exit gases still contain considerable energy that is converted in the propelling nozzle to a high speed jet.

The first jet engines were turbojets, with either a centrifugal compressor (as in the Heinkel HeS 3), or Axial compressors (as in the Junkers Jumo 004) which gave a smaller diameter, although longer, engine. By replacing the propeller used on piston engines with a high speed jet of exhaust higher aircraft speeds were attainable.

One of the last applications for a turbojet engine was the Concorde which used the Olympus 593 engine. At the time of its design the turbojet was still seen as the optimum for cruising at twice the speed of sound despite the advantage of turbofans for lower speeds. For the Concorde less fuel was required to produce a given thrust for a mile at Mach 2.0 than a modern high-bypass turbofan such as General Electric CF6 at its Mach 0.86 optimum speed.

Turbojet engines had a significant impact on commercial aviation. Aside from giving faster flight speeds turbojets had greater reliability than piston engines, with some models demonstrating dispatch reliability rating in excess of 99.9%. Pre-jet commercial aircraft were designed with as many as 4 engines in part because of concerns over in-flight failures. Overseas flight paths were plotted to keep planes within an hour of a landing field, lengthening flights. The increase in reliability that came with the turbojet enabled three and two-engine designs, and more direct long-distance flights.[5]

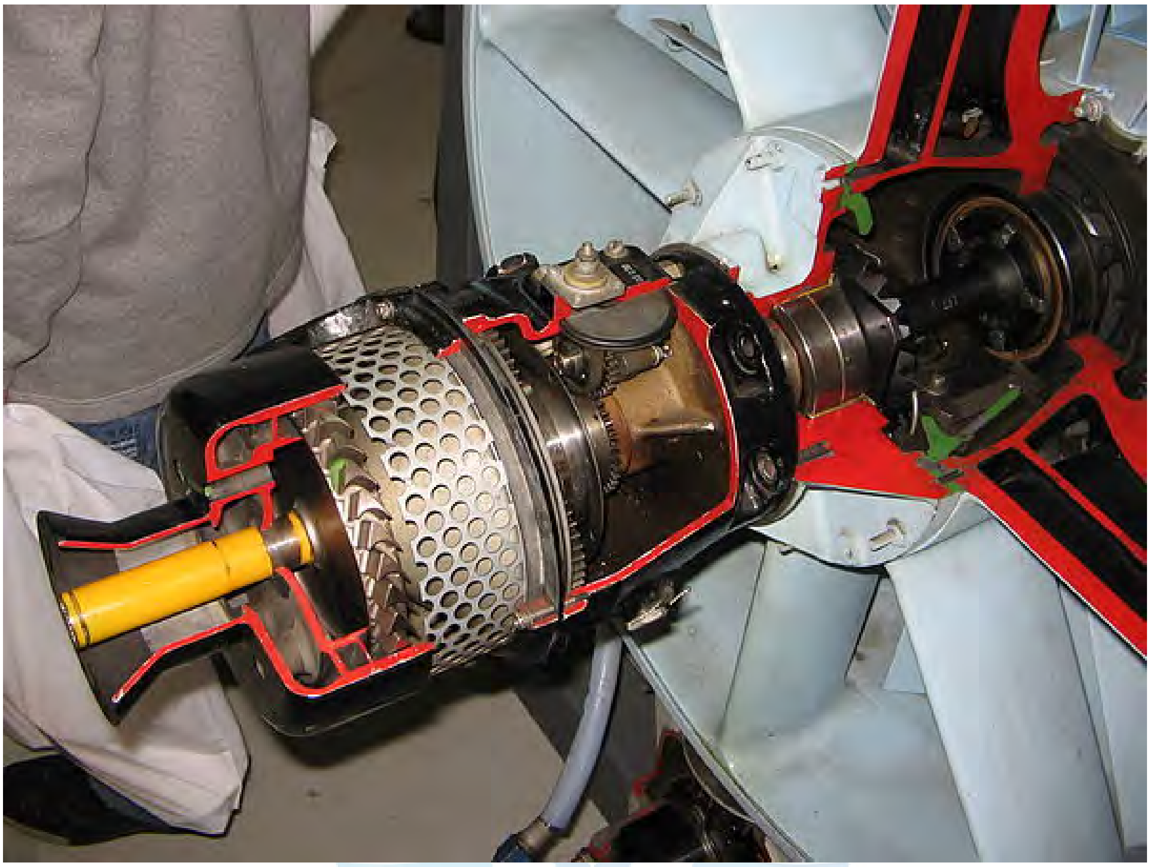
High-temperature alloys were a reverse salient, a key technology that dragged progress on jet engines. Jet engines built in the 1930s and 1940s had to be overhauled every 10 or 20 hours due to creep failure and other types of damage to blades. It was not until the 1950s that superalloy technology allowed more economically practical engines. [6]

1.2 Early designs

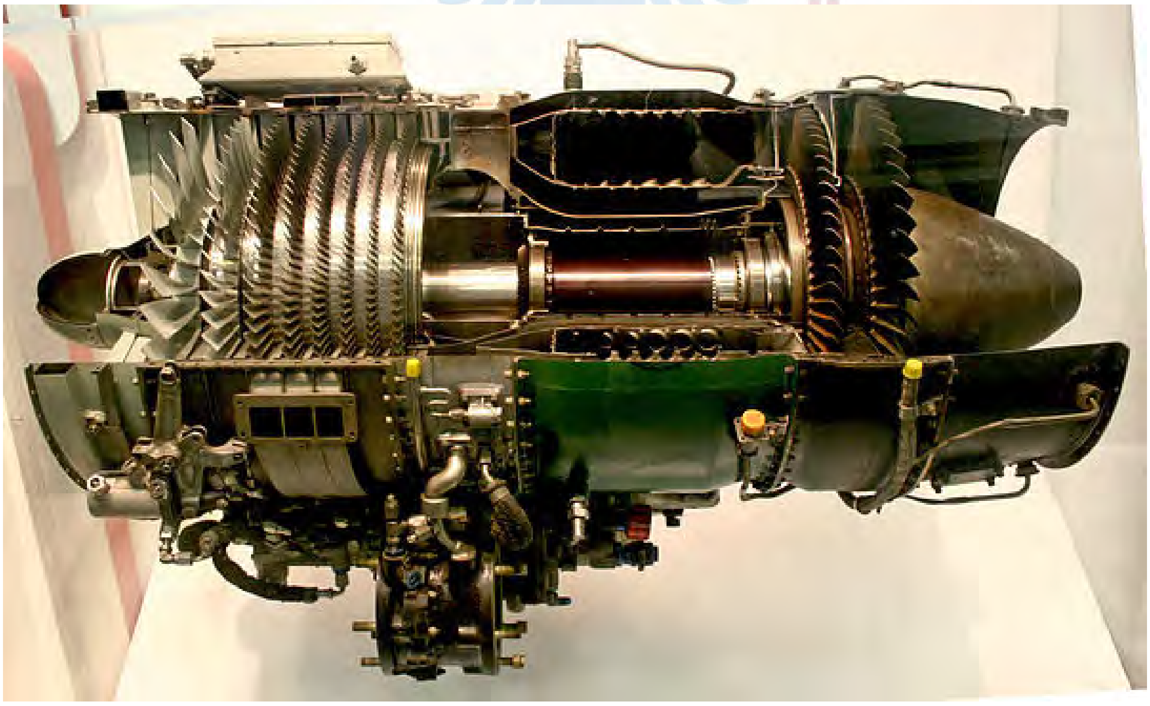
Early German turbojets had severe limitations on the amount of running they could do due to the lack of suitable high temperature materials for the turbines. British engines such as the Rolls-Royce Welland used better materials giving improved durability. The Welland was type certificated for 80 hours initially, later extended to 150 hours between overhauls, as a result of an extended 500 hour run being achieved in tests.[7] A few of the original fighters still exist with their original engines, but many have been re-engined with more modern engines with greater fuel efficiency and a longer TBO (such as the reproduction Me-262 powered by General Electric J85s).

General Electric in the United States was in a good position to enter the jet engine business due to its experience with the high temperature materials used in their turbosuperchargers during World War II.[8]

Water injection was a common method used to increase thrust,usually during takeoff, in early turbojets that were thrust-limited by their allowable turbine entry temperature. The water, whilst it increased thrust at the temperature



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



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

limit, prevented complete combustion often leaving a very visible smoke trail.

Allowable turbine entry temperatures have increased steadily over time both with the introduction of superior alloys, and coatings, and with the introduction and progressive effectiveness of blade cooling designs. On early engines the turbine temperature limit had to be monitored, and avoided, by the pilot, typically during starting and at maximum thrust settings. Automatic temperature limiting was introduced to reduce pilot workload and reduce the liklehood of turbine damage due to overtemperature.

1.3 Design

1.3.1 Air intake

An intake, or tube, is needed in front of the compressor to help direct the incoming air smoothly into the moving compressor blades. Older engines had stationary vanes in front of the moving blades. These vanes also helped to direct the air onto the blades. The intake is also shaped to minimise any flow losses when the compressor is accelerating the air through the intake at zero and low aircraft speeds, and to slow the flow down for the compressor when the aircraft is operating above Mach 1. The air flowing into a turbojet engine must always be subsonic, regardless of the speed of the aircraft itself.

1.3.2 Compressor

The compressor is driven by the turbine. It rotates at high speed, adding energy to the airflow and at the same time squeezing (compressing) it into a smaller space. Compressing the air increases its pressure and temperature. The smaller the compressor the faster it turns. At the large end of the range the GE-90-115 fan rotates at about 2,500 RPM while a small helicopter engine compressor rotates at about 50,000 RPM.

In most turbojet-powered aircraft, bleed air is extracted from the compressor section at various stages to perform a variety of jobs including air conditioning/pressurization, engine inlet anti-icing and turbine cooling. Bleeding air off decreases the overall efficiency of the engine, but the usefulness of the compressed air outweighs the loss in efficiency.

Compressor types used in turbojets were typically axial or centrifugal.

Early turbojet compressors had overall pressure ratios as low as 5:1. Aerodynamic improvements including splitting the compressor into two separately rotating parts, incorporating variable blade angles for entry guide vanes and stators, enabled later turbojets to have overall pressure ratios of 15:1 or more. For comparison, modern civil turbofan engines have overall pressure ratios of 44:1 or more.

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

1.3.3 Combustion chamber

The burning process in the combustor is significantly different from that in a piston engine. In a piston engine the burning gases are confined to a small volume and, as the fuel burns, the pressure increases. In a turbojet the air and fuel mixture burn in the combustor and pass through to the turbine in a continuous flowing process with no pressure build-up. Instead there is a small pressure loss in the combustor.

The fuel-air mixture can only burn in slow moving air so an area of reverse flow is maintained by the fuel nozzles for the approximately stoichiometric burning in the primary zone. Further compressor air is introduced which completes the combustion process and reduces the temperature of the combustion products to a level which the turbine can accept. Less than 25% of the air is typically used for combustion, as an overall lean mixture is required to keep within the turbine temperature limits.

1.3.4 Turbine

Hot gases leaving the combustor expand through the turbine. Typical materials for turbines include inconel and Nimonic.[9] The turbine vanes and blades have internal cooling passages. Air from the compressor is passed through these to keep the metal temperature within limits.

In the first stage the turbine is largely an impulse turbine (similar to a pelton wheel) and rotates because of the impact of the hot gas stream. Later stages are convergent ducts that accelerate the gas. Energy is transferred into the shaft through momentum exchange in the opposite way to energy transfer in the compressor. The power developed by the turbine drives the compressor as well as accessories, like fuel, oil, and hydraulic pumps that are driven by the accessory gearbox.

1.3.5 Nozzle

Main article: propelling nozzle

After the turbine, the gases expand through the exhaust nozzle producing a high velocity jet. In a convergent nozzle, the ducting narrows progressively to a throat. The nozzle pressure ratio on a turbojet is high enough at higher thrust settings to cause the nozzle to choke.

If, however, a convergent-divergent de Laval nozzle is fitted, the divergent (increasing flow area) section allows the gases to reach supersonic velocity within the divergent section. Additional thrust is generated by the higher resulting exhaust velocity.

1.3.6 Thrust augmentation

Thrust was most commonly increased in turbojets with water/methanol injection or afterburning. Some engines used both at the same time.

Afterburner

Main article: afterburner

An afterburner or "reheat jetpipe" is a combustion chamber added to reheat the turbine exhaust gases. The fuel consumption is very high, typically four times that of the main engine. Afterburners are used almost exclusively on supersonic aircraft, most being military aircraft. Two supersonic airliners, Concorde and the TU-144, also used afterburners as does Scaled Composites White Knight, a carrier aircraft for the experimental SpaceShipOne suborbital spacecraft.

1.4 Net thrust

The net thrust F_N of a turbojet is given by:[10][11]

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

where:

If the speed of the jet is equal to sonic velocity the nozzle is said to be choked. If the nozzle is *choked* the pressure at the nozzle exit plane is greater than atmospheric pressure, and extra terms must be added to the above equation to account for the *pressure thrust*.[12]

The rate of flow of fuel entering the engine is very small compared with the rate of flow of air.[10] If the contribution of fuel to the nozzle gross thrust is ignored, the net thrust is:

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

The speed of the jet V_j must exceed the true airspeed of the aircraft V if there is to be a net forward thrust on the airframe. The speed V_j can be calculated thermodynamically based on adiabatic expansion.[13]

1.5 Cycle improvements

The operation of a typical turbojet is modelled approximately by the Brayton Cycle.

The efficiency of a gas turbine is increased by raising the overall pressure ratio, requiring higher temperature compressor materials, and raising the turbine entry temperature, requiring better turbine materials and/or improved vane/blade cooling. However, when used in a turbojet application, where the output from the gas turbine is used in a propelling nozzle, raising the turbine temperature increases the jet velocity. This reduces the propulsive efficiency giving a loss in overall efficiency, as reflected by the higher fuel consumption, or SFC.[14]

1.6 See also

- Air start system
- Brayton Cycle
- Exoskeletal engine
- Jet dragster
- Turbojet development at the RAE
- Turbine engine failure
- Variable Cycle Engine

1.7 Notes

[1] "Turbojet Engine". NASA Glenn Research Center. Retrieved 2009-05-06.

[2] Maxime Guillaume,"Propulseur par réaction sur l'air," French patent FR 534801 (filed: 3 May 1921; issued: 13 January 1922)

[3] Experimental & Prototype US Air Force Jet Fighters, Jenkins & Landis, 2008

[4] Warsitz, Lutz: *THE FIRST JET PILOT - The Story of German Test Pilot Erich Warsitz* (p. 125), Pen and Sword Books Ltd., England, 2009, ISBN 978-1-84415-818-8

[5] Larson, George C. (April–May 2010), *Old Faithful*, *"Air & Space"* **25** (1): 80

[6] Sims, C.T., Chester, A History of Superalloy Metallurgy, Proc. 5th Symp. on Superalloys, 1984.

[7] "Rolls-Royce Derwent | 1945". *Flight* (Flightglobal.com): 448. 1945-10-25. Retrieved 2013-12-14.

[8] "Starting Something Big" Robert V. Garvin ISBN1-56347-289-2, p5

[9] 1960 | Flight | Archive

[10] Cumpsty, Nicholas (2003). "3.1". *Jet Propulsion* (2nd ed.). Cambridge University Press. ISBN 0-521-54144-1.

[11] "Turbojet Thrust". NASA Glenn Research Center. Retrieved 2009-05-06.

[12] Cumpsty, Jet Propulsion, Section 6.3

[13] MIT.EDU Unified: Thermodynamics and Propulsion Prof. Z. S. Spakovszky - Turbojet Engine

[14] "Gas Turbine Theory" Cohen, Rogers, Saravanamuttoo, ISBN 0 582 44927 8, p72-73, fig 3.11

1.8 References

- Springer, Edwin H. (2001). *Constructing A Turbocharger Turbojet Engine*. Turbojet Technologies.

1.9 External links

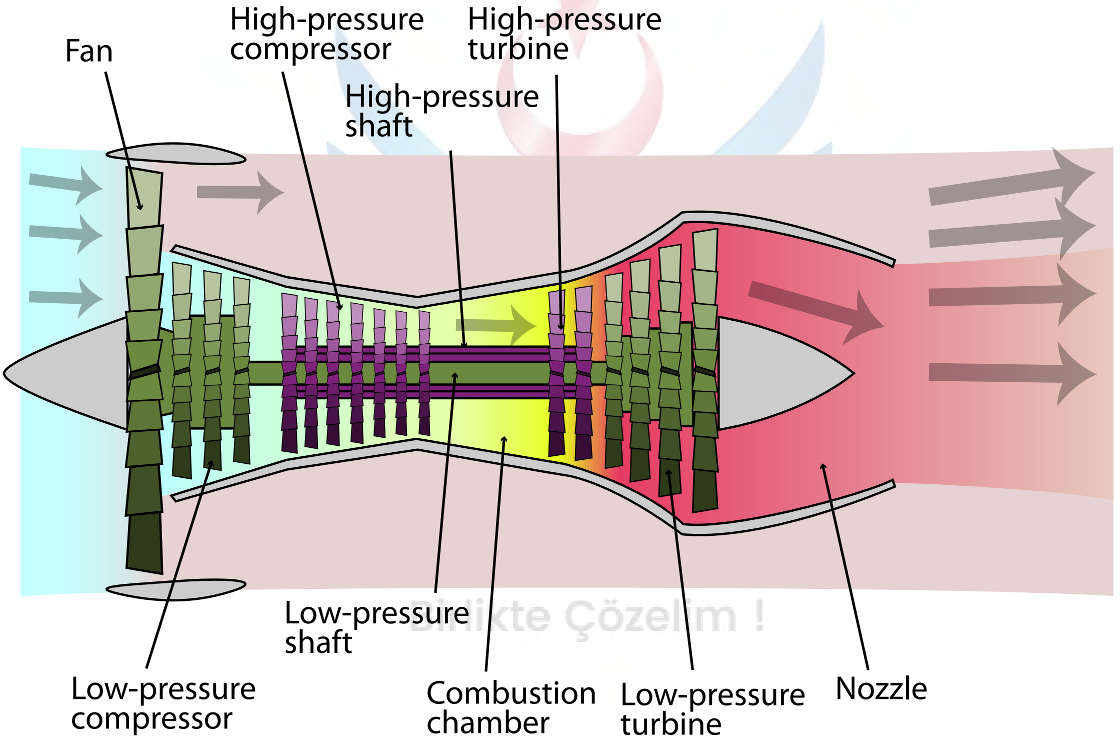
- Erich Warsitz, the world's first jet pilot: includes rare videos (Heinkel He 178) and audio commentaries]
- NASA Turbojet Engine Description: includes a software model]

Chapter 2

Turbofan

Not to be confused with propfan.

The **turbofan** or **fanjet** is a type of airbreathing jet engine that finds wide use in aircraft propulsion. The word "turbofan" is a portmanteau of "turbine" and "fan": the *turbo* portion refers to a gas turbine engine which takes mechanical energy from combustion,[1] and the *fan*, a ducted fan that uses the mechanical energy from the gas turbine to accelerate air rearwards. Thus, whereas all the air taken in by a turbojet passes through the turbine (through the combustion chamber), in a turbofan some of that air bypasses the turbine. A turbofan thus can be thought of as a turbojet being used to drive a ducted fan, with both of those contributing to the thrust. The ratio of the mass-flow of air bypassing the engine core compared to the mass-flow of air passing through the core is referred to as the bypass ratio. The engine produces thrust through a combination of these two portions working in concert; engines that use more jet thrust relative to fan thrust are known as *low bypass turbofans*, conversely those that have considerably more fan thrust than jet thrust are known as *high bypass*. Most commercial aviation jet engines in use today are of the high-bypass type, and most modern military fighter engines are low-bypass. Afterburners are not used on high-bypass turbofan engines but may be used on either low-bypass turbofan or turbojet engines.



Schematic diagram of a high-bypass turbofan engine

Most of the air flow through a high-bypass turbofan is low-velocity bypass flow: even when combined with the much

GE90 turbofan on a Boeing 777-200LR

higher velocity engine exhaust, the net average exhaust velocity is considerably lower than in a pure turbojet. Engine noise is largely a function of exhaust velocity, therefore turbofan engines are significantly quieter than a pure-jet of the same thrust. Other factors include turbine blade and exhaust outlet geometries, such as noise-reducing "chevrons" seen on the Rolls-Royce Trent 1000 and General Electric GEnx engines used on the Boeing 787.

Since the efficiency of propulsion is a function of the relative airspeed of the exhaust to the surrounding air, propellers are most efficient for low speed, pure jets for high speeds, and ducted fans in the middle. Turbofans are thus the most

The CFM56 medium-size turbofan

efficient engines in the range of speeds from about 500 to 1,000 km/h (310 to 620 mph), the speed at which most commercial aircraft operate.[2][3] Turbofans retain an efficiency edge over pure jets at low supersonic speeds up to roughly Mach 1.6, but have also been found to be efficient when used with continuous afterburner at Mach 3 and above.

The vast majority of turbofans follow the same basic design, with a large fan at the front of the engine and a relatively small jet engine behind it. There have been a number of variations on this design, however, including rear-mounted fans which can easily be added to an existing pure-jet design, or designs that combine a low-pressure turbine and a fan stage in a single rear-mounted unit.

2.1 Early turbofans

Early turbojet engines were very fuel-inefficient, as their overall pressure ratio and turbine inlet temperature were severely limited by the technology available at the time. The very first running turbofan was the German Daimler-Benz DB 670 (designated as the 109-007 by the RLM) which was operated on its testbed on April 1, 1943. The engine was abandoned later while the war went on and problems could not be solved. The British wartime Metrovick F.2 axial flow jet was given a fan, as the Metrovick F.3 in 1943, to create the first British turbofan.[4]

Improved materials, and the introduction of twin compressors such as in the Bristol Olympus[5] and the later Pratt & Whitney JT3C engine, increased the overall pressure ratio and thus the thermodynamic efficiency of engines, but they also led to a poor propulsive efficiency, as pure turbojets have a high specific thrust/high velocity exhaust better suited to supersonic flight.

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

View into the outer (propelling or "cold") nozzle of a GEnx-2B turbofan engine

The unusual General Electric CF700 turbofan engine was developed as an aft-fan engine with a 2.0 bypass ratio. This was derived from the General Electric J85/CJ610 turbojet (2,850 lbf or 12,650 N) to power the larger Rockwell Sabreliner 75/80 model aircraft, as well as the Dassault Falcon 20 with about a 50% increase in thrust (4,200 lbf or 18,700 N). The CF700 was the first small turbofan in the world to be certified by the Federal Aviation Administration (FAA). There are now over 400 CF700 aircraft in operation around the world, with an experience base of over 10 million service hours. The CF700 turbofan engine was also used to train Moon-bound astronauts in Project Apollo as the powerplant for the Lunar Landing Research Vehicle. The CJ805-23 was a similar, but larger, design.

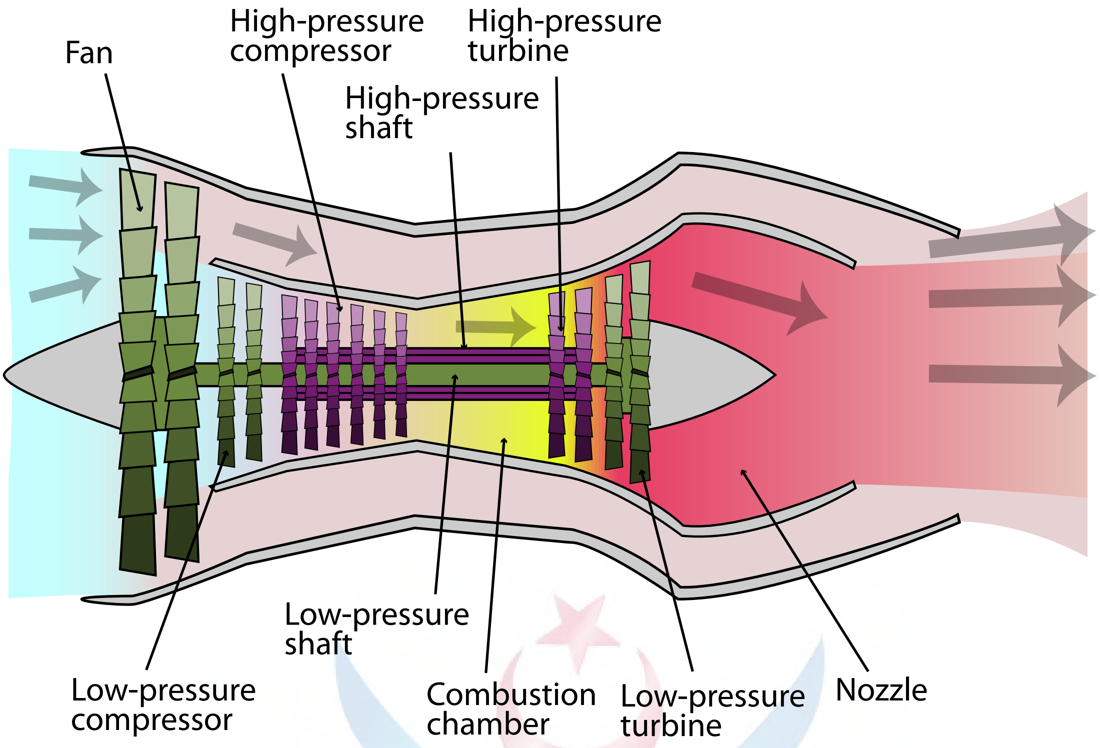
2.2 Low-bypass turbofan

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

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

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

A few low-bypass ratio military turbofans (e.g., F404) have Variable Inlet Guide Vanes, with piano-style hinges, to



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

direct air onto the first rotor stage. This improves the fan surge margin (see compressor map) in the mid-flow range. The swing wing F-111 achieved a very high range/payload capability by pioneering this, and it was also the heart of the famous F-14 Tomcat air superiority fighter which used the same engines in a smaller, more agile airframe to achieve efficient cruise and Mach 2 speed.

2.3 Afterburning turbofan

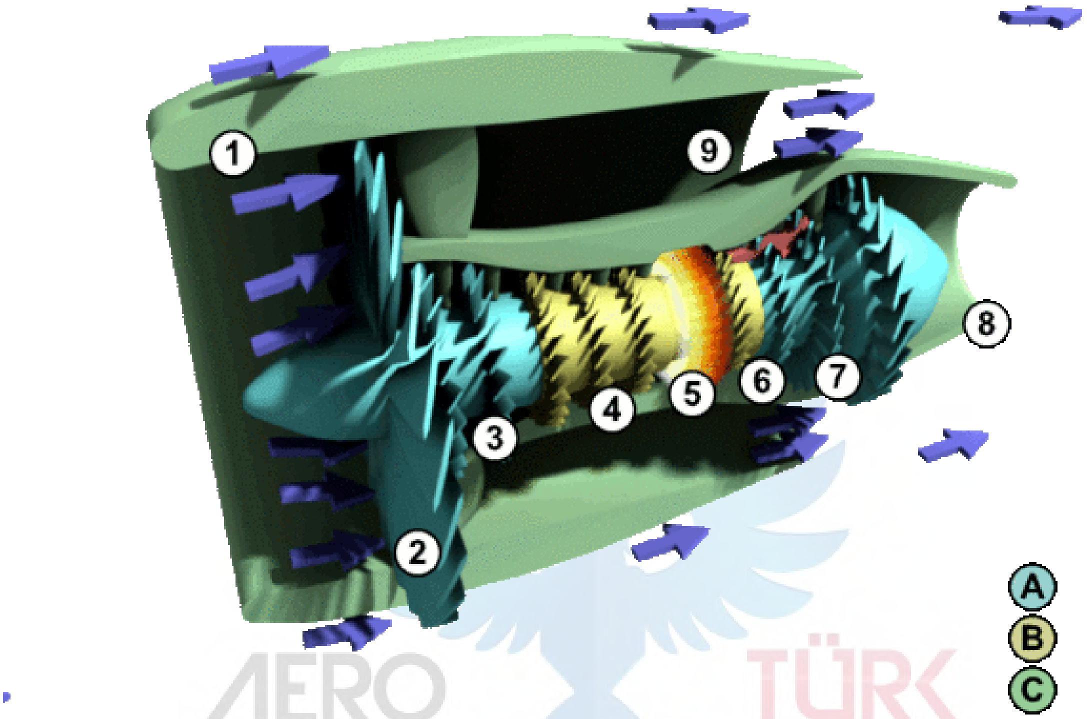
Since the 1970s, most jet fighter engines have been low/medium bypass turbofans with a mixed exhaust, afterburner and variable area final nozzle. An afterburner is a combustor located downstream of the turbine blades and directly upstream of the nozzle, which burns fuel from afterburner-specific fuel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

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

Modern low-bypass military turbofans include the Pratt & Whitney F119, the Eurojet EJ200, the General Electric

F110, the Klimov RD-33, and the Saturn AL-31, all of which feature a mixed exhaust, afterburner and variable area propelling nozzle.

2.4 High-bypass turbofan

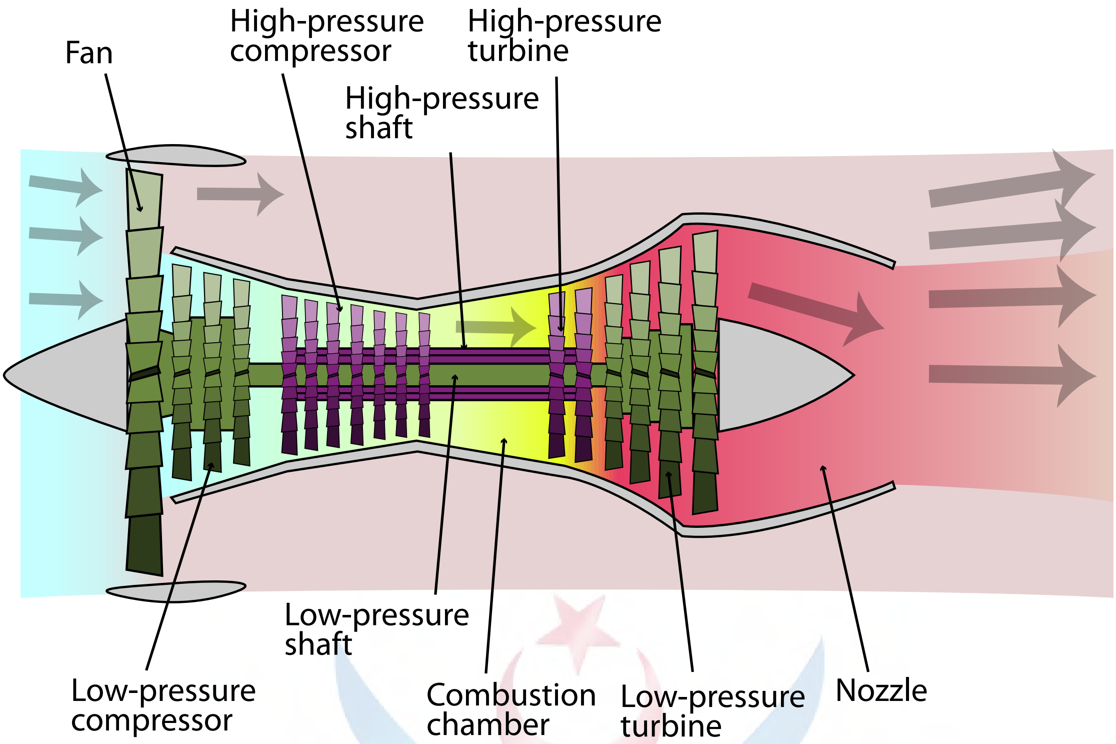


Animation of a 2-spool, high-bypass turbofan.
A. Low-pressure spool
B. High-pressure spool
C. Stationary components
1. Nacelle
2. Fan
3. Low-pressure compressor
4. High-pressure compressor
5. Combustion chamber
6. High-pressure turbine
7. Low-pressure turbine
8. Core nozzle
9. Fan nozzle

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

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

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



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

bypass ratio (5:1, or more, is now common).

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

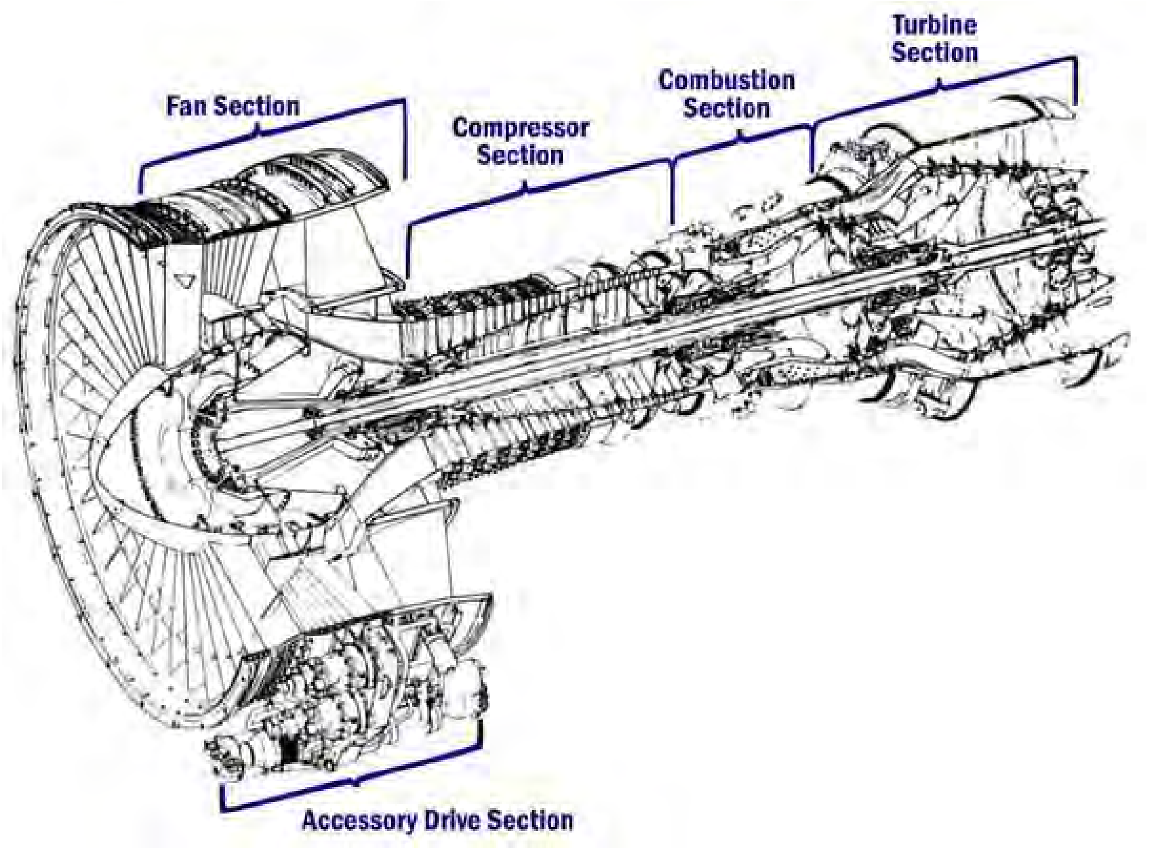
The first high-bypass turbofan engine was the General Electric TF39, designed in mid 1960s to power the Lockheed C-5 Galaxy military transport aircraft.[3] The civil General Electric CF6 engine used a derived design. Other high-bypass turbofans are the Pratt & Whitney JT9D, the three-shaft Rolls-Royce RB211 and the CFM International CFM56; also the smaller TF34. More recent large high-bypass turbofans include the Pratt & Whitney PW4000, the three-shaft Rolls-Royce Trent, the General Electric GE90/GEnx and the GP7000, produced jointly by GE and P&W.

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

The higher the bypass ratio of a turbofan, the lower the mean jet outlet velocity, which in turn translates into high thrust lapse rates (decreasing thrust with increasing speed). Therefore, engines capable of considerably high flight speeds (e.g., Mach 0.83) generate relatively high thrust at low speed or at idle. Among others, this increases runway performance.

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

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



Cutaway diagram of the General Electric CF6−6 engine

2.5 Turbofan configurations

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

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

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

and/or

2) closing variable stators within the compressor

Most modern American civil turbofans employ a relatively high-pressure-ratio high-pressure (HP) compressor, with many rows of variable stators to control surge margin at part-throttle. In the three-spool RB211/Trent the core compression system is split into two, with the IP compressor, which supercharges the HP compressor, being on a different coaxial shaft and driven by a separate (IP) turbine. As the HP compressor has a modest pressure ratio it can be throttled-back surge-free, without employing variable geometry. However, because a shallow IP compressor working line is inevitable, the IPC has one stage of variable geometry on all variants except the −535, which has none.[6]

2.5.1 Single-shaft turbofan

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

2.5.2 Aft-fan turbofan

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

2.5.3 Basic two spool

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

2.5.4 Boosted two spool

Higher overall pressure ratios can be achieved by either raising the HP compressor pressure ratio or adding an intermediate-pressure (IP) Compressor between the fan and HP compressor, to supercharge or boost the latter unit helping to raise the overall pressure ratio of the engine cycle to the very high levels employed today (i.e., greater than 40:1, typically). All of the large American turbofans (e.g., General Electric CF6, GE90 and GEnx plus Pratt & Whitney JT9D and PW4000) feature an IP compressor mounted on the LP shaft and driven, like the fan, by the LP turbine, the mechanical speed of which is dictated by the tip speed and diameter of the fan. The Rolls-Royce BR715 is a non-American example of this. The high bypass ratios (i.e., fan duct flow/core flow) used in modern civil turbofans tends to reduce the relative diameter of the attached IP compressor, causing its mean tip speed to decrease. Consequently more IPC stages are required to develop the necessary IPC pressure rise.

2.5.5 Three spool

Rolls-Royce chose a three spool configuration for their large civil turbofans (i.e., the RB211 and Trent families), where the intermediate pressure (IP) compressor is mounted on a separate (IP) shaft, running concentrically with the LP and HP shafts, and is driven by a separate IP turbine. The first three spool engine was the earlier Rolls-Royce RB.203 Trent of 1967.

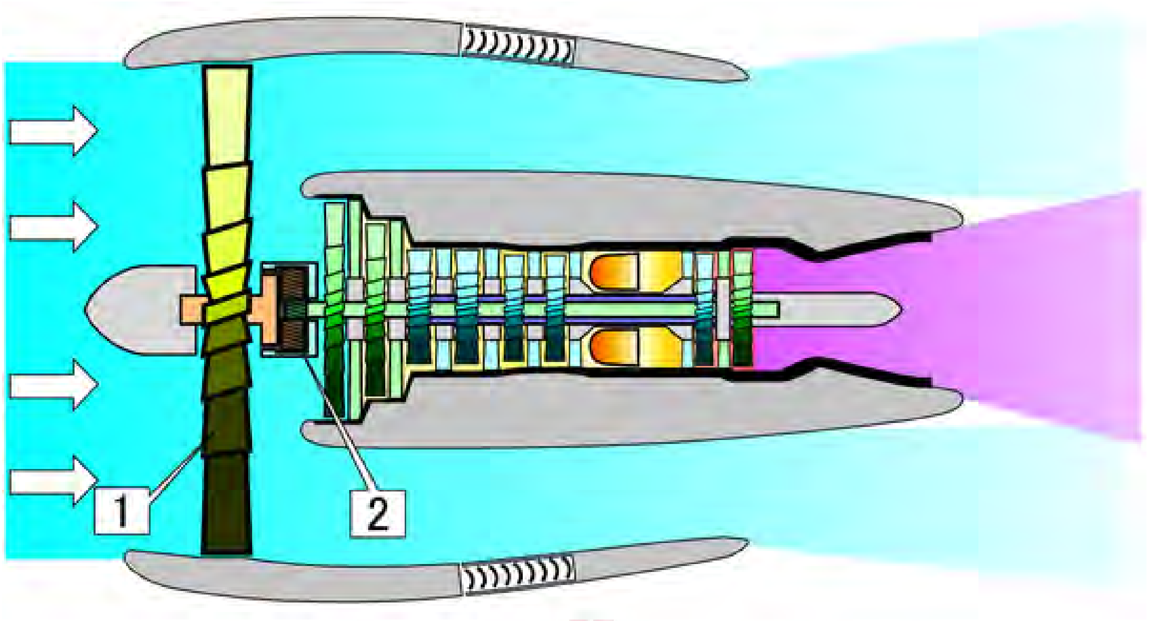
Ivchenko Design Bureau chose the same configuration for their Lotarev D-36 engine, followed by Lotarev/Progress D-18T and Progress D-436.

The Turbo-Union RB199 military turbofan also has a three spool configuration, as do the military Kuznetsov NK-25 and NK-321.

2.5.6 Geared fan

Main article: Geared turbofan

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



Geared turbofan

2.5.7 Military turbofans

Most of the configurations discussed above are used in civilian turbofans, while modern military turbofans (e.g., SNECMA M88) are usually basic two-spool.

2.5.8 High-pressure turbine

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

2.5.9 Low-pressure turbine

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

2.6 Cycle improvements

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

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

Duct work on an Dassault/Dornier Alpha Jet — At subsonic speeds, the increasing diameter of the inlet duct slows incoming air, causing its static pressure to increase.

both turbine rotor inlet temperature and compressor delivery temperature. Increasing the latter may require better compressor materials.

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

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

2.7 Thrust growth

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

1. hot route: increase HP turbine rotor inlet temperature
2. cold route: increase core mass flow

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

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

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

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

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

Changes must also be made to the fan to absorb the extra core power. On a civil engine, jet noise considerations mean that any significant increase in Take-off thrust must be accompanied by a corresponding increase in fan mass flow (to maintain a T/O specific thrust of about 30 lbf/lb/s). To reduce noise civilian turbofans have a specially shaped nozzle that limits the exhaust speed to subsonic speeds. This leads to a thermic clogging termed *choked nozzle* where the mass flow cannot be increased beyond a certain amount. Thus, the mass flow can only be increased through the bypass airstream, usually by increasing fan diameter. On military engines, the fan pressure ratio would probably be increased to improve specific thrust, jet noise not normally being an important factor.

2.8 Technical discussion

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

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

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

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

3. Thrust growth on civil turbofans is usually obtained by increasing fan airflow, thus preventing the jet noise becoming too high. However, the larger fan airflow requires more power from the core. This can be achieved by raising the Overall Pressure Ratio (combustor inlet pressure/intake delivery pressure) to induce more airflow into the core and by increasing turbine inlet temperature. Together, these parameters tend to increase core thermal efficiency and improve fuel efficiency.

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

5. The off-design behaviour of turbofans is illustrated under compressor map and turbine map.

6. Because modern civil turbofans operate at low specific thrust, they only require a single fan stage to develop the required fan pressure ratio. The desired overall pressure ratio for the engine cycle is usually achieved by multiple axial stages on the core compression. Rolls-Royce tend to split the core compression into two with an intermediate pressure (IP) supercharging the HP compressor, both units being driven by turbines with a single stage, mounted on separate shafts. Consequently, the HP compressor need only develop a modest pressure ratio (e.g., ~4.5:1). US civil engines use much higher HP compressor pressure ratios (e.g., ~23:1 on the General Electric GE90) and tend to be driven by a two-stage HP turbine. Even so, there are usually a few IP axial stages mounted on the LP shaft, behind the fan, to further supercharge the core compression system. Civil engines have multi-stage LP turbines, the number of stages being determined by the bypass ratio, the amount of IP compression on the LP shaft and the LP turbine blade speed.

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

2.9 Recent developments in blade technology

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

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

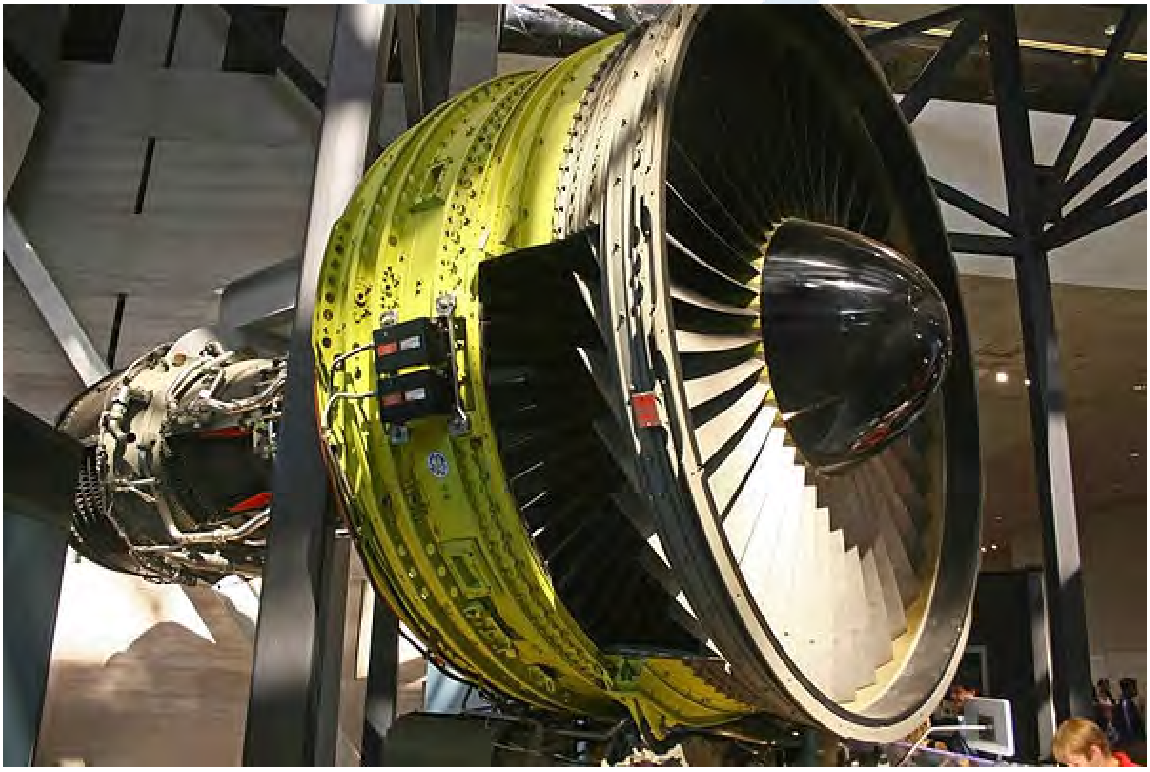
Although turbine blade (and vane) materials have improved over the years, much of the increase in (HP) turbine inlet temperatures is due to improvements in blade/vane cooling technology. Relatively cool air is bled from the compression system, bypassing the combustion process, and enters the hollow blade or vane. The gas temperature can therefore be even higher than the melting temperature of the blade.[8] After picking up heat from the blade/vane, the cooling air is dumped into the main gas stream. If the local gas temperatures are low enough, downstream blades/vanes are uncooled and not adversely affected.

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

2.10 Turbofan engine manufacturers

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

2.10.1 General Electric



GE CF6 Turbofan engine

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

2.10.2 Rolls-Royce

Rolls-Royce plc is the second largest manufacturer of turbofans and is most noted for their RB211 and Trent series, as well as their joint venture engines for the Airbus A320 and McDonnell Douglas MD-90 families (IAE V2500 with Pratt & Whitney and others), the Panavia Tornado (Turbo-Union RB199) and the Boeing 717 (BR700). The Rolls-Royce AE 3007, developed by Allison Engine Company before its acquisition by Rolls-Royce, powers several Embraer regional jets. Rolls-Royce Trent 970s were the first engines to power the new Airbus A380. The famous thrust vectoring Pegasus - actually a Bristol Siddeley design taken on by Rolls-Royce when they took over that company - is the primary powerplant of the Harrier "Jump Jet" and its derivatives.

2.10.3 Pratt & Whitney

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

2.10.4 CFM International

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

2.10.5 Williams International

Williams International is a manufacturer of small gas turbine engines based in Walled Lake, Michigan, United States. It produces jet engines for cruise missiles and small jet-powered aircraft. They have been producing engines since the 1970s and the range produces between 1000 and 3600 pounds of thrust. The engines are used as original equipment on the Cessna CitationJet CJ1 through CJ4 and Cessna Mustang, Beechcraft 400XPR and Premier 1a and there are several development programs with other manufacturers. The range is also very popular with the re-engine market being used by Sierra Jet and Nextant to breath new life into aging platforms.

2.10.6 Aviadvigatel

Aviadvigatel is a Russian manufacturer of aircraft engines that succeeded the Soviet Soloviev Design Bureau. The company currently offers[9] several versions of the Aviadvigatel PS-90 engine that powers Ilyushin Il-96–300/400/400T, Tupolev Tu-204, Tu-214 series and the Ilyushin Il-76-MD-90. The company is also developing the new Aviadvigatel PD-14 engine for the new Russian MS-21 airliner.[10]

2.10.7 Ivchenko-Progress

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

2.10.8 Chinese turbofan manufacturers

Three Chinese corporations build turbofan engines. Some of these are licenced or reverse engineered versions of European and Russian turbofans, and the other are indigenous models, but all are in development phase.

Shenyang Aircraft Corporation (manufacturer of Shenyang WS-10)

Xi'an Aero-Engine Corporation (manufacturer of Xian WS-15)

Guizhou Aircraft Industry Corporation (manufacturer of Guizhou WS-13)

2.10.9 Japanese turbofan manufacturers

Two Japanese corporations build turbofan engines. One of these is Mitsubishi Heavy Industries, that manufactured under license the Pratt & Whitney JT8D turbofan for the Kawasaki C-1 military transport aircraft. The other is IHI Corporation, that manufactured various turbofan engines.

2.10.10 NPO Saturn

NPO Saturn is the manufacturer of the Saturn AL-31 turbofan.

2.10.11 Klimov

Klimov is the manufacturer of the Klimov RD-33 turbofan.

2.11 Extreme bypass jet engines

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

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

2.12 Terminology

Afterburner extra combustor immediately upstream of final nozzle (also called reheat)

Augmentor afterburner on low-bypass turbofan engines.

Average stage loading constant × (delta temperature)/[(blade speed) × (blade speed) × (number of stages)]

Bypass airstream that completely bypasses the core compression system, combustor and turbine system

Bypass ratio bypass airflow /core compression inlet airflow

Core turbomachinery handling the airstream that passes through the combustor.

Core power residual shaft power from ideal turbine expansion to ambient pressure after deducting core compression power

Core thermal efficiency core power/power equivalent of fuel flow

Dry afterburner (if fitted) not lit

EGT Exhaust Gas Temperature

EPR Engine Pressure Ratio

Fan turbofan LP compressor

Fan pressure ratio fan outlet total pressure/intake delivery total pressure

Flex temp use of artificially high apparent air temperature to reduce engine wear

Gas generator engine core

HP compressor high-pressure compressor (also HPC)

HP turbine high-pressure turbine

Intake ram drag penalty associated with jet engines picking up air from the atmosphere (conventional rocket motors do not have this drag term, because the oxidiser travels with the vehicle)

IEPR Integrated engine pressure ratio

IP compressor intermediate pressure compressor (also IPC)

IP turbine intermediate pressure turbine (also IPT)

LP compressor low-pressure compressor (also LPC)

LP turbine low-pressure turbine (also LPT)

Net thrust nozzle total gross thrust - intake ram drag (excluding nacelle drag, etc., this is the basic thrust acting on the airframe)

Overall pressure ratio combustor inlet total pressure/intake delivery total pressure

Overall thermal efficiency thermal efficiency * propulsive efficiency

Propulsive efficiency propulsive power/rate of production of propulsive kinetic energy (maximum propulsive efficiency occurs when jet velocity equals flight velocity, which implies zero net thrust!)

Specific fuel consumption (SFC) total fuel flow/net thrust (proportional to flight velocity/overall thermal efficiency)

Spooling up accelerating, marked by a delay

Static pressure normal meaning of pressure. Excludes any kinetic energy effects

Specific thrust net thrust/intake airflow

Thermal efficiency rate of production of propulsive kinetic energy/fuel power

Total fuel flow combustor (plus any afterburner) fuel flow rate (e.g., lb/s or g/s)

Total pressure static pressure **plus** kinetic energy term

Turbine rotor inlet temperature gas absolute mean temperature at principal (e.g., HP) turbine rotor entry

2.13 See also

- Jet engine
- Turbojet
- Turboprop
- Turboshaft
- Propfan
- Axial fan design
- Variable cycle engine

- Jet engine performance
- Gas turbine
- Turbine engine failure

2.14 Notes and references

[1] Marshall Brain. "How Gas Turbine Engines Work". howstuffworks.com. Retrieved 2010-11-24.

[2] "Turbofan Engine". www.grc.nasa.gov. Retrieved 2010-11-24.

[3] Neumann, Gerhard (2004) [1984], *Herman the German: Just Lucky I Guess*, Bloomington, IN, USA: Authorhouse, ISBN 1-4184-7925-X. *First published by Morrow in 1984 as* Herman the German: Enemy Alien U.S. Army Master Sergeant. *Republished with a new title in 2004 by Authorhouse, with minor or no changes.*, pp. 228–230.

[4] "Metrovick F3 Cutaway - Pictures & Photos on FlightGlobal Airspace". Flightglobal.com. 2007-11-07. Retrieved 2013-04-29.

[5] "1954 | 0985 | Flight Archive". Flightglobal.com. 1954-04-09. Retrieved 2013-04-29.

[6]

[7] "The geared turbofan technology - Opportunities, challenges and readiness status" PDF C. Riegler, C. Bichlmaier:, 1st CEAS European Air and Space Conference, 10–13 September 2007, Berlin, Germany

[8] Spittle, Peter. "Gas turbine technology" *Rolls-Royce plc*, 2003. Retrieved: 21 July 2012.

[9] PS-90A turbofan, Aviadvigatel, 2011-01-17

[10] Turbofan Engine Family for Regional Jet, Aviadvigatel, 2011-01-17

2.15 External links

- Wikibooks: Jet propulsion

Chapter 3

Propfan

Not to be confused with turboprop or turbofan.

A **propfan** is a type of aircraft engine related in concept to both the turboprop and turbofan, but distinct from both.

NASA / GE Unducted Fan

The engine uses a gas turbine to drive an unshielded propeller like a turboprop, but the propeller itself is designed with a large number of short, highly twisted blades, similar to a turbofan's bypass compressor (the "fan" itself). For this reason, the propfan has been variously described as an "unducted fan" or an "ultra-high-bypass (UHB) turbofan". In technical papers it is described as "a small diameter, highly loaded multiple bladed variable pitch propulsor having swept blades with thin advanced airfoil sections, integrated with a nacelle contoured to retard the airflow through the blades thereby reducing compressibility losses and designed to operate with a turbine engine and using a single stage reduction gear resulting in high performance." The design is intended to offer the speed and performance of a turbofan, with the fuel economy of a turboprop. The propfan concept was first revealed by Carl Rohrbach and Bruce

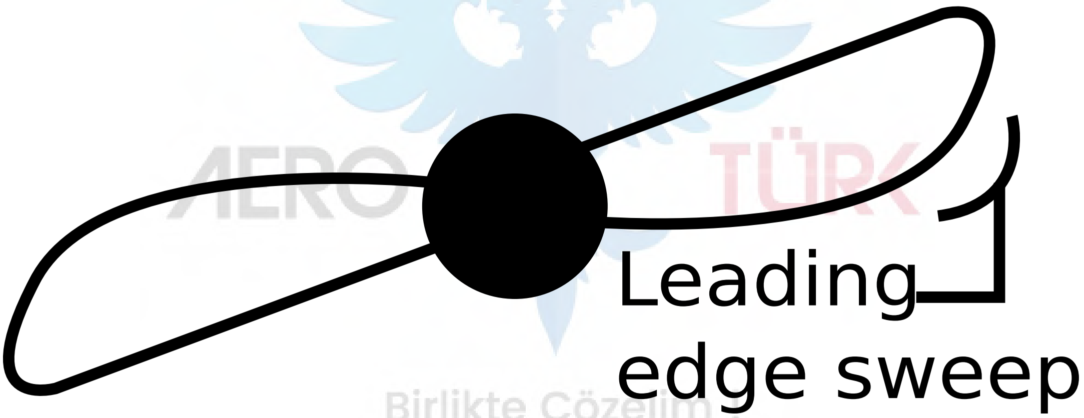
Metzger of the Hamilton Standard Division of United Technologies in 1975[1] and was patented by Robert Cornell and Carl Rohrbach of Hamilton Standard in 1979.[2] Later work by General Electric on similar propulsors was done under the name **unducted fan**, which was a modified turbofan engine, with the fan placed outside the engine nacelle on the same axis as the compressor blades.

3.1 Limitations and solutions

3.1.1 Propeller blade tip speed limit

Turboprops have an optimum speed below about 450 mph (700 km/h).[3] The reason is that all propellers lose efficiency at high speed, due to an effect known as wave drag that occurs just below supersonic speeds. This powerful form of drag has a sudden onset, and led to the concept of a sound barrier when it was first encountered in the 1940s. In the case of a propeller, this effect can happen any time the propeller is spun fast enough that the blade tips near the speed of sound, even if the aircraft is motionless on the ground.

The most effective way to counteract this problem (to some degree) is by adding more blades to the propeller, allowing it to deliver more power at a lower rotational speed. This is why many World War II fighter designs started with two or three-blade propellers and by the end of the war were using up to five blades in some cases as the engines were upgraded and new propellers were needed to more efficiently convert that power. The major downside to this approach is that adding blades makes the propeller harder to balance and maintain and the additional blades cause minor performance penalties (due to drag and efficiency issues). But even with these sorts of measures at some point the forward speed of the plane combined with the rotational speed of the propeller will once again result in wave drag problems. For most aircraft this will occur at speeds over about 450 mph (700 km/h).



Swept propeller

A method of decreasing wave drag was discovered by German researchers in 1935—sweeping the wing backwards. Today, almost all aircraft designed to fly much above 450 mph (700 km/h) use a swept wing. In the 1970s, Hamilton Standard started researching propellers with similar sweep. Since the inside of the propeller is moving slower than the outside, the blade is progressively more swept toward the outside, leading to a curved shape similar to a scimitar - a practice that was first used as far back as 1909, in the Chauvière make of two-bladed wood propeller used on the Blériot XI.

3.1.2 Jet aircraft fuel economy

Jet aircraft are well known for permitting greater thrusts and higher speeds than could be achieved by conventional propeller-driven aircraft operating within the same aerodynamic envelope. However, jet aircraft are limited in fuel economy. In fact, for the same fuel consumption, a propeller-driven aircraft can produce greater thrust. As fuel costs become an increasingly important aspect of commercial aviation, aircraft engine designers continue to seek an optimal combination of jet engine thrust ratios and propeller fuel efficiency.

The propfan concept was developed to deliver 35% better fuel efficiency than contemporary turbofans. In static and air tests on a modified Douglas DC-9, propfans reached a 30% improvement over the OEM turbofans. This efficiency came at a price, as one of the major problems with the propfan is noise, particularly in an era where aircraft are required to comply with increasingly strict aircraft noise regulations. However, in 2012 GE expects that openrotors can meet these noise levels by 2030 when new narrowbody generations from Boeing and Airbus become available. Airlines consistently ask for low noise, and then maximum fuel efficiency.[4]

The Hamilton Standard Division of United Technologies developed the propfan concept in the early 1970s. Numerous design variations of the propfan were tested by Hamilton Standard, in conjunction with NASA in this decade.[5][6] This testing led to the Propfan Test Assessment (PTA) program, where Lockheed-Georgia proposed modifying a Gulfstream II to act as in-flight testbed for the propfan concept and McDonnell Douglas proposed modifying a DC-9 for the same purpose.[7] NASA chose the Lockheed proposal, where the aircraft had a nacelle added to the left wing, containing a 6000 hp Allison 570 turboprop engine (derived from the XT701 turboshaft developed for the Boeing Vertol XCH-62 program), powering a 9-foot diameter Hamilton Standard SR-7 propfan. The aircraft, so configured, first flew in March 1987. After an extensive test program, the modifications were removed from the aircraft.[8][9]

General Electric's GE36 Unducted Fan was a variation on the original propfan concept, and appears similar to a pusher configuration piston engine. GE's UDF has a novel direct drive arrangement, where the reduction gearbox is replaced by a low-speed seven-stage free turbine. The turbine rotors drive the forward set of propellers, while the rear set is connected to the free turbine stators and rotates in the opposite direction. So, in effect, the power turbine has 14 stages. Boeing intended to offer GE's pusher UDF engine on the 7J7 platform, and McDonnell Douglas was going to do likewise on their MD-94X airliner. The GE36 was first flight tested mounted on the #3 engine station of a Boeing 727-100 in 1986.[10]

McDonnell Douglas developed a proof-of-concept aircraft by modifying its company-owned MD-80. They removed the JT8D turbofan engine from the left side of the fuselage and replaced it with the GE36. A number of test flights were conducted, initially out of Mojave, California, which proved the airworthiness, aerodynamic characteristics, and noise signature of the design. Following the initial tests, a first-class cabin was installed inside the aft fuselage and airline executives were offered the opportunity to experience the UDF-powered aircraft first-hand. The test and marketing flights of the GE-outfitted demonstrator aircraft concluded in 1988, exhibiting a 30% reduction in fuel consumption over turbo-fan powered MD-80, full Stage III noise compliance, and low levels of interior noise/vibration. Due to jet fuel price drops and shifting marketing priorities, Douglas shelved the program the following year.

In the 1980s, Allison collaborated with Pratt & Whitney on demonstrating the 578-DX propfan. Unlike the competing GE36 UDF, the 578-DX was fairly conventional, having a reduction gearbox between the LP turbine and the propfan blades. The 578-DX was successfully flight tested on a McDonnell Douglas MD-80. However, none of the above projects came to fruition, mainly because of excessive cabin noise (compared to turbofans) and low fuel prices.[11]

The Progress D-27 propfan, developed in the U.S.S.R., is even more unconventional in layout, with the propfan blades at the front of the engine in a tractor configuration. Two rear-mounted D-27 propfans propelled the Antonov An-180, which was scheduled for a 1995 entry into service. Another Russian propfan application was the Yakovlev Yak-46. During the 1990s, Antonov also developed the An-70, powered by four Progress D-27s in a tractor configuration; the Russian Air Force placed an order for 164 aircraft in 2003, which was subsequently canceled. However, the An-70 remains available for further investment and production.

With the current high price for jet fuel and the emphasis on engine/airframe efficiency to reduce emissions, there is renewed interest in the propfan concept for jetliners that might come into service beyond the Boeing 787 and Airbus A350XWB. For instance, Airbus has patented aircraft designs with twin rear-mounted counter-rotating propfans.[12]

3.2 Aircraft with propfans

Main category: Propfan-powered aircraft

- Antonov An-70
- EcoJet

3.3 See also

- Ducted fan

Progress D27 Propfans fitted to an Antonov An-70

Comparable engines

- Europrop TP400
- General Electric GE-36 UDF
- Kuznetsov NK-12
- Rolls-Royce RB3011
- Pratt & Whitney/Allison 578-DX
- Progress D-27
- Metrovick F.5

Related lists

- List of aircraft engines

3.4 References

[1] Rohrback, C. and Metzger, F.B., 'The Prop-Fan, a New Look at Propulsors', AIAA paper 75-1208, presented at the AIAA/SAE 11th Propulsion Conference, Anaheim California, September 1975.

[2] US Patent 4171183 Retrieved 28 June 2011.

[3] Spakovszky, Zoltan (2009). "Unified Propulsion Lecture 1". *Unified Engineering Lecture Notes*. MIT. Retrieved 2009-04-03.

[4] Croft, John. "Open rotor noise not a barrier to entry: GE" *Flight International*, 5 July 2012. Retrieved: 21 July 2012.

[5] Rohrbach, Carl, 'A Report on the Aerodynamic Design and Wind Tunnel Test of a Prop-fan Model', AIAA paper 76-667, presented at the AIAA/SAE 12th Propulsion Conference, Palo Alto California, July 1976.

[6] Jeracki, Robert J., Mikkelson, Daniel C. and Blaha, Bernard J., 'Wind Tunnel Performance of Four Energy Efficient Propellers Designed for Mach 0.8 Cruise', SAE Paper 790573, presented at the SAE Business Aircraft Meeting and Exposition, Wichita Kansas, April 1979.

[7] NASA-CR-166138. Retrieved 28 June 2011

[8] 'Propfan Test Assessment (PTA)' NASA-CR-185138. Retrieved 28 June 2011

[9] 'Propfan Test Assessment (PTA): Flight Test Report' NASA-CR-182278. Retrieved 28 June 2011

[10] 'The Power of Persuasion' Flight International. May 23, 1987. Retrieved 28 June 2011.

[11] Flight International (2007-07-12). "Whatever happened to propfans?". Retrieved 2007-07-14.

[12] US application 2009020643, Airbus & Christophe Cros, "Aircraft having reduced environmental impact", published 2009-01-22

General ressources

- Prop fan propulsion concepts: Technology Review, Design Methodology, State-of-the-art designs and future outlook. Raymond Scott Ciszek. University of Virginia Department of Mechanical and Aerospace Engineering. Senior Thesis Project. March 25, 2002

3.5 External links

- "Green sky thinking - carbon credits and the propfan comeback?", Flight International, June 12, 2007.
- The "easyJet ecoJet" to cut CO2 emissions by 50% by 2015
- The Short, Happy Life of the Prop-fan Air & Space Magazine, September 1, 2005
- "open rotor" jet engine
- "Metrovick F.5 - Open-Fan Thrust Augmenter" a 1947 *Flight* article on an early propfan

Chapter 4

Pulsejet

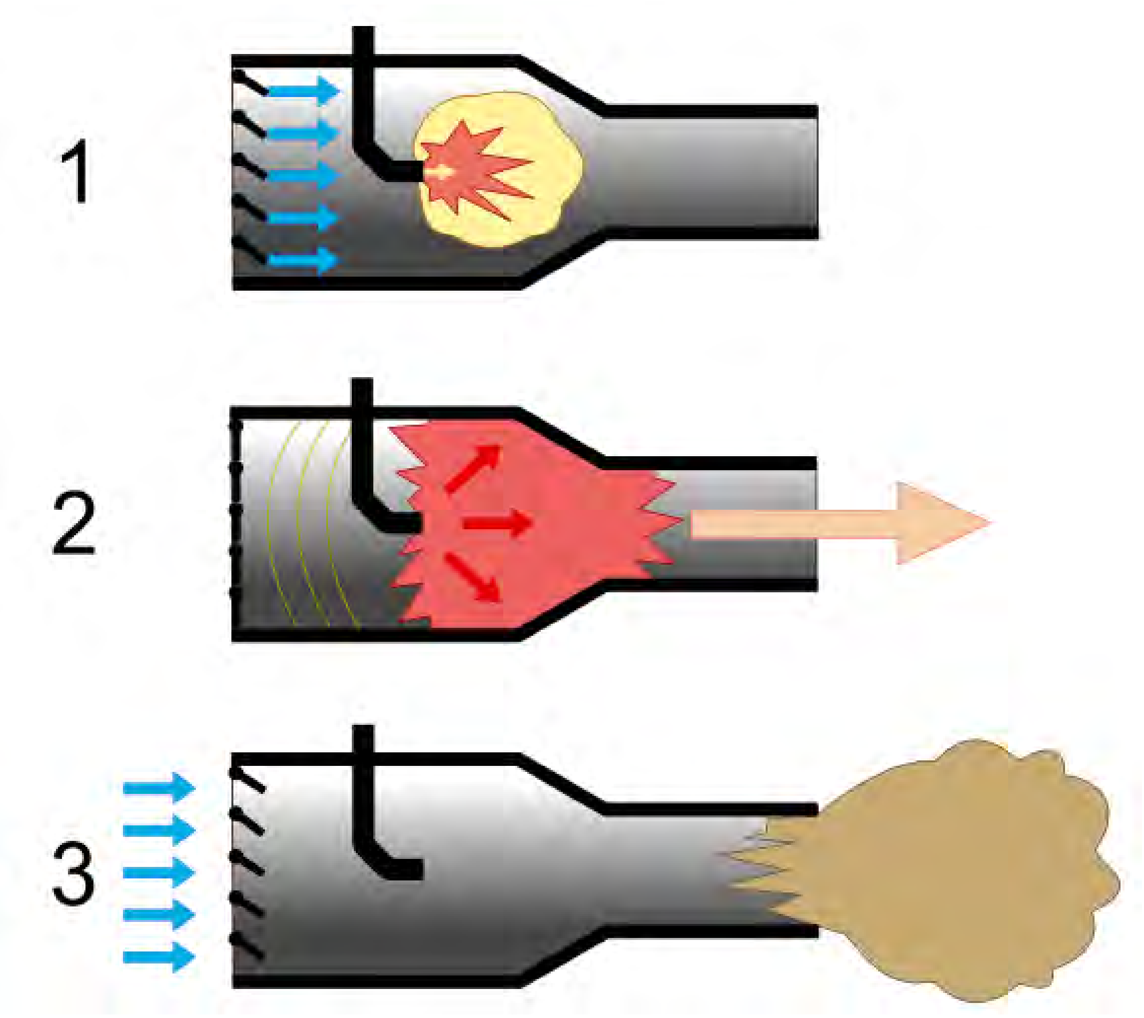


Diagram of a pulsejet

A **pulse jet engine** (or **pulsejet**) is a type of jet engine in which combustion occurs in pulses. Pulsejet engines can be made with few[1] or no moving parts,[2][3][4] and are capable of running statically.

Pulse jet engines are a lightweight form of jet propulsion, but usually have a poor compression ratio, and hence give a low specific impulse.

One notable line of research of pulsejet engines includes the pulse detonation engine which involves repeated detonations in the engine, and which can potentially give high compression and good efficiency.

4.1 Types

There are two main types of pulsejet engines, both of which use resonant combustion and harness the expanding combustion products to form a pulsating exhaust jet which produces thrust intermittently.

4.1.1 Valved pulsejets

Valved pulsejet engines use a mechanical valve to control the flow of expanding exhaust, forcing the hot gas to go out of the back of the engine through the tailpipe only, and allow fresh air and more fuel to enter through the intake.

The valved pulsejet comprises an intake with a one-way valve arrangement. The valves prevent the explosive gas of the ignited fuel mixture in the combustion chamber from exiting and disrupting the intake airflow, although with all practical valved pulsejets there is some 'blowback' while running statically and at low speed, as the valves cannot close fast enough to stop all the gas from exiting the intake. The superheated exhaust gases exit through an acoustically resonant exhaust pipe.

The intake valve is typically a reed valve. The two most common configurations are the daisy valve, and the rectangular valve grid. A daisy valve consists of a thin sheet of material to act as the reed, cut into the shape of a stylized daisy with “petals” that widen towards their ends. Each “petal” covers a circular intake hole at its tip. The daisy valve is bolted to the manifold through its center. Although easier to construct on a small scale, it is less effective than a valve grid.

4.1.2 Valveless pulsejets

Main article: Valveless pulse jet

Valveless pulsejet engines have no moving parts and use only their geometry to control the flow of exhaust out of the engine. Valveless pulsejets expel exhaust out of both the intakes and the exhaust, though most try to have the majority of exhaust go out of the longer tail pipe for more efficient propulsion.

The valveless pulsejet operates on the same principle as the valved pulsejet, but the 'valve' is the engine’s geometry. Fuel, as a gas or atomized liquid spray, is either mixed with the air in the intake or directly injected into the combustion chamber. Starting the engine usually requires forced air and an ignition source, such as a spark plug, for the fuel-air mix. With modern manufactured engine designs, almost any design can be made to be self-starting by providing the engine with fuel and an ignition spark, starting the engine with no compressed air. Once running, the engine only requires input of fuel to maintain a self-sustaining combustion cycle.

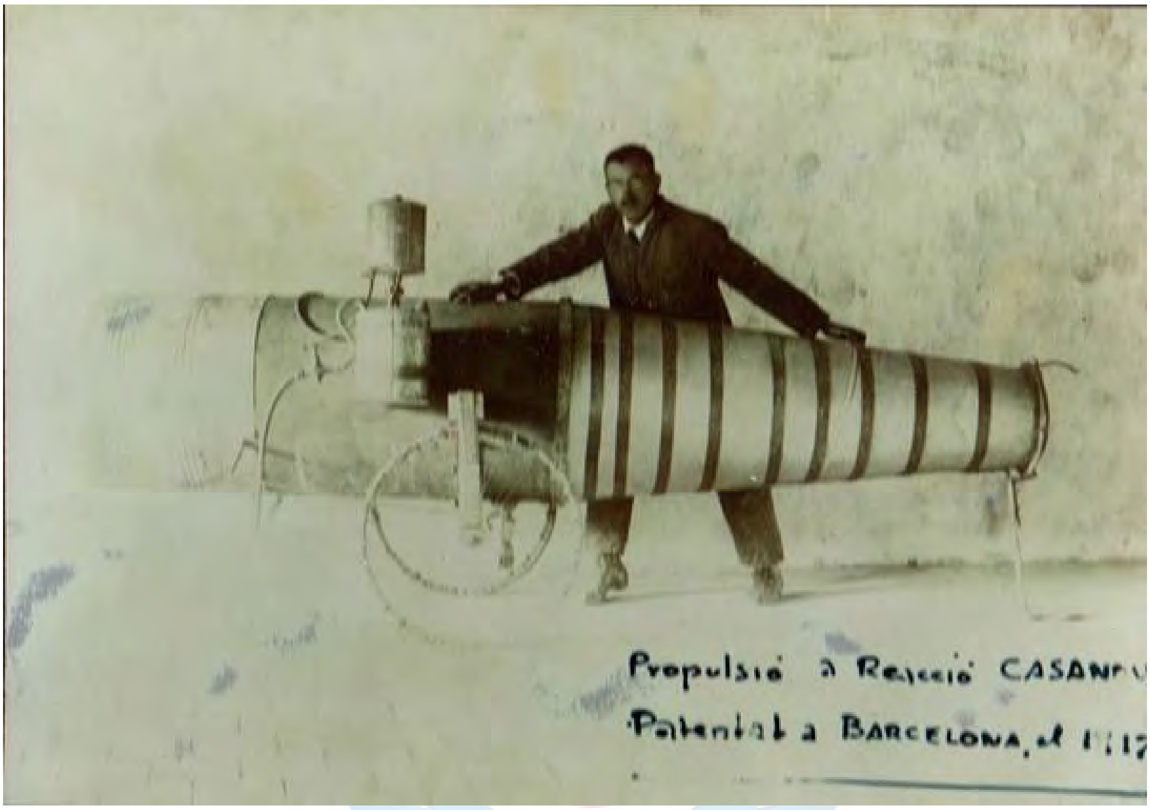
4.2 History

Russian inventor and artillery officer N. Teleshov patented a pulse jet engine in 1864 while Swedish inventor Martin Wiberg also has a claim to having invented the first pulse jet, in Sweden, but details are unclear.

The first working pulsejet was patented in 1906 by Russian engineer V.V. Karavodin, who completed a working model in 1907. The French inventor Georges Marconnet patented his valveless pulsejet engine in 1908, and Ramon Casanova, in Ripoll, Spain patented a pulsejet in Barcelona in 1917, having constructed one beginning in 1913. Engineer Paul Schmidt, pioneered a more efficient design based on modification of the intake valves (or flaps), earning him government support from the German Air Ministry in 1933.[5]

4.2.1 Argus As 109-014

In 1934, Georg Madelung and Munich-based Paul Schmidt proposed to the German Air Ministry a “flying bomb” powered by Schmidt’s pulse jet. Madelung co-invented the ribbon parachute, a device used to stabilise the V-1 in its terminal dive. Schmidt’s prototype bomb failed to meet German Air Ministry specifications, especially owing to poor accuracy, range and high cost. The original Schmidt design had the pulsejet placed in a fuselage like a modern jet fighter, unlike the eventual V-1 which had the engine placed above the warhead and fuselage.



Ramon Casanova and the pulsejet engine he constructed and patented in 1917

The Argus Company began work based on Schmidt's work. Other German manufacturers working on similar pulsejets and flying bombs were The Askania Company, Robert Lusser of Fieseler, Dr. Fritz Gosslau of Argus and the Siemens company, which were all combined to work on the V-1.[5]

With Schmidt now working for Argus, the pulsejet was perfected and was officially known by its RLM designation as the Argus As 109-014. The first unpowered drop occurred at Peenemünde on 28 October 1942 and the first powered flight on 10 December 1942.

The pulsejet was evaluated to be an excellent balance of cost and function: a simple design that performed well for minimal cost.[5] It would run on any grade of petroleum and the ignition shutter system was not intended to last beyond the V-1's normal operational flight life of one hour. Although it generated insufficient thrust for takeoff, the V-1's resonant jet could operate while stationary on the launch ramp. The simple resonant design based on the ratio (8.7:1) of the diameter to the length of the exhaust pipe functioned to perpetuate the combustion cycle, and attained stable resonance frequency at 43 cycles per second. The engine produced 500 lbf (2,200 N) of static thrust and approximately 750 lbf (3,300 N) in flight.[5]

Ignition in the As 014 was provided by a single automotive spark plug, mounted approximately 75 cm (30 in) behind the front-mounted valve array. The spark only operated for the start sequence for the engine; the Argus As 014, like all pulsejets, did not require ignition coils or magnetos for ignition — the ignition source being the tail of the preceding fireball during the run. Contrary to popular belief, the engine casing did not provide sufficient heat to cause Diesel-type ignition of the fuel, as there is insignificant compression within a pulsejet engine.

The Argus As 014 valve array was based on a shutter system that operated at the 43 to 45 cycles-per-second frequency of the engine.

Three air nozzles in the front of the Argus As 014 were connected to an external high pressure source to start the engine. The fuel used for ignition was acetylene, with the technicians having to place a baffle of wood or cardboard in the exhaust pipe to stop the acetylene diffusing before complete ignition. Once the engine ignited and minimum operating temperature was attained, external hoses and connectors were removed.

The V-1, being a cruise missile, lacked landing gear, instead the Argus As 014 was launched on an inclined ramp powered by a piston-driven steam catapult. Steam power to fire the piston was generated by the violent exothermic chemical reaction created when hydrogen peroxide and potassium permanganate (termed T-Stoff and Z-Stoff) are

Argus As 014 pulse jet engine of a V-1 flying bomb at the Royal Air Force Museum London

combined.

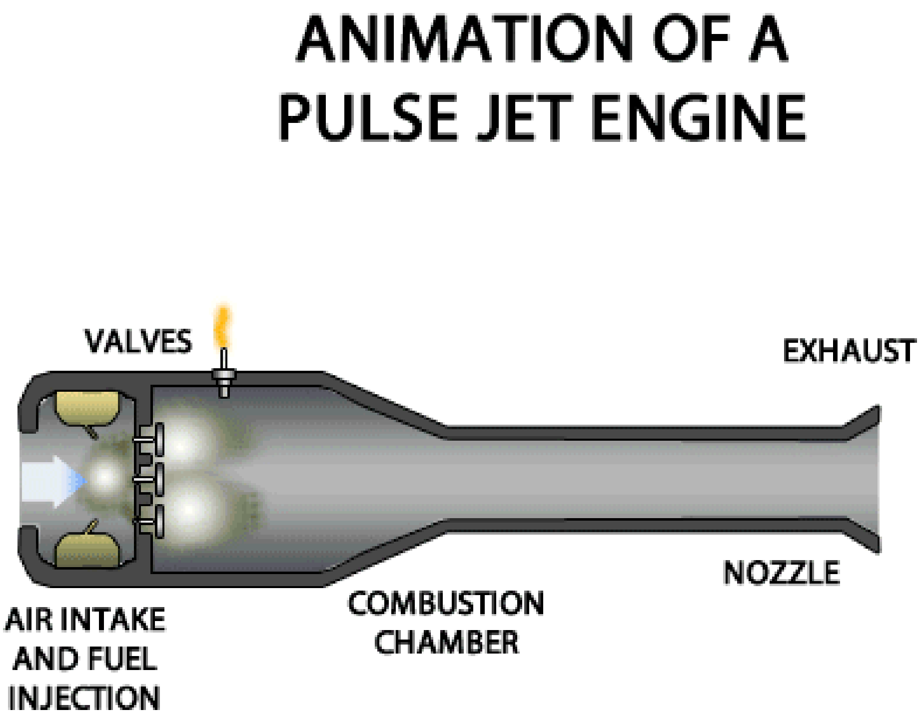
The principal military use of the pulsejet engine, with the volume production of the Argus As 014 unit (the first pulsejet engine ever in volume production), was for use with the V-1 flying bomb. The engine's characteristic droning noise earned it the nicknames "buzz bomb" or "doodlebug". The V-1 was a German cruise missile used in World War II, most famously in the bombing of London in 1944. Pulsejet engines, being cheap and easy to construct, were the obvious choice for the V-1's designers, given the Germans' materials shortages and overstretched industry at that stage of the war. Designers of modern cruise missiles do not choose pulsejet engines for propulsion, preferring turbojets or rocket engines.

Wright Field technical personnel reverse-engineered the V-1 from the remains of a V-1 that had failed to detonate in Britain. The result was the creation of the JB-2 Loon, with the airframe built by Republic Aviation, and the Argus As 014 reproduction pulsejet powerplant made by Ford Motor Company. General Henry Harley "Hap" Arnold of the United States Army Air Forces was concerned that this weapon could be built of steel and wood, in 2000 man hours and approximate cost of US$600 (in 1943).[5]

4.3 Operation

Pulsejet engines are characterized by simplicity, low cost of construction, and high noise levels. While the thrust-to-weight ratio is excellent, thrust specific fuel consumption is very poor. The pulsejet uses the Lenoir cycle which lacking an external compressive driver such as the Otto cycle's piston, or the Brayton cycle's compression turbine, drives compression with acoustic resonance in a tube. This limits the maximum pre-combustion pressure ratio, to around 1.2 to 1.

The high noise levels usually make them impractical for other than military and other similarly restricted applications.[6] However, pulsejets are used on a large scale as industrial drying systems, and there has been a resurgence in studying these engines for applications such as high-output heating, biomass conversion, and alternative energy systems, as pulsejets can run on almost anything that burns, including particulate fuels such as sawdust or coal powder.



Animation of a pulse jet engine.

Pulsejets have been used to power experimental helicopters, the engines being attached to the ends of the rotor blades. In providing power to helicopter rotors, pulsejets have the advantage over turbine or piston engines of not producing torque upon the fuselage since they don't apply force to the shaft, but push the tips. A helicopter may then be built without a tail rotor and its associated transmission and drive shaft, simplifying the aircraft (cyclic and collective control of the main rotor is still necessary). This concept was being considered as early as 1947 when the American Helicopter Company started work on its XA-5 Top Sergeant helicopter prototype powered by pulsejet engines at the rotor tips. [7] The XA-5 first flew in January 1949 and was followed by the XA-6 Buck Private with the same pulsejet design. Also in 1949 Hiller Helicopters built and tested the Hiller Powerblade, the world's first hot-cycle pressure-jet rotor. Hiller switched to tip mounted ramjets but American Helicopter went on to develop the XA-8 under a U.S. Army contract. It first flew in 1952 and was known as the XH-26 Jet Jeep. It used XPJ49 pulse jets mounted at the rotor tips. The XH-26 met all its main design objectives but the Army cancelled the project because of the unacceptable level of noise of the pulsejets and the fact that the drag of the pulsejets at the rotor tips made autorotation landings very problematic. Rotor-tip propulsion has been claimed to reduce the cost of production of rotary-wing craft to 1/10 of that for conventional powered rotary-wing aircraft.[6] Pulsejets have also been used in both control-line and radio-controlled model aircraft. The speed record for control-line model aircraft is greater than 200 miles per hour (323 km/h).

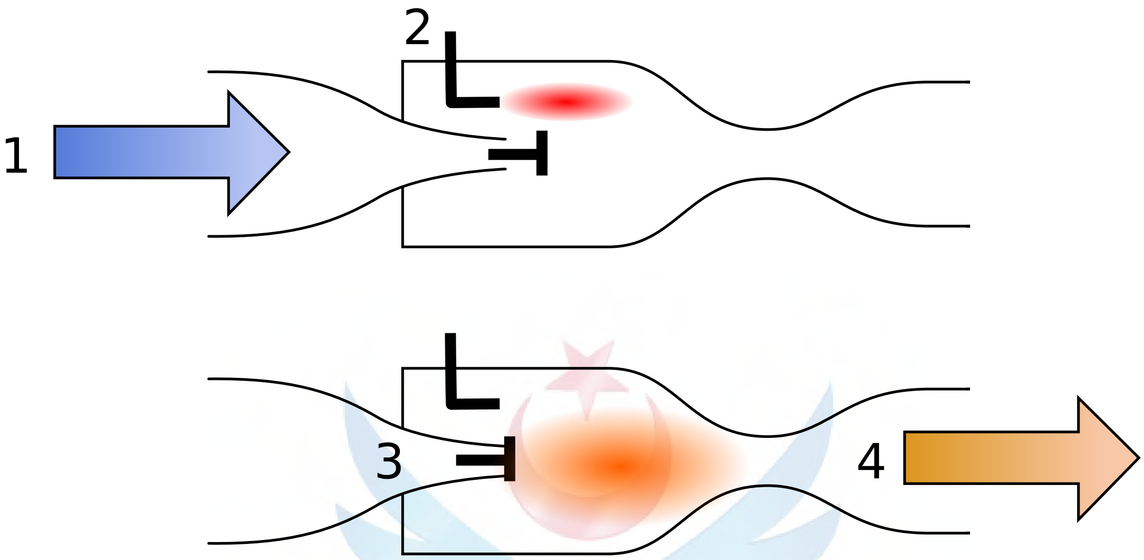
A free-flying radio-controlled pulsejet is limited by the engine's intake design. At around 450 km/h (280 mph) most valved engines' valve systems stop fully closing owing to ram air pressure, which results in performance loss.

Variable intake geometry lets the engine produce full power at most speeds by optimizing for whatever speed the air is entering pulsejet at. Valveless designs are not as negatively affected by ram air pressure as other designs, as they were never intended to stop the flow out of the intake, and can significantly increase in power at speed.

Another feature of pulsejet engines is that their thrust can be increased by a specially shaped duct placed behind the engine. The duct acts as an annular wing, which evens out the pulsating thrust, by harnessing aerodynamic forces in the pulsejet exhaust. The duct, typically called an augmenter, can significantly increase the thrust of a pulsejet with no additional fuel consumption. Gains of 100% increases in thrust are possible, resulting in a much higher fuel efficiency.

However, the larger the augmenter duct, the more drag it produces, and it is only be effective within specific speed ranges.

4.4 Function



Pulse jet schematic. First part of the cycle: air flows through the intake (1), and is mixed with fuel (2). Second part: the valve (3) is closed and the ignited fuel-air mix (4) propels the craft.

The combustion cycle comprises five or six phases depending on the engine: Induction, Compression, (optional) Fuel Injection, Ignition, Combustion, and Exhaust.

Starting with ignition within the combustion chamber, a high pressure is raised by the combustion of the fuel-air mixture. The pressurized gas from combustion cannot exit forward through the one-way intake valve and so exits only to the rear through the exhaust tube.

The inertial reaction of this gas flow causes the engine to provide thrust, this force being used to propel an airframe or a rotor blade. The inertia of the traveling exhaust gas causes a low pressure in the combustion chamber. This pressure is less than the inlet pressure (upstream of the one-way valve), and so the induction phase of the cycle begins.

In the simplest of pulsejet engines this intake is through a venturi which causes fuel to be drawn from a fuel supply. In more complex engines the fuel may be injected directly into the combustion chamber. When the induction phase is under way, fuel in atomized form is injected into the combustion chamber to fill the vacuum formed by the departing of the previous fireball; the atomized fuel tries to fill up the entire tube including the tailpipe. This causes atomized fuel at the rear of the combustion chamber to "flash" as it comes in contact with the hot gases of the preceding column of gas—this resulting flash "slams" the reed-valves shut or in the case of valveless designs, stops the flow of fuel until a vacuum is formed and the cycle repeats.

4.4.1 Valved design

There are two basic types of pulsejets. The first is known as a valved or traditional pulsejet and it has a set of one-way valves through which the incoming air passes. When the air-fuel is ignited, these valves slam shut which means that the hot gases can only leave through the engine's tailpipe, thus creating forward thrust.

The cycle frequency is primarily dependent on the length of the engine. For a small model-type engine the frequency may be around 250 pulses per second, whereas for a larger engine such as the one used on the German V-1 flying bomb, the frequency was closer to 45 pulses per second. The low-frequency sound produced resulted in the missiles being nicknamed "buzz bombs."

4.4.2 Valveless design

Main article: Valveless pulse jet

The second type of pulsejet is known as the valveless pulsejet.[8] Technically the term for this engine is the acoustic-type pulsejet, or aerodynamically valved pulsejet.

Valveless pulsejets come in a number of shapes and sizes, with different designs being suited for different functions. A typical valveless engine will have one or more intake tubes, a combustion chamber section, and one or more exhaust tube sections.

The intake tube takes in air and mixes it with fuel to combust, and also controls the expulsion of exhaust gas, like a valve, limiting the flow but not stopping it altogether. While the fuel-air mixture burns, most of the expanding gas is forced out of the exhaust pipe of the engine. Because the intake tube(s) also expel gas during the exhaust cycle of the engine, most valveless engines have the intakes facing backwards so that the thrust created adds to the overall thrust, rather than reducing it.

The combustion creates two pressure wave fronts, one traveling down the longer exhaust tube and one down the short intake tube. By properly 'tuning' the system (by designing the engine dimensions properly), a resonating combustion process can be achieved.

While some valveless engines are known for being extremely fuel-hungry, other designs use significantly less fuel than a valved pulsejet, and a properly designed system with advanced components and techniques can rival or exceed the fuel efficiency of small turbojet engines.

In 1909, Georges Marconnet developed the first pulsating combustor without valves. It was the grandfather of all valveless pulsejets. The valveless pulsejet was experimented with by the French propulsion research group SNECMA (Société Nationale d'Étude et de Construction de Moteurs d'Aviation), in the late 1940s.

The valveless pulsejet's first widespread use was the Dutch drone Aviolanda AT-21[9] A properly designed valveless engine will excel in flight; as it does not have valves, ram air pressure from traveling at high speed does not cause the engine to stop running like a valved engine. They can achieve higher top speeds, with some advanced designs being capable of operating at Mach 7 or possibly higher.

The advantage of the acoustic-type pulsejet is simplicity. Since there are no moving parts to wear out, they are easier to maintain and simpler to construct.

4.4.3 Future uses

Pulsejets are used today in target drone aircraft, flying control line model aircraft (as well as radio-controlled aircraft), fog generators, and industrial drying and home heating equipment. Because pulsejets are an efficient and simple way to convert fuel into heat, experimenters are using them for new industrial applications such as biomass fuel conversion, boiler and heater systems, and other applications.

Some experimenters continue to work on improved designs. The engines are difficult to integrate into commercial manned aircraft designs because of noise and vibration, though they excel on the smaller-scale unmanned vehicles.

The pulse detonation engine (PDE) marks a new approach towards non-continuous jet engines and promises higher fuel efficiency compared to turbofan jet engines, at least at very high speeds. Pratt & Whitney and General Electric now have active PDE research programs. Most PDE research programs use pulsejet engines for testing ideas early in the design phase.

Boeing has a proprietary pulse jet engine technology called Pulse Ejector Thrust Augmentor (PETA), which proposes to use pulse jet engines for vertical lift in military and commercial VTOL aircraft.[10]

4.5 See also

- Pulse detonation engine
- Valveless pulse jet
- List of aircraft engines

4.6 Notes

[1] "Pulse Detonation Engine". Gofurther.utsi.edu. Retrieved 2014-03-03.

[2]

[3] "Patent US6216446 - Valveless pulse-jet engine with forward facing intake duct - Google Patents". Google.com. Retrieved 2014-03-03.

[4] "Valveless Pulsjet". Home.no. Retrieved 2014-03-03.

[5] George Mindling, Robert Bolton: *US Airforce Tactical Missiles:1949-1969*: The Pioneers*, Lulu.com, 200: ISBN 0-557-00029-7. pp6-31*

[6] Jan Roskam, Chuan-Tau Edward Lan; *Airplane aerodynamics and performance* DARcorporation: 1997: ISBN 1-884885-44-6: 711 pages

[7] "Excerpt of Flight May 12, 1949". flightglobal.com. Retrieved 2014-08-31.

[8] Geng, T.; Schoen, M. A.; Kuznetsov, A. V.; Roberts, W. L. (2007). "Combined Numerical and Experimental Investigation of a 15-cm Valveless Pulsejet". *Flow, Turbulence and Combustion* **78** (1): 17–33. doi:10.1007/s10494-006-9032-8.

[9] Jan Roskam, Chuan-Tau Edward Lan; *Airplane aerodynamics and performance*, DARcorporation: 1997 ISBN 1-884885-44-6: 711 pages

[10] Diaz, Jesus (2011-07-28). "Boeing's Millennium Falcon Floats Using Nazi Technology". Wired.com.

4.7 References

- *Aeronautical Engineering Review*, Institute of the Aeronautical Sciences (U.S.): 1948, vol. 7.
- George Mindling, Robert Bolton: *US Airforce Tactical Missiles:1949-1969*: The Pioneers*, Lulu.com, 200: ISBN 0-557-00029-7. pp6–31*

4.8 External links

- - An international site dedicated to pulsejets, including design and experimentation. Includes an extremely active forum composed of knowledgeable enthusiasts
- - A site for hobby jet propulsion, specifically valved and valveless pulsejet engines. They offer many free pulse jet plans, and have a lot of useful information
- Video of 21st century-built German reproduction Argus As 014 pulsejet testing
- - A detailed guide documenting all the steps required to build one's own Pulsejet. The example created on this site is eventually mounted onto a home-built kart and tested
- Pulsejets in aeromodels
- Popular Rotocraft Association
- Pulse Jet Bike
- Apocalyptic robotics performance group Survival Research Labs operates a collection of pulse jet engines in some of their creations, including the Hovercraft, V1, and the Flame Hurricane.
- PETA (Pulse-Ejector-Thrust-Augmentors) article
- Ramon Casanova's pulsejet
- American Helicopter XA-5 Flight

Chapter 5

Valveless pulse jet

A **valveless pulse jet** (or **pulsejet**) is the simplest known jet propulsion device. Valveless pulsejets are low in cost, light weight, powerful and easy to operate. They have all the advantages (and most of the disadvantages) of conventional valved pulse jets, but without the reed valves that need frequent replacement - a valveless pulsejet can operate for its entire useful life with practically zero maintenance. They have been used to power model aircraft, experimental go-karts, and unmanned military aircraft such as cruise missiles and target drones.

5.1 Basic characteristics

A pulsejet engine is an air-breathing reaction engine employing an ongoing sequence of discrete combustion events rather than a constant level of combustion. This clearly distinguishes it from other reaction engine types such as rockets, turbojets and ramjets, which are all constant combustion devices. All other reaction engines are driven by maintaining high internal pressure; pulsejets are driven by an alternation between high and low pressure. This alternation is not maintained by any mechanical contrivance, but rather by the natural acoustic resonance of the rigid tubular engine structure. The valveless pulsejet is, mechanically speaking, the simplest form of pulsejet, and is, in fact, the simplest known air-breathing propulsion device that can operate “statically”, i.e. without forward motion.

The combustion events driving a pulsejet are often informally called "explosions"; however, the preferred term is "deflagrations". They are not the violent, very high energy detonations employed in "Pulse Detonation Engines (PDEs)"; rather, deflagration within the combustion zone of a pulsejet is characterized by a sudden rise in temperature and pressure followed by a rapid subsonic expansion in gas volume. It is this expansion that performs the main work of moving air rearward through the device as well as setting up conditions in the main tube for the cycle to continue.

A pulsejet engine works by alternately accelerating a contained mass of air rearward and then breathing in a fresh mass of air to replace it. The energy to accelerate the air mass is provided by the deflagration of fuel mixed thoroughly into the newly acquired fresh air mass. This cycle is repeated many times per second. During the brief mass acceleration phase of each cycle, the engine’s physical action is like that of other reaction engines — gas mass is accelerated rearward, resulting in an application of force forward into the body of the engine. These “pulses” of force, rapidly repeated over time, comprise the measurable thrust force of the engine.

Some basic differences between valved and valveless pulsejets are:

- Valveless pulsejet engines have no mechanical valve, eliminating the only internal “moving part” of the conventional pulsejet;
- In valveless engines, the intake section has an important role to play throughout the entire pulsejet cycle;
- Valveless engines produce thrust forces in two distinct but synchronized mass acceleration events per cycle, rather than just one.

5.2 Basic (valved) pulsejet theory

In a conventional “valved” pulsejet, like the engine of the infamous V-1 “buzz bomb” of World War II, there are two ducts connected to the combustion zone where the explosions occur. These are generally known as the “intake” (a very short duct) and the “tailpipe” (a very long duct). The function of the forward-facing intake is to provide air (and in many smaller pulsejets, the fuel/air mixing action) for combustion. The purpose of the rear-facing tailpipe is to provide air mass for acceleration by the explosive blast as well as to direct the accelerated mass totally rearward. The combustion zone (usually a widened “chamber” section) and tailpipe make up the main tube of the engine. A flexible, low mass one-way valve (or multiple identical valves) separates the intake from the combustion zone.

At the beginning of each cycle, air must be pulled into the combustion zone. At the end of each cycle, the tailpipe must be reloaded with air from the surrounding atmosphere. Both of these basic actions are accomplished by a significant drop in pressure that occurs naturally after the deflagration expansion, a phenomenon known as the Kadenacy effect (named after the scientist who first fully described it). This temporary low pressure opens the metal valve and draws in the intake air (or air/fuel mixture). It also causes a reversal of flow in the tailpipe that draws fresh air forward to re-fill the pipe. When the next deflagration occurs, the rapid pressure rise slams the valve shut very quickly, ensuring that almost no explosion mass exits in the forward direction so the expansion of the combustion gases will all be used to accelerate the replenished mass of air in the long tailpipe rearward.

5.3 Valveless pulsejet operation

The “valveless” pulsejet is not really valveless — it just uses the mass of air in the intake tube as its valve, in place of a mechanical valve. It cannot do this without moving the intake air outward, and this volume of air itself has significant mass, just as the air in the tailpipe does — therefore, it is not blown away instantly by the deflagration but is accelerated over a significant fraction of the cycle time. In all known successful valveless pulsejet designs, the intake air mass is a small fraction of the tailpipe air mass (due to the smaller dimensions of the intake duct). This means that the intake air mass will be cleared out of contact with the body of the engine faster than the tailpipe mass will. The carefully designed imbalance of these two air masses is important for the proper timing of all parts of the cycle.

When the deflagration begins, a zone of significantly elevated pressure travels outward through both air masses as a "compression wave". This wave moves at the speed of sound through both the intake and tailpipe air masses. (Because these air masses are significantly elevated in temperature as a result of earlier cycles, the speed of sound in them is much higher than it would be in normal outdoor air.) When a compression wave reaches the open end of either tube, a low pressure rarefaction wave starts back in the opposite direction, as if “reflected” by the open end. This low pressure region returning to the combustion zone is, in fact, the internal mechanism of the Kadenacy effect. There will be no “breathing” of fresh air into the combustion zone until the arrival of the rarefaction wave.

The wave motion through the air masses should not be confused with the separate motions of the masses themselves. At the start of deflagration, the pressure wave immediately moves through both air masses, while the gas expansion (due to combustion heat) is just beginning in the combustion zone. The intake air mass will be rapidly accelerated outward behind the pressure wave, because its mass is relatively small. The tailpipe air mass will follow the outgoing pressure wave much more slowly. Also, the eventual flow reversal will take place much sooner in the intake, due to its smaller air mass. The timing of the wave motions is determined basically by the lengths of the intake and main tube of the engine; the timing of mass motions is determined mostly by the volumes and exact shapes of these sections. Both are affected by local gas temperatures.

In the valveless engine, there will actually be two arrivals of rarefaction waves — first, from the intake and then from the tailpipe. In typical valveless designs, the wave that comes back from the intake will be relatively weak. Its main effect is to begin flow reversal in the intake itself, in effect “pre-loading” the intake duct with fresh outdoor air. The actual “breathing” of the engine as a whole will not begin in earnest until the major low pressure wave from the tailpipe reaches the combustion zone. Once that happens, significant flow reversal begins, driven by the drop in combustion zone pressure.

During this phase, too, there is a difference in action between the very different masses in the intake and tailpipe. The intake air mass is again fairly low, but it now almost totally consists of outside air; therefore, fresh air is available almost immediately to begin re-filling the combustion zone from the front. The tailpipe air mass is also pulled, eventually reversing direction as well. The tailpipe will never be completely purged of hot combustion gases, but at reversal it will be easily able to pull in fresh air from all sides around the tailpipe opening, so its contained mass will be gradually increasing until the next deflagration event. As air flows rapidly into the combustion zone, the rarefaction wave is reflected rearward by the front of the engine body, and as it moves rearward the air density in the combustion zone naturally rises until the pressure of the air/fuel mixture reaches a value where deflagration can again commence.

5.4 Practical design issues

In practical designs there is no need for a continuous ignition system — the combustion zone is never totally purged of combustion gases and free radicals, so there is enough chemical action in the residue in the combustion zone to act as an igniter for the next blast once the mixture is up to a reasonable density and pressure: the cycle repeats, controlled only by the synchronization of pressure and flow events in the two ducts.

While it is theoretically possible to have such an engine without a distinct "combustion chamber" larger than the tailpipe diameter, all successful valveless engines designed so far have a widened chamber of some sort, roughly similar to that found in typical valved engine designs. The chamber typically takes up a fairly small fraction of the overall main tube length.

The acceleration of air mass back through the intake duct doesn't make sense for engine thrust if the intake is aimed forward, since the intake thrust is a fairly large fraction of the tailpipe thrust. Various engine geometries have been used to make the thrust forces from the two ducts act in the same direction. One simple method is to turn the engine around and then put a U-bend in the tailpipe, so both ducts are spouting rearward, as in the Ecrevisse and Lockwood (also known as Lockwood-Hiller) types. The Escopette and Kentfield designs use recuperators (U-shaped auxiliary tubes) mounted in front of the front-firing intakes to turn the intake blast and flow rearward. The so-called "Chinese" and Thermojet styles simply mount the intake on the chamber in a rear-spouting direction, leaving the front face of the chamber unbroken. The basic internal operation of the engine with these geometries is no different from that described above, however. The Lockwood is unique in one respect, namely, its very large diameter intake — the thrust from this large tube is no less than 40 percent of the engine thrust as a whole. The tailpipe volume of this design is quite large, though, so the imbalance of the contained masses is still clearly seen.

5.5 "Jam jar jet" design

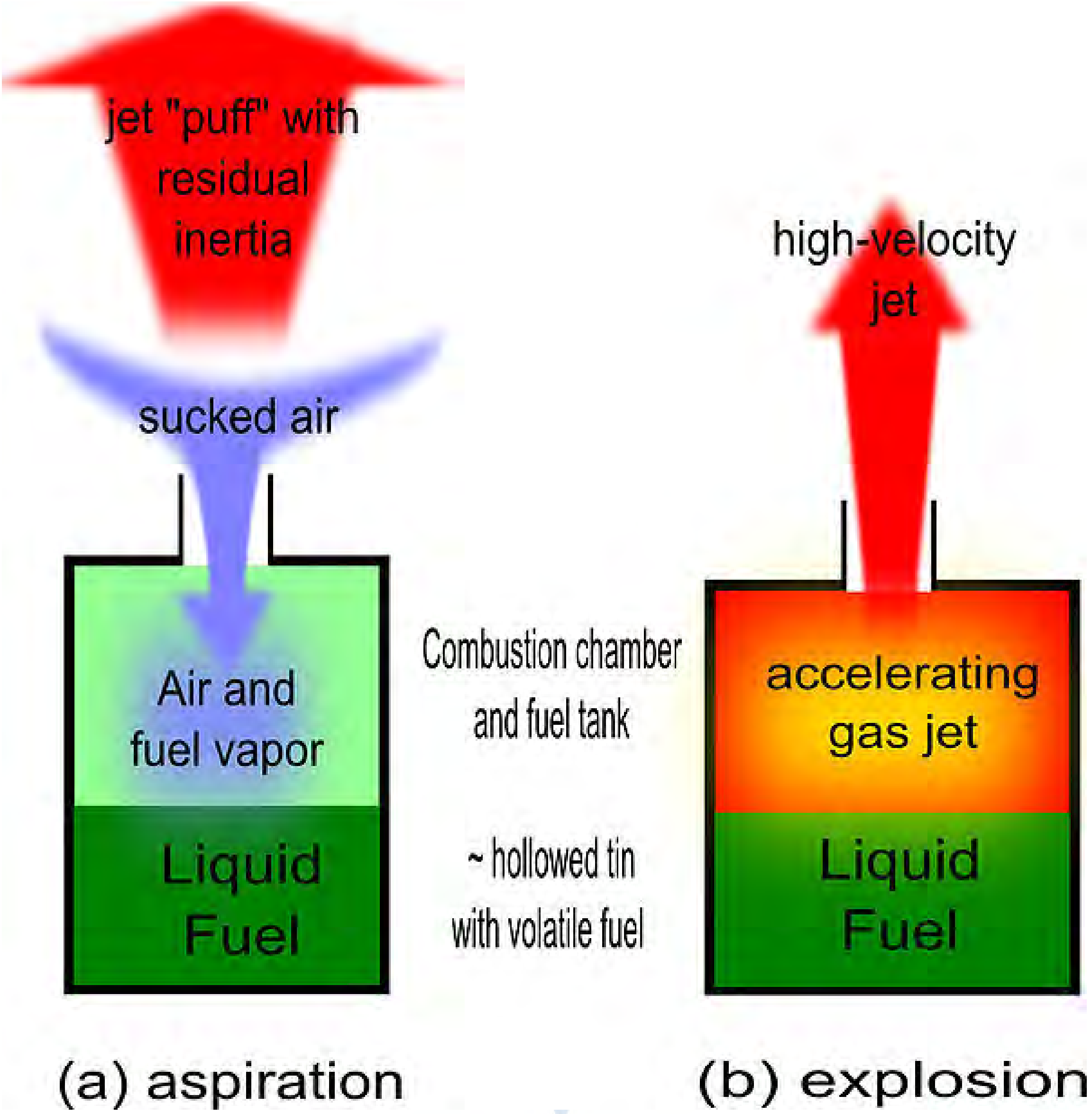
Most pulse jet engines use independent intake and exhaust pipes. A physically simpler design combines the intake and exhaust aperture. This is possible due to the oscillating behaviour of a pulse engine. One aperture can act as exhaust pipe during the high-pressure phase of the work cycle and as intake during the aspiration phase. This engine design is less efficient in this primitive form due to its lack of a resonant pipe and thus a lack of reflected compressing and sucking acoustic waves. However it works fairly well with a simple instrument such as jam jar with a pierced lid and fuel inside, hence the name.

Successful versions of the jam jar jet have been run in a plastic bottle. The bottle is far less efficient than the jam jar versions and is unable to sustain a decent jet for more than a few seconds. It is theorized that the alcohol that was used to operate the simple jet was acting as a barrier to stop the heat getting all the way through to the plastic. For the jam jar jet design to work the propellant must be vaporised to ignite which is most often done by a shaking of the jet which causes the propellant to coat the container, therefore giving the theory some validity.

5.6 Pros and cons

Successful valveless pulsejets have been built from a few centimeters in length to huge sizes, though the largest and smallest have not been used for propulsion. The smallest ones are only successful when extremely fast-burning fuels are employed (acetylene or hydrogen, for example). Medium and larger sized engines can be made to burn almost any flammable material that can be delivered uniformly to the combustion zone, though of course volatile flammable liquids (gasoline, kerosene, various alcohols) and standard fuel gases (LPG, propane, butane, MAPP gas) are easiest to use. Because of the deflagration nature of pulsejet combustion, these engines are extremely efficient combustors, producing practically no hazardous pollutants, even when using hydrocarbon fuels. With modern high-temperature metals for the main structure, engine weight can be kept extremely low. Without the presence of a mechanical valve, the engines require practically no ongoing maintenance to remain operational.

Up to the present, the physical size of successful valveless designs has always been somewhat larger than valved engines



Work mechanism of jam jar jet. (b) Mixture of air and fuel vapors could ignite using external igniter or by residual free radicals from last work cycle. (a) The previous jet expelled more air than conform to equilibrium pressure in chamber, thus some of the fresh air is sucked back. The pressure drop in this case is caused more by cooling of the gas in chamber than by gas inertia. Gas inertia can not be used well in this design because of lack of exhaust (resonator) pipe and very dissipative aerodynamics of the aperture.

for the same thrust value, though this is theoretically not a requirement. Like valved pulsejets, heat (engines frequently run white hot) and very high operational noise levels (140 decibels is possible) are among the greatest disadvantages of these engines. An ignition system of some sort is required for engine startup. In the smallest sizes, forced air at the intake is also typically needed for startup. There is still much room for improvement in the development of really efficient, fully practical designs for propulsion uses.

One possible solution to the ongoing problem of pulse jet inefficiency would be to have two pulse jets in one, with each blast compressing the mixture of fuel and air in the other, and both ends discharging into a common chamber through which air flows only one way. This could potentially allow much higher compression ratios, better fuel efficiencies, and greater thrust.[1]

5.7 See also

- Gluhareff Pressure Jet

5.8 References

[1] Ogorelec, Bruno. "Blast Compression Valveless Pulsejet Engine (A Layman's Concept)". Retrieved 2013-05-29.

5.9 External links

- http://www.pulse-jets.com/ - An international site dedicated to pulsejets, including design and experimentation. Includes an extremely active forum composed of knowledgeable enthusiasts.
- http://www.PulseJetEngines.com/ - A site for hobby jet propulsion, specifically valved and valveless pulsejet engines. They offer many free pulse jet plans, and have a lot of useful information.
- Valveless you can find under Pulso

Chapter 6

Pulse detonation engine

A **pulse detonation engine**, or "PDE", is a type of propulsion system that uses detonation waves to combust the fuel and oxidizer mixture.[1][2] The engine is pulsed because the mixture must be renewed in the combustion chamber between each detonation wave initiated by an ignition source. Theoretically, a PDE can operate from subsonic up to a hypersonic flight speed of roughly Mach 5. An ideal PDE design can have a thermodynamic efficiency higher than other designs like turbojets and turbofans because a detonation wave rapidly compresses the mixture and adds heat at constant volume. Consequently, moving parts like compressor spools are not necessarily required in the engine, which could significantly reduce overall weight and cost. PDEs have been considered for propulsion for over 70 years.[3] Key issues for further development include fast and efficient mixing of the fuel and oxidizer, the prevention of autoignition, and integration with an inlet and nozzle.

To date, no practical PDE has been put into production, but several testbed engines have been built and one was successfully integrated into a low-speed demonstration aircraft that flew in sustained PDE powered flight in 2008. In June 2008, the Defense Advanced Research Projects Agency (DARPA) unveiled Blackswift, which was intended to use this technology to reach speeds of up to Mach 6.[4] However the project was cancelled soon afterward, in October 2008.

6.1 Concept

6.1.1 Pulse jets

The basic operation of the PDE is similar to that of the pulse jet engine. In the pulse jet, air is mixed with fuel to create a flammable mixture that is then ignited in an open chamber. The resulting combustion greatly increases the pressure of the mixture to approximately 100 atmospheres (10 MPa),[5] which then expands through a nozzle for thrust.

To ensure that the mixture exits to the rear, thereby pushing the aircraft forward, a series of shutters are used to close off the front of the engine. Careful tuning of the inlet ensures the shutters close at the right time to force the air to travel in one direction only through the engine. Some pulse jet designs used a tuned resonant cavity to provide the valving action through the airflow in the system. These designs normally look like a U-shaped tube, open at both ends.

In either system, the pulse jet has problems during the combustion process. As the fuel burns expands to create thrust, it is also pushing any remaining unburnt charge rearward, out the nozzle. In many cases some of the charge is ejected before burning, which causes the famous trail of flame seen on the V-1 flying bomb and other pulse jets. Even while inside the engine, the mixture's volume is constantly changing which inefficiently converts fuel into usable energy.

6.1.2 PDEs

All regular jet engines and most rocket engines operate on the *deflagration* of fuel, that is, the rapid but subsonic combustion of fuel. The pulse detonation engine is a concept currently in active development to create a jet engine that operates on the supersonic *detonation* of fuel. Because the combustion takes place so rapidly, the charge (fuel/air mix) does not have time to expand during this process, so it takes place under almost constant volume. Constant volume combustion is more efficient than open-cycle designs like gas turbines, which leads to greater fuel efficiency.

As the combustion process is so rapid, mechanical shutters are difficult to arrange with the required performance. Instead, PDEs generally use a series of valves to carefully time the process. In some PDE designs from General Electric, the shutters are eliminated through careful timing, using the pressure differences between the different areas of the engine to ensure the “shot” is ejected rearward.

Another side effect, not yet demonstrated in practical use, is the cycle time. A traditional pulsejet tops out at about 250 pulses per second due to the cycle time of the mechanical shutters, but the aim of the PDE is thousands of pulses per second, so fast that it is basically continuous from an engineering perspective. This should help smooth out the otherwise highly vibrational pulsejet engine — many small pulses will create less volume than a smaller number of larger pulses for the same net thrust. Unfortunately, detonations are many times louder than deflagrations.

This is said to increase the amount of heat produced per unit of fuel above any other engines, although conversion of that energy into thrust would remain inefficient. A combustion process able to produce more heat per unit of fuel would, of course, be incredibly valuable in countless applications.

The major difficulty with a pulse-detonation engine is starting the detonation. While it is possible to start a detonation directly with a large spark, the amount of energy input is very large and is not practical for an engine. The typical solution is to use a deflagration-to-detonation transition (DDT)—that is, start a high-energy deflagration, and have it accelerate down a tube to the point where it becomes fast enough to become a detonation. Alternatively the detonation can be sent around a circle and valves ensure that only the highest peak power can leak into exhaust.

This process is far more complicated than it sounds, due to the resistance the advancing wavefront encounters (similar to wave drag). DDTs occur far more readily if there are obstacles in the tube. The most widely used is the "Shchelkin spiral", which is designed to create the most useful eddies with the least resistance to the moving fuel/air/exhaust mixture. The eddies lead to the flame separating into multiple fronts, some of which go backwards and collide with other fronts, and then accelerate into fronts ahead of them.

The behavior is difficult to model and to predict, and research is ongoing. As with conventional pulsejets, there are two main types of designs: valved and valveless. Designs with valves encounter the same difficult-to-resolve wear issues encountered with their pulsejet equivalents. Valveless designs typically rely on abnormalities in the air flow to ensure a one-way flow, and are very hard to achieve in a regular DDT.

NASA maintains a research program on the PDE, which is aimed at high-speed, about Mach 5, civilian transport systems. However most PDE research is military in nature, as the engine could be used to develop a new generation of high-speed, long-range reconnaissance aircraft that would fly high enough to be out of range of any current anti-aircraft defenses, while offering range considerably greater than the SR-71, which required a massive tanker support fleet to use in operation.

While most research is on the high speed regime, newer designs with much higher pulse rates in the hundreds of thousands appear to work well even at subsonic speeds. Whereas traditional engine designs always include tradeoffs that limit them to a “best speed” range, the PDE appears to outperform them at all speeds. Both Pratt & Whitney and General Electric now have active PDE research programs in an attempt to commercialize the designs.

Key difficulties in pulse detonation engines are achieving DDT without requiring a tube long enough to make it impractical and drag-imposing on the aircraft (adding a U-bend into the tube extinguishes the detonation wave); reducing the noise (often described as sounding like a jackhammer); and damping the severe vibration caused by the operation of the engine.

6.2 First PDE powered flight

The first flight of an aircraft powered by a pulse detonation engine took place at the Mojave Air & Space Port on January 31, 2008.[6] The project was developed by the Air Force Research Laboratory and Innovative Scientific Solutions, Inc. The aircraft selected for the flight was a heavily modified Scaled Composites Long-EZ, named *Borealis*.[7] The engine consisted of four tubes producing pulse detonations at a frequency of 80 Hz, creating up to 200 pounds of thrust (890 newtons). Many fuels were considered and tested by the engine developers in recent years, but a refined octane was used for this flight. A small rocket system was used to facilitate the liftoff of the Long-EZ, but the PDE operated under its own power for 10 seconds at an altitude of approximately 100 feet (30 m). Obviously, this flight took place at a low speed whereas the appeal of the PDE engine concept lies more at high speeds, but the demon-

In-flight picture of the pulsed detonation powered, and heavily modified, Rutan Long-EZ on January 31, 2008.

stration showed that a PDE can be integrated into an aircraft frame without experiencing structural problems from the 195-200 dB detonation waves. No more flights are planned for the modified Long-EZ, but the success is likely to fuel more funding for PDE research. The aircraft itself has been moved to the National Museum of the United States Air Force for display.[8]

6.3 Popular culture

- In the sci-fi novel *Aelita* (1923), two Russians travel to Mars in a pulse detonation rocket utilizing “a fine powder of unusual explosive force” (p. 19).
- In the drama television series *JAG*, the Season Nine episode “The One That Got Away” (original air date October 17, 2003) features the Aurora — which in the show is a super-secret hypersonic aircraft under development by the CIA that uses a pulse-detonation engine.
- In the movie *Stealth* (2005), the advanced fighters use pulse-detonation engines with scramjet boosters.
- The PDE has been used as a story point in a number of modern novels such as Dan Brown's thriller, *Deception Point* (the second page of the book states that all technologies in the story are non-fictional and exist, albeit without referencing any sources), and Victor Koman's science fiction polemic, *Kings of the High Frontier*.
- In X-COM (UFO: Enemy Unknown), the initial basic Interceptor aircraft, containing only completely human-developed technology (as opposed to later craft that incorporate reverse-engineered alien technology), is equipped with dual pulse detonation engines, capable of sustained flight speed of 2100 knots, minimal speed of about 1000 knots.
- In the SyFy television series, Eureka, season 4 episode 10 features a flying sleigh described as being powered by a PDE.

6.4 See also

- Scramjet
- Nuclear pulse propulsion

6.5 References

[1] Kailasanath, K., “Review of Propulsion Applications of Detonation Waves,” *AIAA Journal*, Vol. 39, No. 9, pp. 1698-1708, 2000.

[2] Roy, G.D., Frolov, S.M., Borisov, A.A., and Netzer, D.W., “Pulse Detonation Propulsion: Challenges, Current Status, and Future Perspective,” *Progress in Energy and Combustion Science*, Vol. 30, No. 6, pp. 545-672, 2004.

[3] Hoffmann, N., *Reaction Propulsion by Intermittent Detonative Combustion,* German Ministry of Supply, Volkenrode Translation, 1940.

[4] Shachtman, Noah (June 24, 2008). “Explosive Engine Key to Hypersonic Plane”. *Wired (magazine)* (San Francisco, California: Condé Nast Publications). Retrieved 2009-06-27.

[5] “Pulse Detonation Engines”, An interview with Dr John Hoke, head researcher from Innovative Scientific Solutions Incorporated PDE program under contract to the United States Air Force Research Laboratory, broadcast on New Zealand radio, 14th April 2007

[6] Norris, G., “Pulse Power: Pulse Detonation Engine-powered Flight Demonstration Marks Milestone in Mojave,” *Aviation Week & Space Technology*, Vol. 168, No. 7, 2008, pp. 60.

[7] *Borealis* display poster text at Museum of USAF

[8] “Pulse Detonation Engine Flies Into History”, *Air Force Print News Today*, May 16, 2008, accessed August 16, 2008

6.6 External links

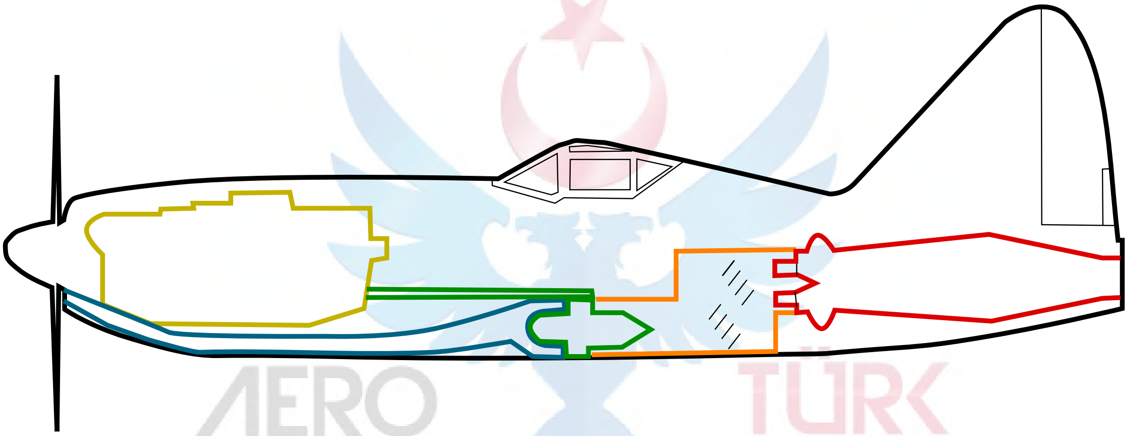
- Innovative Scientific Solutions Inc.
- Pulse Detonation Engines
- Popular Science
- 1952 Pulse Detonation Jet Propulsion Patent by William Bollay
- Apparatus powered using laser-supplied energy, US patent Issued on August 6, 1996 Boyd B. Bushman
- (Video) The high detonation temperature inside the tube of an experimental PDE causes the seals to heat up and catch fire.
- (Video) An experimental PDE operating with a detonation frequency of 1 Hz where the pulses are clearly defined.
- (Video) An experimental PDE operating with a detonation frequency of 25 Hz.
- 2-D pulse-detonation engine simulation
- Fox News report on the Blackswift
- DARPA May 2009 notes on PDE

Chapter 7

Motorjet

“Thermojet” redirects here. For the type of pulsejet, see pulse jet engine.

A **motorjet** is a rudimentary type of jet engine which is sometimes referred to as *thermojet*, a term now commonly used to describe a particular and completely unrelated pulsejet design.



Main components of motorjet-powered aircraft; the propeller is absent on some designs

7.1 Design

At the heart the motorjet is an ordinary piston engine (hence, the term *motor*), but instead of (or sometimes, as well as) driving a propeller, it drives a compressor. The compressed air is channeled into a combustion chamber, where fuel is injected and ignited. The high temperatures generated by the combustion cause the gases in the chamber to expand and escape at high velocity from the exhaust, creating a thermal reactive force that provides useful thrust.

Motorjet engines provide greater thrust than a propeller alone mounted on a piston engine; this has been successfully demonstrated in a number of different aircraft. A jet engine also can provide thrust at higher speeds where a propeller becomes less efficient or even ineffective; in fact, a jet engine gains efficiency as speed rises, while a propeller loses it (outside of a certain design range). This gives better efficiency in either operating range than an aircraft powered by just a propeller or a jet. The same is true of the dual-powerplant aircraft experimented with after the turbojet became practicable, which were equipped with both a piston-driven propeller and a turbojet engine.

7.2 History

- In 1908 French inventor René Lorin proposed using a piston engine to compress air that would then be mixed with fuel and burned to produce pulses of hot gas that would be expelled through a nozzle to generate a propelling force.[1]

- In 1917, O. Morize of Chateaudun, France, proposed the Morize ejector scheme in which a reciprocating engine drove a compressor supplying air to a liquid-fueled combustion chamber which discharged into a convergent-divergent tube and ultimately out into the atmosphere.
- The term “motor jet” was established in a patent filed in Britain by J.H. Harris of Esher, U.K., in 1917.
- It was next explored by Secondo Campini in the early 1930s, although it was not until 1940 that an aircraft, the Caproni Campini N.1 (sometimes referred to as C.C.2), would fly powered by his engine. Campini established the misnomer ***thermojet*** at this time to describe his motorjet.
- NACA engineer Eastman Jacobs was actively pursuing thermojet research in the early 1940s for a project that came to be known as Jake’s jeep which was never completed as turbojet technology overtook it.
- Japanese engineers developed the Tsu-11 motorjet engine to power Ohka aircraft as an alternative to the solid-fuel rocket engines that these aircraft were then using.
- The Soviet Mikoyan-Gurevich I-250 (N) designed in 1944 used a piston engine to drive both a propeller at the nose of the plane, and a motorjet compressor leading to a jet exhaust at the tail. Between 10 and 50 I-250 (a.k.a. MiG-13) aircraft were produced, serviced, and flown by the Soviet Navy through 1950. A similar Sukhoi Su-5 plane had been designed, but never produced.
- Canadian inventor Mark Nye (Nye Thermodynamics Corporation) built a successful thermojet based on a single-stage axial fan of his own design driven by a V6 automobile engine in 2002. The jet pipe consisted of three 55-gallon drums welded together with a cable-operated variable-area nozzle and a fabricated flame holder. This gasoline-fueled, 85 lbf (0.38 kN) thrust design was used to power his three-wheeled dragster to victory on Discovery Channel’s *JunkYard Wars* in Los Angeles in August 2002.

Motorjet research was nearly abandoned at the end of World War II as the turbojet was a more practical solution to jet power as it used the jet exhaust to drive a gas turbine, providing the power to drive the compressor without the additional weight of a piston engine that generated no thrust. One of the primary advantages of the motorjet layout was that the reciprocating engine provided power for the compressor and no turbine power section was needed. However, metallurgy and understanding of the design of turbines had advanced to a point after WWII where it was feasible to create a turbine to operate reliably in the high-velocity hot-gas environment downstream of the combustor, and the motorjet idea lost focus.

7.3 Notes

[1] Reithmaier, Larry (1994). *Mach 1 and Beyond*. McGraw-Hill Professional. p. 74. ISBN 0-07-052021-6.

7.4 External links

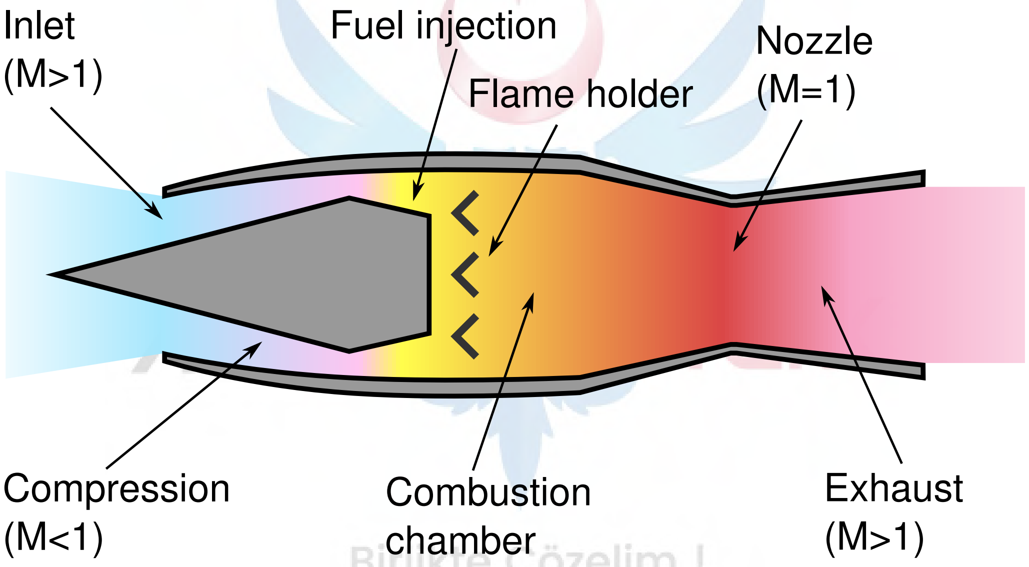
- A motorjet history and research webpage
- Nye Thermodynamics Thermojet

Chapter 8

Ramjet

For other uses, see Ramjet (disambiguation).

A **ramjet**, sometimes referred to as a **flying stovepipe** or an **athodyd** (an abbreviation of **a**ero **th**erm**ody**namic **d**uct), is a form of airbreathing jet engine that uses the engine's forward motion to compress incoming air without a rotary compressor. Ramjets cannot produce thrust at zero airspeed; they cannot move an aircraft from a standstill. A ramjet powered vehicle, therefore, requires an assisted take off like a JATO to accelerate it to a speed where it begins to produce thrust. Ramjets work most efficiently at supersonic speeds around Mach 3. This type of engine can operate up to speeds of Mach 6.



Simple ramjet operation, with Mach numbers of flow shown

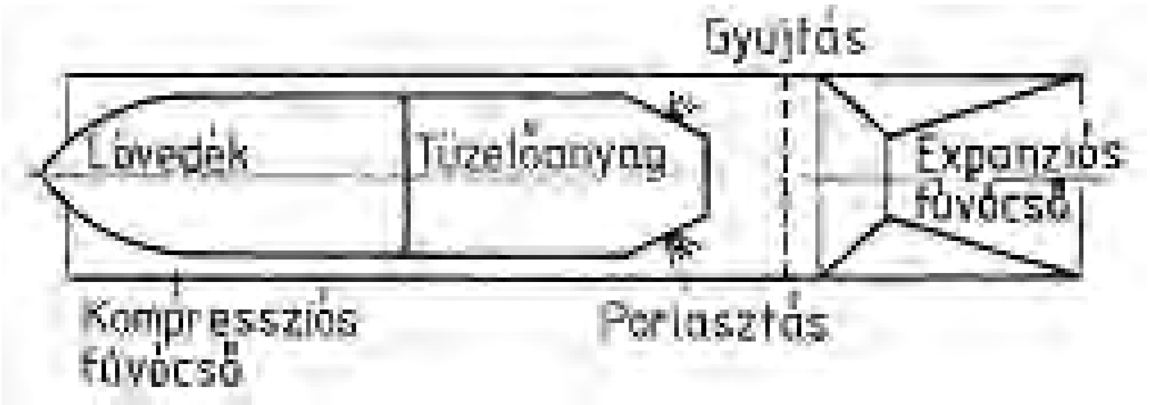
Ramjets can be particularly useful in applications requiring a small and simple mechanism for high-speed use, such as missiles or artillery shells. Weapon designers are looking to use ramjet technology in artillery shells to give added range; a 120 mm mortar shell, if assisted by a ramjet, is thought to be able to attain a range of 22 mi (35 km).[1] They have also been used successfully, though not efficiently, as tip jets on the end of helicopter rotors.[2]

Ramjets are frequently confused with pulsejets, which use an intermittent combustion; however, ramjets employ a continuous combustion process. They are also confused with scramjets, a similar system designed for higher speeds that uses a supersonic airflow in its combustion chamber. While a scramjet works with the same technology, the combustion process differs slightly, resulting in a higher cruise speed.

8.1 History

8.1.1 Cyrano de Bergerac

L'Autre Monde: ou les États et Empires de la Lune (*Comical History of the States and Empires of the Moon*) was the first of three satirical novels written by Cyrano de Bergerac, that are considered among the first science fiction stories. Arthur C Clarke credited this book for inventing the ramjet,[3] and being the first example of a rocket-powered space flight.



Albert Fonó's ramjet-cannonball from 1915

8.1.2 René Lorin

The ramjet was conceived in 1913 by French inventor René Lorin, who was granted a patent for his device. Attempts to build a prototype failed due to inadequate materials.[4]

8.1.3 Albert Fonó

In 1915, Hungarian inventor Albert Fonó devised a solution for increasing the range of artillery, comprising a gun-launched projectile which was to be united with a ramjet propulsion unit, thus giving a long range from relatively low muzzle velocities, allowing heavy shells to be fired from relatively lightweight guns. Fonó submitted his invention to the Austro-Hungarian Army, but the proposal was rejected.[5] After World War I, Fonó returned to the subject of jet propulsion, in May 1928 describing an "air-jet engine" which he described as being suitable for high-altitude supersonic aircraft, in a German patent application. In an additional patent application, he adapted the engine for subsonic speed. The patent was finally granted in 1932 after four years of examination (German Patent No. 554,906, 1932-11-02).[6]

8.1.4 Soviet Union

In the Soviet Union, a theory of supersonic ramjet engines was presented in 1928 by Boris Stechkin. Yuri Pobedonostsev, chief of GIRD's 3rd Brigade, carried out a great deal of research into ramjet engines. The first engine, the GIRD-04, was designed by I.A. Merkulov and tested in April 1933. To simulate supersonic flight, it was fed by air compressed to 200 atmospheres, and was fueled with hydrogen. The GIRD-08 phosphorus-fueled ramjet was tested by firing it from an artillery cannon. These shells may have been the first jet-powered projectiles to break the speed of sound.

In 1939, Merkulov did further ramjet tests using a two-stage rocket, the R-3. In August of that year, he developed the first ramjet engine for use as an auxiliary motor of an aircraft, the DM-1. The world's first ramjet-powered airplane flight took place in December 1939, using two DM-2 engines on a modified Polikarpov I-15. Merkulov designed a ramjet fighter "Samolet D" in 1941, which was never completed. Two of his DM-4 engines were installed on the Yak-7 PVRD fighter, during World War II. In 1940, the Kostikov-302 experimental plane was designed, powered by a liquid fuel rocket for take-off and ramjet engines for flight. That project was cancelled in 1944.

In 1947, Mstislav Keldysh proposed a long-range antipodal bomber, similar to the Sänger-Bredt bomber, but powered by ramjet instead of rocket. In 1954, NPO Lavochkin and the Keldysh Institute began development of a trisonic ramjet-powered cruise missile, *Burya*. This project competed with the R-7 ICBM being developed by Sergei Korolev, and was cancelled in 1957.

8.1.5 Germany

In 1936, Hellmuth Walter constructed a test engine powered by natural gas. Theoretical work was carried out at BMW and Junkers, as well as DFL. In 1941, Eugen Sänger of DFL proposed a ramjet engine with a very high combustion chamber temperature. He constructed very large ramjet pipes with 500 millimetres (20 in) and 1,000 millimetres (39 in) diameter and carried out combustion tests on lorries and on a special test rig on a Dornier Do 17Z at flight speeds of up to 200 m/s (720 km/h, 450 mph). Later, with petrol becoming scarce in Germany due to wartime conditions, tests were carried out with blocks of pressed coal dust as a fuel, which were not successful due to slow combustion.[7]

8.1.6 Gorgon IV

The Gorgon IV mounted on the wing of a P-61 Black Widow in preparation for flight testing

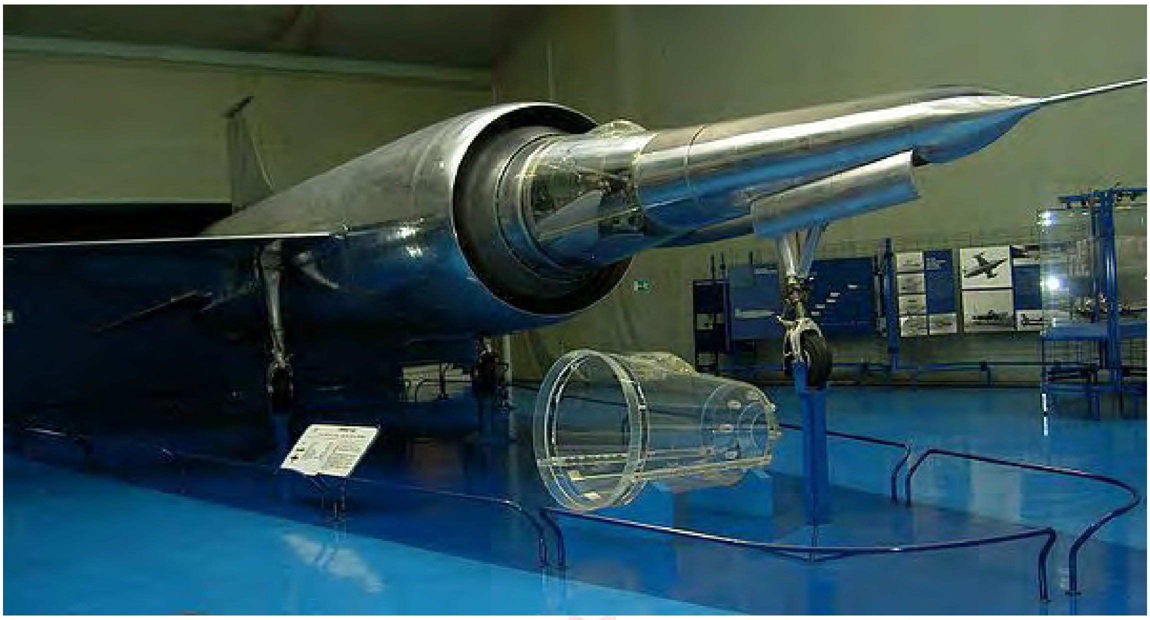
The US Navy developed a series of air-to-air missiles under the name of "Gorgon" using different propulsion mechanisms, including ramjet propulsion. The ramjet Gorgon IVs, made by Glenn Martin, were tested in 1948 and 1949 at Naval Air Station Point Mugu. The ramjet engine itself was designed at the University of Southern California and manufactured by the Marquardt Aircraft Company. The engine was 7 ft long and 20 in in diameter and was positioned below the missile (see photo).

8.1.7 Fritz Zwicky

Eminent Swiss astrophysicist Fritz Zwicky was research director at Aerojet and holds many patents in jet propulsion. U.S. Patent 5121670 is for the Ram Accelerator and U.S. Patent 4722261 is the Extendable Ram Cannon. The U.S. Navy would not allow Fritz Zwicky to publicly discuss his own invention, U.S. Patent 2,461,797 for the Underwater Jet, a ram jet that performs in a fluid medium. *Time* chronicles Fritz Zwicky's work in the "Missed Swiss", July 11, 1955, and the "Underwater Jet" in the March 14, 1949 issue.

8.1.8 France

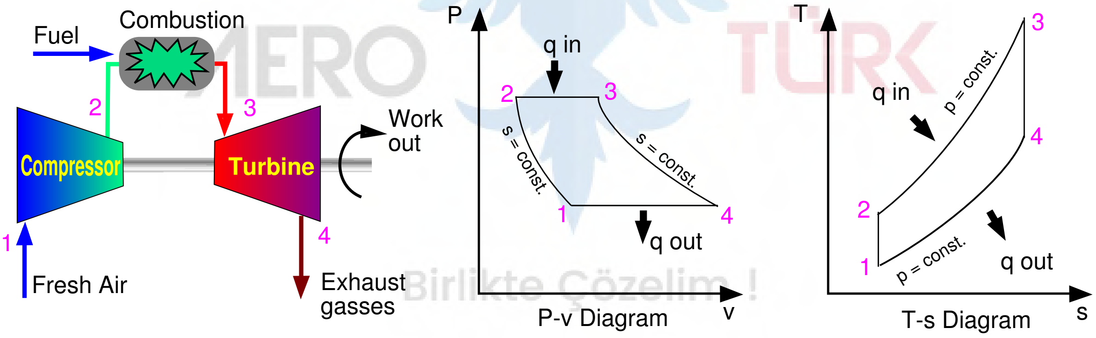
In France, the works of René Leduc were notable. Leduc's Model, the Leduc 0.10 was one of the first ramjet-powered aircraft to fly, in 1949.



Leduc 022

The Nord 1500 Griffon reached Mach 2.19 in 1958.

8.2 Engine cycle



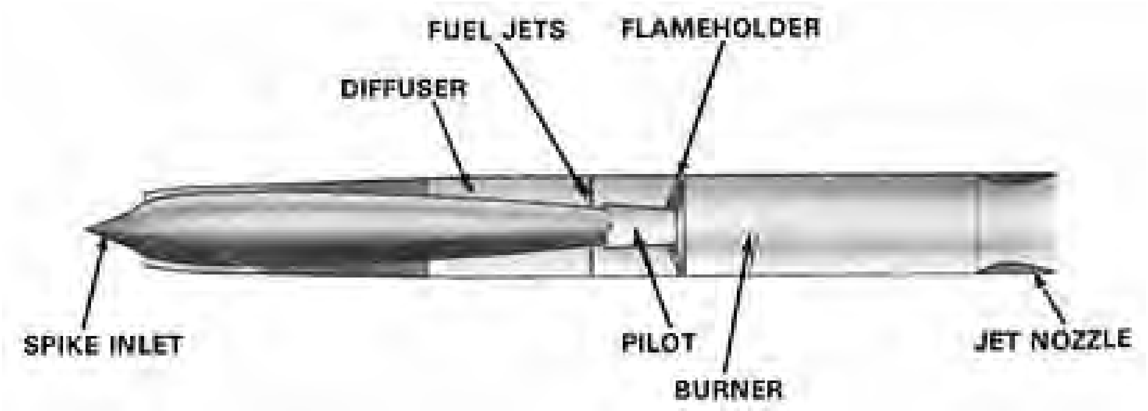
Brayton cycle

Main article: Brayton cycle

The **Brayton cycle** is a thermodynamic cycle that describes the workings of the gas turbine engine, the basis of the airbreathing jet engine and others. It is named after George Brayton (1830–1892), the American engineer who developed it, although it was originally proposed and patented by Englishman John Barber in 1791.[8] It is also sometimes known as the **Joule cycle**.

8.3 Design

A ramjet is designed around its inlet. An object moving at high speed through air generates a high pressure region upstream. A ramjet uses this high pressure in front of the engine to force air through the tube, where it is heated



A typical ramjet

by combusting some of it with fuel. It is then passed through a nozzle to accelerate it to supersonic speeds. This acceleration gives the ramjet forward thrust.

A ramjet is sometimes referred to as a 'flying stovepipe', a very simple device comprising an air intake, a combustor, and a nozzle. Normally, the only moving parts are those within the turbopump, which pumps the fuel to the combustor in a liquid-fuel ramjet. Solid-fuel ramjets are even simpler.

By way of comparison, a turbojet uses a gas turbine-driven fan to compress the air further. This gives greater compression and efficiency and far more power at low speeds, where the ram effect is weak, but is also more complex, heavier and expensive, and the temperature limits of the turbine section limit the top speed and thrust at high speed.

8.3.1 Inlet

Ramjets try to exploit the very high dynamic pressure within the air approaching the intake lip. An efficient intake will recover much of the freestream stagnation pressure, which is used to support the combustion and expansion process in the nozzle.

Most ramjets operate at supersonic flight speeds and use one or more conical (or oblique) shock waves, terminated by a strong normal shock, to slow down the airflow to a subsonic velocity at the exit of the intake. Further diffusion is then required to get the air velocity down to a suitable level for the combustor.

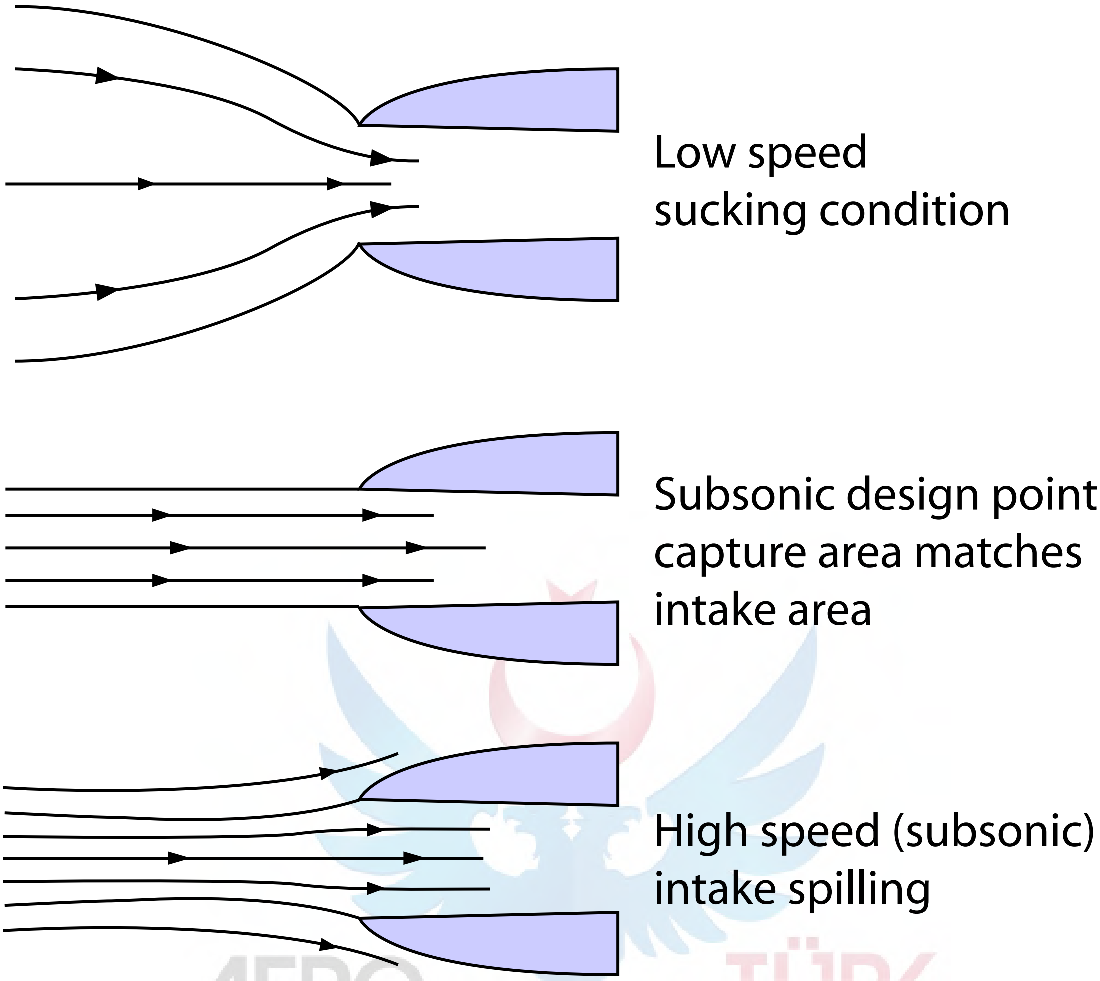
Subsonic ramjets do not need such a sophisticated inlet since the airflow is already subsonic and a simple hole is usually used. This would also work at slightly supersonic speeds, but as the air will choke at the inlet, this is inefficient.

The inlet is divergent, to provide a constant inlet speed of Mach 0.5.

8.3.2 Combustor

As with other jet engines, the combustor's job is to create hot air, by burning a fuel with the air at essentially constant pressure. The airflow through the jet engine is usually quite high, so sheltered combustion zones are produced by using 'flame holders' to stop the flames from blowing out.

Since there is no downstream turbine, a ramjet combustor can safely operate at stoichiometric fuel:air ratios, which implies a combustor exit stagnation temperature of the order of 2400 K for kerosene. Normally, the combustor must be capable of operating over a wide range of throttle settings, for a range of flight speeds/altitudes. Usually, a sheltered pilot region enables combustion to continue when the vehicle intake undergoes high yaw/pitch during turns. Other flame stabilization techniques make use of flame holders, which vary in design from combustor cans to simple flat plates, to shelter the flame and improve fuel mixing. Overfuelling the combustor can cause the normal shock within a supersonic intake system to be pushed forward beyond the intake lip, resulting in a substantial drop in engine airflow and net thrust.



Subsonic intakes on ramjets are relatively simple.

8.3.3 Nozzles

The propelling nozzle is a critical part of a ramjet design, since it accelerates exhaust flow to produce thrust.

For a ramjet operating at a subsonic flight Mach number, exhaust flow is accelerated through a converging nozzle. For a supersonic flight Mach number, acceleration is typically achieved via a convergent-divergent nozzle.

8.3.4 Performance and control

Although ramjets have been run from as low as 45 m/s (162 km/h, 100 mph)[9] upwards, below about Mach 0.5, they give little thrust and are highly inefficient due to their low pressure ratios.

Above this speed, given sufficient initial flight velocity, a ramjet will be self-sustaining. Indeed, unless the vehicle drag is extremely high, the engine/airframe combination will tend to accelerate to higher and higher flight speeds, substantially increasing the air intake temperature. As this could have a detrimental effect on the integrity of the engine and/or airframe, the fuel control system must reduce engine fuel flow to stabilize the flight Mach number and, thereby, air intake temperature to reasonable levels.

Due to the stoichiometric combustion temperature, efficiency is usually good at high speeds (Mach 2-3), whereas at low speeds the relatively poor pressure ratio means the ramjets are outperformed by turbojets, or even rockets.

One of the two Bristol Thor ramjet engines on a Bristol Bloodhound missile

8.4 Types

Ramjets can be classified according to the type of fuel, liquid or solid; and the booster.[10]

In a liquid fuel ramjet (LFRJ), hydrocarbon fuel (typically) is injected into the combustor ahead of a flameholder which stabilises the flame resulting from the combustion of the fuel with the compressed air from the intake(s). A means of pressurizing and supplying the fuel to the ramcombustor is required, which can be complicated and expensive. Aérospatiale-Celerg designed an LFRJ where the fuel is forced into the injectors by an elastomer bladder which inflates progressively along the length of the fuel tank. Initially, the bladder forms a close-fitting sheath around the compressed air bottle from which it is inflated, which is mounted lengthwise in the tank.[11] This offers a lower-cost approach than a regulated LFRJ requiring a turbopump and associated hardware to supply the fuel.[12]

A ramjet generates no static thrust and needs a booster to achieve a forward velocity high enough for efficient operation of the intake system. The first ramjet-powered missiles used external boosters, usually solid-propellant rockets, either in tandem, where the booster is mounted immediately aft of the ramjet, e.g. Sea Dart, or wraparound where multiple boosters are attached alongside the outside of the ramjet, e.g. SA-4 Ganef. The choice of booster arrangement is usually driven by the size of the launch platform. A tandem booster increases the overall length of the system, whereas wraparound boosters increase the overall diameter. Wraparound boosters will usually generate higher drag than a tandem arrangement.

Integrated boosters provide a more efficient packaging option, since the booster propellant is cast inside the otherwise empty combustor. This approach has been used on solid, for example SA-6 Gainful, liquid, for example ASMP, and ducted rocket, for example Meteor, designs. Integrated designs are complicated by the different nozzle requirements of the boost and ramjet phases of flight. Due to the higher thrust levels of the booster, a differently shaped nozzle is required for optimum thrust compared to that required for the lower thrust ramjet sustainer. This is usually achieved via a separate nozzle, which is ejected after booster burnout. However, designs such as Meteor feature nozzleless boosters. This offers the advantages of elimination of the hazard to launch aircraft from the ejected boost nozzle debris, simplicity, reliability, and reduced mass and cost,[13] although this must be traded against the reduction in performance compared with that provided by a dedicated booster nozzle.

8.5 Integral rocket ramjet/ducted rocket

Main article: Air-augmented rocket

A slight variation on the ramjet uses the supersonic exhaust from a rocket combustion process to compress and react with the incoming air in the main combustion chamber. This has the advantage of giving thrust even at zero speed.

In a solid fuel integrated rocket ramjet (SFIRR), the solid fuel is cast along the outer wall of the ramcombustor. In this case, fuel injection is through ablation of the propellant by the hot compressed air from the intake(s). An aft mixer may be used to improve combustion efficiency. SFIRRs are preferred over LFRJs for some applications because of the simplicity of the fuel supply, but only when the throttling requirements are minimal, i.e. when variations in altitude or Mach number are limited.

In a ducted rocket, a solid fuel gas generator produces a hot fuel-rich gas which is burnt in the ramcombustor with the compressed air supplied by the intake(s). The flow of gas improves the mixing of the fuel and air and increases total pressure recovery. In a throttleable ducted rocket, also known as a variable flow ducted rocket, a valve allows the gas generator exhaust to be throttled allowing control of the thrust. Unlike an LFRJ, solid propellant ramjets cannot flame out. The ducted rocket sits somewhere between the simplicity of the SFRJ and the unlimited throttleability of the LFRJ.

8.6 Flight speed

Ramjets generally give little or no thrust below about half the speed of sound, and they are inefficient (less than 600 seconds) until the airspeed exceeds 1000 km/h (600 mph) due to low compression ratios. Even above the minimum speed, a wide flight envelope (range of flight conditions), such as low to high speeds and low to high altitudes, can force significant design compromises, and they tend to work best optimised for one designed speed and altitude (point designs). However, ramjets generally outperform gas turbine-based jet engine designs and work best at supersonic speeds (Mach 2–4).[14] Although inefficient at slower speeds, they are more fuel-efficient than rockets over their entire useful working range up to at least Mach 6.

The performance of conventional ramjets falls off above Mach 6 due to dissociation and pressure loss caused by shock as the incoming air is slowed to subsonic velocities for combustion. In addition, the combustion chamber's inlet temperature increases to very high values, approaching the dissociation limit at some limiting Mach number.

8.7 Related engines

8.7.1 Air turboramjet

Main article: Air turboramjet

Another example of this is the air turboramjet, which has a compressor powered by a gas heated via a heat exchanger within the combustion chamber.

8.7.2 Scramjets

Main article: Scramjet

Ramjets always slow the incoming air to a subsonic velocity within the combustor. Scramjets, or "supersonic combustion ramjet" are similar to ramjets, but some of the air goes through the entire engine at supersonic speeds. This increases the stagnation pressure recovered from the freestream and improves net thrust. Thermal choking of the exhaust is avoided by having a relatively high supersonic air velocity at combustor entry. Fuel injection is often into a sheltered region below a step in the combustor wall. Although scramjet engines have been studied for many decades, only recently have small experimental units been flight tested and then only very briefly (e.g. the Boeing X-43).[15]

As of May, 2010, this engine has been tested to attain Mach 5 for 200 seconds on the X-51A Waverider.[16]

8.7.3 Precooled engines

Main article: Precooled jet engine

A variant of the pure ramjet is the 'combined cycle' engine, intended to overcome the limitations of the pure ramjet. One example of this is the SABRE engine; this uses a precooler, behind which is the ramjet and turbine machinery.

The ATREX engine developed in Japan is an experimental implementation of this concept. It uses liquid hydrogen fuel in a fairly exotic, single-fan arrangement. The liquid hydrogen fuel is pumped through a heat exchanger in the air intake, simultaneously heating the liquid hydrogen, and cooling the incoming air. This cooling of the incoming air is critical to achieving a reasonable efficiency. The hydrogen then continues through a second heat exchanger position after the combustion section, where the hot exhaust is used to further heat the hydrogen, turning it into a very high pressure gas. This gas is then passed through the tips of the fan to provide driving power to the fan at subsonic speeds. After mixing with the air, it is burned in the combustion chamber.

The Reaction Engines Scimitar has been proposed for the LAPCAT hypersonic airliner, and the Reaction Engines SABRE for the Reaction Engines Skylon spaceplane.

8.7.4 Nuclear-powered ramjets

Main article: Project Pluto

During the Cold War, the United States designed and ground-tested a nuclear-powered ramjet called Project Pluto. This system used no combustion; a nuclear reactor heated the air instead. The project was ultimately canceled because ICBMs seemed to serve the purpose better, and because a low-flying radioactive missile could cause problems for any allied soldiers.

8.7.5 Ionospheric ramjet

The upper atmosphere above about 100 km contains monatomic oxygen produced by the sun through photochemistry. A concept was created by NASA for recombining this thin gas back to diatomic molecules at orbital speeds to power a ramjet.[17]

8.7.6 Bussard ramjet

Main article: Bussard ramjet

The Bussard ramjet is a space drive concept intended to fuse interstellar wind and exhaust it at high speed from the rear of the vehicle.

8.8 See also

- Aircraft engines
- Bussard ramjet
- Gas turbine
- Hypersonic
- Jet aircraft
- Jet engine
- Jet Engine Performance
- Jetboat

- Liquid air cycle engine/Reaction Engines SABRE
- Precooled jet engine/Reaction Engines Scimitar
- Ram accelerator
- Scramjet
- Spacecraft propulsion
- Supercharger
- Turbocharger
- Turbofan
- Turbojet
- Turboprop
- Turboshaft

- Wikibooks: Jet propulsion

8.9 Aircraft using ramjets

- Hiller Hornet (a ramjet-powered helicopter)
- Focke-Wulf Super Lorin
- Focke-Wulf Ta 283
- Focke-Wulf Triebflügel
- Leduc experimental aircraft
- Lockheed D-21
- Lockheed X-7
- Nord 1500 Griffon
- Republic XF-103
- SR-71 Blackbird (Turbojet engines that function as ramjets at mach 1+ speeds.)
- Skoda-Kauba Sk P.14

8.10 Missiles using ramjets

- Bomarc
- BrahMos
- MBDA Meteor
- Bristol Bloodhound
- Bendix RIM-8 Talos
- Orbital Sciences GQM-163 Coyote
- North American SM-64 Navaho
- P-270 Moskit

- Akash missile
- Sea Dart missile
- 2K11 Krug
- MBDA ASMP

8.11 References

[1] McNab, Chris; Hunter Keeter (2008). *Tools of Violence: Guns, Tanks and Dirty Bombs*. Osprey Publishing. p. 145. ISBN 1-84603-225-3.

[2] "Here Comes the Flying Stovepipe". TIME. 26 November 1965. Retrieved 2008-03-09.

[3] Savien Cyrano de Bergerac (1619-1655)

[4] Zucker, Robert D.; Oscar Biblarz (2002). *Fundamentals of gas dynamics*. John Wiley and Sons. ISBN 0-471-05967-6.

[5]
- Gyorgy, Nagy Istvan (1977). "Albert Fono: A Pioneer of Jet Propulsion". "International Astronautical Congress, 1977". IAF/IAA.

[6] Dugger, Gordon L. (1969). *Ramjets*. American Institute of Aeronautics and Astronautics. p. 15.

[7] Hirschel, Ernst-Heinrich; Horst Prem; Gero Madelung (2004). *Aeronautical Research in Germany*. Springer. pp. 242–243. ISBN 3-540-40645-X.

[8] according to Gas Turbine History.

[9] RAMJET PRIMER.

[10] "A Century of Ramjet Propulsion Technology Evolution", AIAA Journal of Propulsion and Power, Vol. 20, No. 1, January – February 2004.

[11] "Aérospatiale studies low-cost ramjet", Flight International, 13–19 December 1995.

[12] "Hughes homes in on missile pact", Flight International, 11–17 September 1996.

[13] Procinsky, I.M., McHale, C.A., "Nozzleless Boosters for Integral-Rocket-Ramjet Missile Systems, Paper 80-1277, AIAA/SAE/ASME 16th Joint Propulsion Conference, 30 June to 2 July 1980.

[14] 11.6 Performance of Jet Engines.

[15] "Boeing: History – Chronology 2002–2004".

[16] "USAF vehicle breaks record for hypersonic flight".

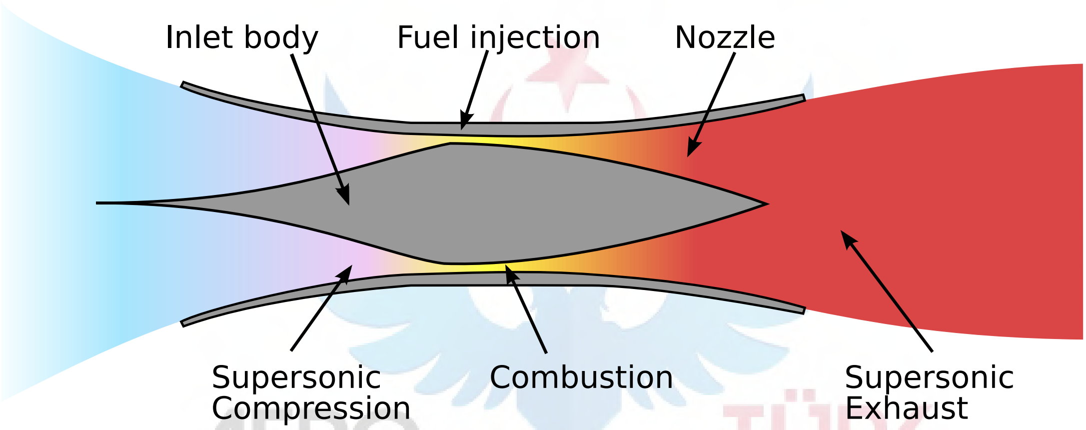
[17] PRELIMINARY SURVEY OF PROPULSION USING CHEMICAL ENERGY STORED IN THE UPPER ATMOSPHERE By Lionel V, Baldwin and Perry L. Blackshear.

8.12 External links

- NASA ramjet information and model
- *"Riding The Ramjet"* January 1949, Popular Mechanics article that covers the USAF first experiment with ramjets on a P-80 fighter
- The Boeing Logbook: 2002–2004
- Design notes on a ramjet-powered helicopter

Chapter 9

Scramjet



A **scramjet** (*supersonic combusting* ***ramjet***) is a variant of a ramjet airbreathing jet engine in which combustion takes place in supersonic airflow. As in ramjets, a scramjet relies on high vehicle speed to forcefully compress the incoming air before combustion (hence *ram*jet), but a ramjet decelerates the air to subsonic velocities before combustion, while airflow in a scramjet is supersonic throughout the entire engine. This allows the scramjet to operate efficiently at extremely high speeds: theoretical projections place the top speed of a scramjet between Mach 12 (8,400 mph; 14,000 km/h) and Mach 24 (16,000 mph; 25,000 km/h).

The scramjet is composed of three basic components: a converging inlet, where incoming air is compressed; a combustor, where gaseous fuel is burned with atmospheric oxygen to produce heat; and a diverging nozzle, where the heated air is accelerated to produce thrust. Unlike a typical jet engine, such as a turbojet or turbofan engine, a scramjet does not use rotating, fan-like components to compress the air; rather, the achievable speed of the aircraft moving through the atmosphere causes the air to compress within the inlet. As such, no moving parts are needed in a scramjet. In comparison, typical turbojet engines require inlet fans, multiple stages of rotating compressor fans, and multiple rotating turbine stages, all of which add weight, complexity, and a greater number of failure points to the engine.

Due to the nature of their design, scramjet operation is limited to near-hypersonic velocities. As they lack mechanical compressors, scramjets require the high kinetic energy of a hypersonic flow to compress the incoming air to operational conditions. Thus, a scramjet-powered vehicle must be accelerated to the required velocity (usually about Mach 4) by some other means of propulsion, such as turbojet, railgun, or rocket engines.[1] In the flight of the experimental scramjet-powered Boeing X-51A, the test craft was lifted to flight altitude by a Boeing B-52 Stratofortress before being released and accelerated by a detachable rocket to near Mach 4.5.[2] In May 2013, another flight achieved an increased speed of Mach 5.1.[3]

While scramjets are conceptually simple, actual implementation is limited by extreme technical challenges. Hypersonic flight within the atmosphere generates immense drag, and temperatures found on the aircraft and within the engine can be much greater than that of the surrounding air. Maintaining combustion in the supersonic flow presents additional challenges, as the fuel must be injected, mixed, ignited, and burned within milliseconds. While scramjet technology has been under development since the 1950s, only very recently have scramjets successfully achieved powered flight.[4]

9.1 History

During World War II, a tremendous amount of time and effort were put into researching high-speed jet- and rocket-powered aircraft, predominantly by the Germans. After the war, the US and UK took in several German scientists and military technologies through Operation Paperclip to begin putting more emphasis on their own weapons development, including jet engines. The Bell X-1 attained supersonic flight in 1947 and, by the early 1960s, rapid progress towards faster aircraft suggested that operational aircraft would be flying at "hypersonic" speeds within a few years. Except for specialized rocket research vehicles like the North American X-15 and other rocket-powered spacecraft, aircraft top speeds have remained level, generally in the range of Mach 1 to Mach 3.

In the 1950s and 1960s a variety of experimental scramjet engines were built and ground tested in the US and the UK. In 1964, Dr. Frederick S. Billig and Dr. Gordon L. Dugger submitted a patent application for a supersonic combustion ramjet based on Billig's Ph.D. thesis. This patent was issued in 1981 following the removal of an order of secrecy.[5]

In 1981 tests were made in Australia under the guidance of Professor Ray Stalker in the T3 ground test facility at ANU.[6]

The first successful flight test of a Scramjet was performed by Russia in 1991. It was an axisymmetric hydrogen-fueled dual-mode scramjet developed by Central Institute of Aviation Motors (CIAM), Moscow in the late 1970s. The scramjet flight was flown captive-carry atop the SA-5 surface-to-air missile that included an experiment flight support unit known as the "Hypersonic Flying Laboratory" (HFL), "Kholod".[7] Then from 1992 to 1998 an additional 6 flight tests of the axisymmetric high-speed scramjet-demonstrator were conducted by CIAM together with France and then with NASA, USA.[8][9] Maximum flight velocity greater than Mach 6.4 was achieved and Scramjet operation during 77 seconds was demonstrated. These flight test series also provided insight into autonomous hypersonic flight controls.

9.1.1 Progress in the 2000s

Main article: Scramjet programs

In the 2000s, significant progress was made in the development of hypersonic technology, particularly in the field of scramjet engines.

US efforts are probably the best funded, and the Hyper-X team claimed the first flight of a thrust-producing scramjet-powered vehicle with full aerodynamic maneuvering surfaces in 2004 with the X-43A.[10][11] However, the first group to demonstrate a scramjet working in an atmospheric test was a project by a joint British and Australian team from UK defense company QinetiQ and the University of Queensland.[12]

The HyShot project demonstrated scramjet combustion on July 30, 2002. The scramjet engine worked effectively and demonstrated supersonic combustion in action. However, the engine was not designed to provide thrust to propel a craft. It was designed more or less as a technology demonstrator.

On Friday, June 15, 2007, the US Defense Advanced Research Project Agency (DARPA), in cooperation with the Australian Defence Science and Technology Organisation (DSTO), announced a successful scramjet flight at Mach 10 using rocket engines to boost the test vehicle to hypersonic speeds.[13]

A series of scramjet ground test were completed at NASA Langley Arc-Heated Scramjet Test Facility (AHSTF) at simulated Mach 8 flight conditions. These experiments were used to support HIFiRE flight 2.[14]

On May 22, 2009, Woomera hosted the first successful test flight of a hypersonic aircraft in HIFiRE. The launch was one of 10 planned test flights. The series of up to 10 planned hypersonic flight experiments are part of a joint research program between the Defence Science and Technology Organisation and the US Air Force, designated as the Hypersonic International Flight Research Experimentation (HIFiRE).[15] HIFiRE is investigating hypersonics technology (the study of flight exceeding five times the speed of sound) and its application to advanced scramjet-powered space launch vehicles — the objective is to support the new Boeing X-51 scramjet demonstrator while also

Artist's conception of the NASA X-43 with scramjet attached to the underside

building a strong base of flight test data for quick-reaction space launch development and hypersonic "quick-strike" weapons.[15]

On 22 and 23 March 2010, Australian and American defence scientists successfully tested a (HIFiRE) hypersonic rocket. It reached an atmospheric velocity of "more than 5,000 kilometres per hour" after taking off from the Woomera Test Range in outback South Australia.[16][17]

On May 27, 2010, NASA and the United States Air Force successfully flew the X-51A Waverider for approximately 200 seconds at Mach 5, setting a new world record hypersonic airspeed. The Waverider flew autonomously before losing acceleration for an unknown reason and destroying itself as planned. The test was declared a success. The X-51A was carried aboard a B-52, accelerated to Mach 4.5 via a solid rocket booster, and then ignited the Pratt & Whitney Rocketdyne scramjet engine to reach Mach 5 at 70,000 feet.[18] However, a second flight June 13, 2011 was ended prematurely when the engine lit briefly on ethylene but failed to transition to its primary JP7 fuel, failing to reach full power.[19][20]

On 16 November 2010, Australian scientists successfully demonstrated that the high-speed flow in a naturally non-burning scramjet engine can be ignited using a pulsed laser source.[21]

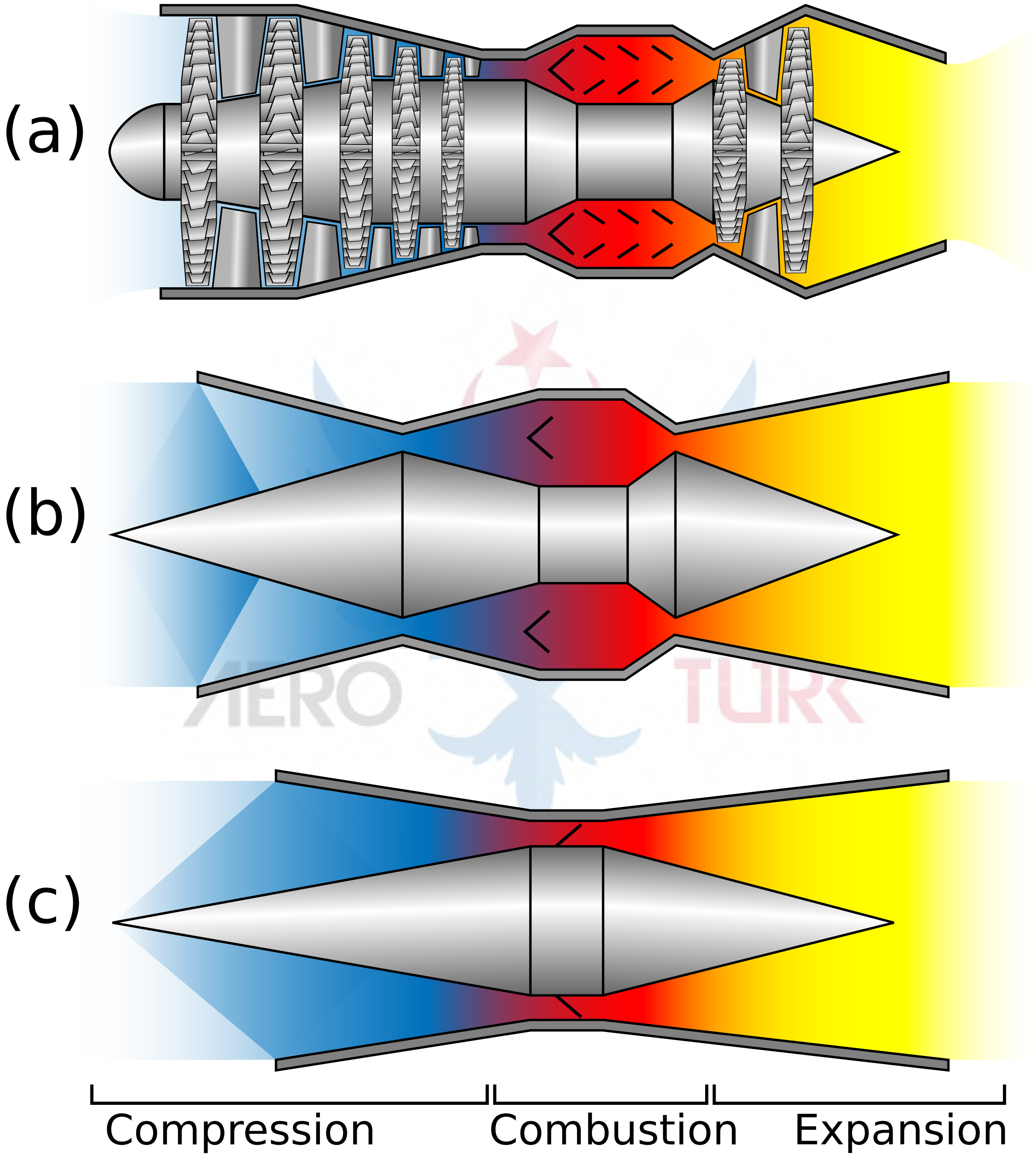
A further X-51A Waverider test failed on August 15, 2012. The attempt to fly the Scramjet, carried by a B-52 for a prolonged period at Mach 6 was cut short when, only 15 seconds into the unmanned flight, the X-51A craft lost control and broke apart, falling into the Pacific Ocean north-west of Los Angeles. The cause of the failure was blamed on a faulty control fin.[22]

In May 2013 an unmanned X-51A WaveRider reached 4828 km/h (Mach 5.1) during a three-minute flight under scramjet power. The WaveRider was dropped at 50,000 feet from a B-52 bomber, and then accelerated to Mach 4.8 by a solid rocket booster which then separated before the WaveRider's scramjet engine came into effect.[23]

On 9 January 2014 US surveillance satellites observed a supersonic flying object at a speed of Mach 5 up to Mach 10 in around 100 kilometers height. Following Chinese statements the preliminary designation for this object is WU-

14. In the first phase this unmanned vehicle was brought to its operating height and speed by a military long-range missile.[24][25]

9.2 Design principles



The compression, combustion, and expansion regions of: (a) turbojet, (b) ramjet, and (c) scramjet engines.

Scramjet engines are a type of jet engine, and rely on the combustion of fuel and an oxidizer to produce thrust. Similar to conventional jet engines, scramjet-powered aircraft carry the fuel on board, and obtain the oxidizer by the ingestion of atmospheric oxygen (as compared to rockets, which carry both fuel and an oxidizing agent). This requirement limits scramjets to suborbital atmospheric flight, where the oxygen content of the air is sufficient to maintain combustion.

9.2.1 Basic principles

Scramjets are designed to operate in the hypersonic flight regime, beyond the reach of turbojet engines, and, along with ramjets, fill the gap between the high efficiency of turbojets and the high speed of rocket engines. Turbomachinery-based engines, while highly efficient at subsonic speeds, become increasingly inefficient at transonic speeds, as the compressor fans found in turbojet engines require subsonic speeds to operate. While the flow from transonic to low supersonic speeds can be decelerated to these conditions, doing so at supersonic speeds results in a tremendous increase in temperature and a loss in the total pressure of the flow. Around Mach 3–4, turbomachinery is no longer useful, and ram-style compression becomes the preferred method.[26]

Ramjets utilize high-speed characteristics of air to literally 'ram' air through an inlet nozzle into the combustor. At transonic and supersonic flight speeds, the air upstream of the nozzle is not able to move out of the way quickly enough, and is compressed within the nozzle before being diffused into the combustor. Combustion in a ramjet takes place at subsonic velocities, similar to turbojets, but the combustion products are then accelerated through a convergent-divergent nozzle to supersonic speeds. As they have no mechanical means of compression, ramjets cannot start from a standstill, and generally do not achieve sufficient compression until supersonic flight. The lack of intricate turbomachinery allows ramjets to deal with the temperature rise associated with decelerating a supersonic flow to subsonic speeds, but this only goes so far: at near-hypersonic velocities, the temperature rise and inefficiencies discourage decelerating the flow to the magnitude found in ramjet engines.[26]

Scramjet engines operate on the same principles as ramjets, but do not decelerate the flow to subsonic velocities. Rather, a scramjet combustor is supersonic: the inlet decelerates the flow to a lower Mach number for combustion, after which it is accelerated to an even higher Mach number through the nozzle. By limiting the amount of deceleration, temperatures within the engine are kept at a tolerable level, from both a material and combustive standpoint. Even so, current scramjet technology requires the use of high-energy fuels and active cooling schemes to maintain sustained operation, often using hydrogen and regenerative cooling techniques.[27]

9.3 Theory

All scramjet engines have an intake which compresses the incoming air, fuel injectors, a combustion chamber, and a divergent thrust nozzle. Sometimes engines also include a region which acts as a flame holder, although the high stagnation temperatures mean that an area of focused waves may be used, rather than a discrete engine part as seen in turbine engines. Other engines use pyrophoric fuel additives, such as silane, to avoid such issues. An isolator between the inlet and combustion chamber is often included to improve the homogeneity of the flow in the combustor and to extend the operating range of the engine.

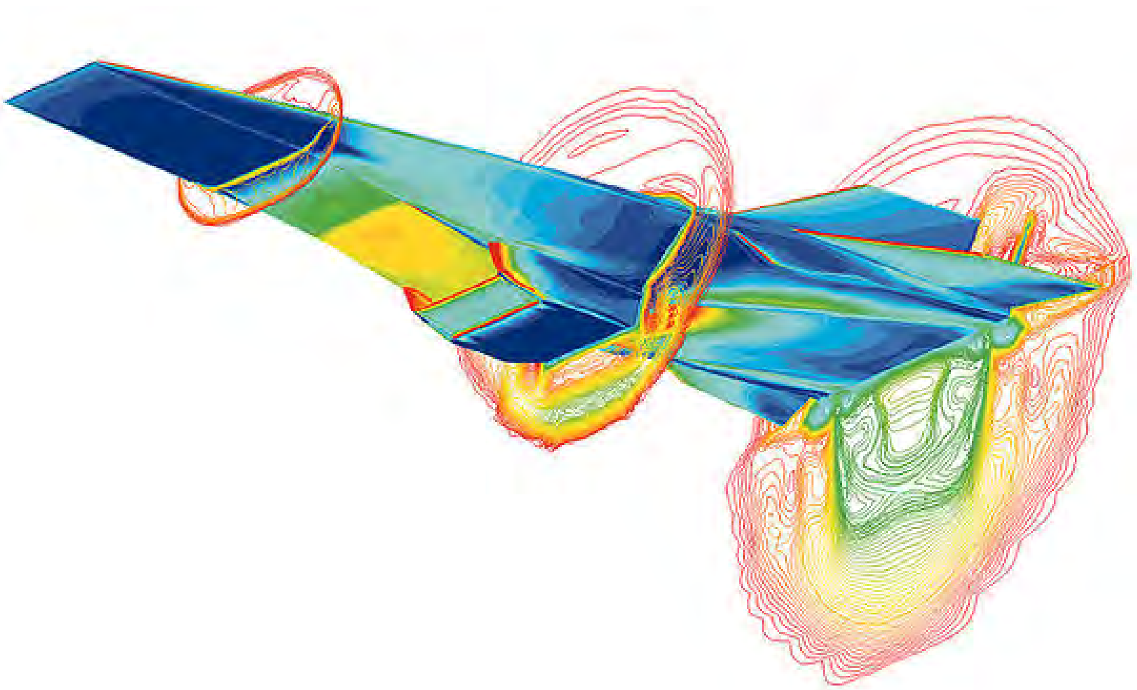
A scramjet is reminiscent of a ramjet. In a typical ramjet, the supersonic inflow of the engine is decelerated at the inlet to subsonic speeds and then reaccelerated through a nozzle to supersonic speeds to produce thrust. This deceleration, which is produced by a normal shock, creates a total pressure loss which limits the upper operating point of a ramjet engine.

For a scramjet, the kinetic energy of the freestream air entering the scramjet engine is large comparable to the energy released by the reaction of the oxygen content of the air with a fuel (say hydrogen). Thus the heat released from combustion at Mach 25 is around 10% of the total enthalpy of the working fluid. Depending on the fuel, the kinetic energy of the air and the potential combustion heat release will be equal at around Mach 8. Thus the design of a scramjet engine is as much about minimizing drag as maximizing thrust.

This high speed makes the control of the flow within the combustion chamber more difficult. Since the flow is supersonic, no downstream influence propagates within the freestream of the combustion chamber. Thus throttling of the entrance to the thrust nozzle is not a usable control technique. In effect, a block of gas entering the combustion chamber must mix with fuel and have sufficient time for initiation and reaction, all the while traveling supersonically through the combustion chamber, before the burned gas is expanded through the thrust nozzle. This places stringent requirements on the pressure and temperature of the flow, and requires that the fuel injection and mixing be extremely efficient. Usable dynamic pressures lie in the range 20 to 200 kilopascals (2.9 to 29.0 psi), where

$$q = \frac{1}{2}\rho v^2$$

where



Computational fluid dynamics (CFD) image of the NASA X-43A with scramjet attached to the underside at Mach 7

q is the dynamic pressure of the gas

ϱ (rho) is the density of the gas

v is the velocity of the gas

To keep the combustion rate of the fuel constant, the pressure and temperature in the engine must also be constant. This is problematic because the airflow control systems that would facilitate this are not physically possible in a scramjet launch vehicle due to the large speed and altitude range involved, meaning that it must travel at an altitude specific to its speed. Because air density reduces at higher altitudes, a scramjet must climb at a specific rate as it accelerates to maintain a constant air pressure at the intake. This optimal climb/descent profile is called a “constant dynamic pressure path”. It is thought that scramjets might be operable up to an altitude of 75 km.[28]

Fuel injection and management is also potentially complex. One possibility would be that the fuel be pressurized to 100 bar by a turbo pump, heated by the fuselage, sent through the turbine and accelerated to higher speeds than the air by a nozzle. The air and fuel stream are crossed in a comb like structure, which generates a large interface. Turbulence due to the higher speed of the fuel leads to additional mixing. Complex fuels like kerosene need a long engine to complete combustion.

The minimum Mach number at which a scramjet can operate is limited by the fact that the compressed flow must be hot enough to burn the fuel, and have pressure high enough that the reaction be finished before the air moves out the back of the engine. Additionally, in order to be called a scramjet, the compressed flow must still be supersonic after combustion. Here two limits must be observed: Firstly, since when a supersonic flow is compressed it slows down, the level of compression must be low enough (or the initial speed high enough) not to slow the gas below Mach 1. If the gas within a scramjet goes below Mach 1 the engine will “choke”, transitioning to subsonic flow in the combustion chamber. This effect is well known amongst experimenters on scramjets since the waves caused by choking are easily observable. Additionally, the sudden increase in pressure and temperature in the engine can lead to an acceleration of the combustion, leading to the combustion chamber exploding.

Secondly, the heating of the gas by combustion causes the speed of sound in the gas to increase (and the Mach number to decrease) even though the gas is still travelling at the same speed. Forcing the speed of air flow in the combustion chamber under Mach 1 in this way is called “thermal choking”. It is clear that a pure scramjet can operate at Mach numbers of 6-8,[29] but in the lower limit, it depends on the definition of a scramjet. There are engine designs where a ramjet transforms into a scramjet over the Mach 3-6 range, known as dual-mode scramjets.[30] In this range however, the engine is still receiving significant thrust from subsonic combustion of the ramjet type.

The high cost of flight testing and the unavailability of ground facilities have hindered scramjet development. A large amount of the experimental work on scramjets has been undertaken in cryogenic facilities, direct-connect tests, or burners, each of which simulates one aspect of the engine operation. Further, vitiated facilities, storage heated facilities, arc facilities and the various types of shock tunnels each have limitations which have prevented perfect simulation of scramjet operation. The HyShot flight test showed the relevance of the 1:1 simulation of conditions in the T4 and HEG shock tunnels, despite having cold models and a short test time. The NASA-CIAM tests provided similar verification for CIAM's C-16 V/K facility and the Hyper-X project is expected to provide similar verification for the Langley AHSTF,[31] CHSTF[32] and 8 ft (2.4 m) HTT.

Computational fluid dynamics has only recently reached a position to make reasonable computations in solving scramjet operation problems. Boundary layer modeling, turbulent mixing, two-phase flow, flow separation, and real-gas aerothermodynamics continue to be problems on the cutting edge of CFD. Additionally, the modeling of kinetic-limited combustion with very fast-reacting species such as hydrogen makes severe demands on computing resources. Reaction schemes are numerically stiff requiring reduced reaction schemes.

Much of scramjet experimentation remains classified. Several groups, including the US Navy with the SCRAM engine between 1968 and 1974, and the Hyper-X program with the X-43A, have claimed successful demonstrations of scramjet technology. Since these results have not been published openly, they remain unverified and a final design method of scramjet engines still does not exist.

The final application of a scramjet engine is likely to be in conjunction with engines which can operate outside the scramjet's operating range. Dual-mode scramjets combine subsonic combustion with supersonic combustion for operation at lower speeds, and rocket-based combined cycle (RBCC) engines supplement a traditional rocket's propulsion with a scramjet, allowing for additional oxidizer to be added to the scramjet flow. RBCCs offer a possibility to extend a scramjet's operating range to higher speeds or lower intake dynamic pressures than would otherwise be possible.

9.4 Advantages and disadvantages of scramjets

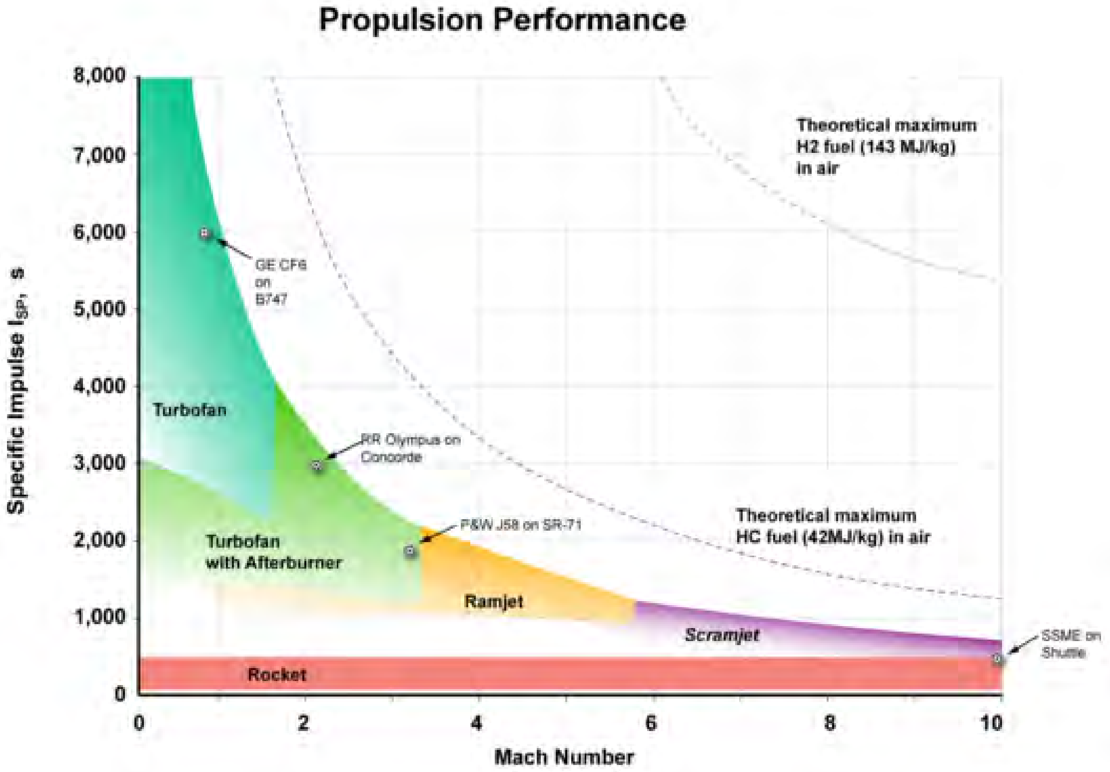
9.4.1 Advantages

1. Does not have to carry oxygen
2. No rotating parts makes it easier to manufacture than a turbojet
3. Has a higher specific impulse (change in momentum per unit of propellant) than a rocket engine; could provide between 1000 and 4000 seconds, while a rocket only provides 450 seconds or less
4. Higher speed could mean cheaper access to outer space in the future

9.4.2 Special cooling and materials

Unlike a rocket that quickly passes mostly vertically through the atmosphere or a turbojet or ramjet that flies at much lower speeds, a hypersonic airbreathing vehicle optimally flies a "depressed trajectory", staying within the atmosphere at hypersonic speeds. Because scramjets have only mediocre thrust-to-weight ratios,[33] acceleration would be limited. Therefore time in the atmosphere at hypersonic speed would be considerable, possibly 15–30 minutes. Similar to a reentering space vehicle, heat insulation would be a formidable task, with protection required for a duration longer than that of a typical space capsule, although less than the space shuttle.

New materials offer good insulation at high temperature, but they often sacrifice themselves in the process. Therefore studies often plan on "active cooling", where coolant circulating throughout the vehicle skin prevents it from disintegrating. Often the coolant is the fuel itself, in much the same way that modern rockets use their own fuel and oxidizer as coolant for their engines. All cooling systems add weight and complexity to a launch system. The cooling of scramjets in this way may result in greater efficiency, as heat is added to the fuel prior to entry into the engine, but result in increased complexity and weight which ultimately could outweigh any performance gains.



The specific impulse of various engines

9.4.3 Vehicle performance

The performance of a launch system is complex and depends greatly on its weight. Normally craft are designed to maximise range (R), orbital radius (R) or payload mass fraction (Γ) for a given engine and fuel. This results in tradeoffs between the efficiency of the engine (takeoff fuel weight) and the complexity of the engine (takeoff dry weight), which can be expressed by the following:

$$\Pi_e + \Pi_f + \frac{1}{\Gamma} = 1$$

Where :

- $\Pi_e = \frac{m_{\text{empty}}}{m_{\text{initial}}}$ is the empty mass fraction, and represents the weight of the superstructure, tankage and engine.
- $\Pi_f = \frac{m_{\text{fuel}}}{m_{\text{initial}}}$ is the fuel mass fraction, and represents the weight of fuel, oxidiser and any other materials which are consumed during the launch.
- $\Gamma = \frac{m_{\text{initial}}}{m_{\text{payload}}}$ is initial mass ratio, and is the inverse of the payload mass fraction. This represents how much payload the vehicle can deliver to a destination.

A scramjet increases the mass of the engine Π_e over a rocket, and decreases the mass of the fuel Π_f . It can be difficult to decide whether this will result in an increased Γ (which would be an increased payload delivered to a destination for a constant vehicle takeoff weight). The logic behind efforts driving a scramjet is (for example) that the reduction in fuel decreases the total mass by 30%, while the increased engine weight adds 10% to the vehicle total mass. Unfortunately the uncertainty in the calculation of any mass or efficiency changes in a vehicle is so great that slightly different assumptions for engine efficiency or mass can provide equally good arguments for or against scramjet powered vehicles.

Additionally, the drag of the new configuration must be considered. The drag of the total configuration can be considered as the sum of the vehicle drag (D) and the engine installation drag (D_e). The installation drag traditionally results from the pylons and the coupled flow due to the engine jet, and is a function of the throttle setting. Thus it is often written as:

$D_e = \phi_e F$ Where:

- ϕ_e is the loss coefficient
- F is the thrust of the engine

For an engine strongly integrated into the aerodynamic body, it may be more convenient to think of (D_e) as the difference in drag from a known base configuration.

The overall engine efficiency can be represented as a value between 0 and 1 (η_0), in terms of the specific impulse of the engine:

$$\eta_0 = \frac{g_0 V_0}{h_{PR}} \cdot I_{sp} = \frac{\text{Thrust Power}}{\text{Chemical energy rate}}$$

Where:

- g_0 is the acceleration due to gravity at ground level
- V_0 is the vehicle speed
- I_{sp} is the specific impulse
- h_{PR} is fuel heat of reaction

Specific impulse is often used as the unit of efficiency for rockets, since in the case of the rocket, there is a direct relation between specific impulse, specific fuel consumption and exhaust velocity. This direct relation is not generally present for airbreathing engines, and so specific impulse is less used in the literature. Note that for an airbreathing engine, both η_0 and I_{sp} are a function of velocity.

The specific impulse of a rocket engine is independent of velocity, and common values are between 200 and 600 seconds (450s for the space shuttle main engines). The specific impulse of a scramjet varies with velocity, reducing at higher speeds, starting at about 1200s, although values in the literature vary.

For the simple case of a single stage vehicle, the fuel mass fraction can be expressed as:

$$\Pi_f = 1 - \exp\left[-\frac{\left(\frac{V_{initial}^2}{2} - \frac{V_i^2}{2}\right) + \int g\,dr}{\eta_0 h_{PR}\left(1 - \frac{D+D_e}{F}\right)} \right]$$

Where this can be expressed for single stage transfer to orbit as:

$$\Pi_f = 1 - \exp\left[-\frac{g_0 r_0 \left(1 - \frac{1}{2}\frac{r_0}{r}\right)}{\eta_0 h_{PR}\left(1 - \frac{D+D_e}{F}\right)} \right]$$

or for level atmospheric flight from air launch (missile flight):

$$\Pi_f = 1 - \exp\left[-\frac{g_0 R}{\eta_0 h_{PR}\left(1 - \phi_e\right)\frac{C_L}{C_D}} \right]$$

Where R is the range, and the calculation can be expressed in the form of the Breguet range formula:

$$\Pi_f = 1 - e^{-BR}$$

$$B = \frac{g_0}{\eta_0 h_{PR}\left(1 - \phi_e\right)\frac{C_L}{C_D}}$$

Where:

- C_L is the lift coefficient
- C_D is the drag coefficient

This extremely simple formulation, used for the purposes of discussion assumes:

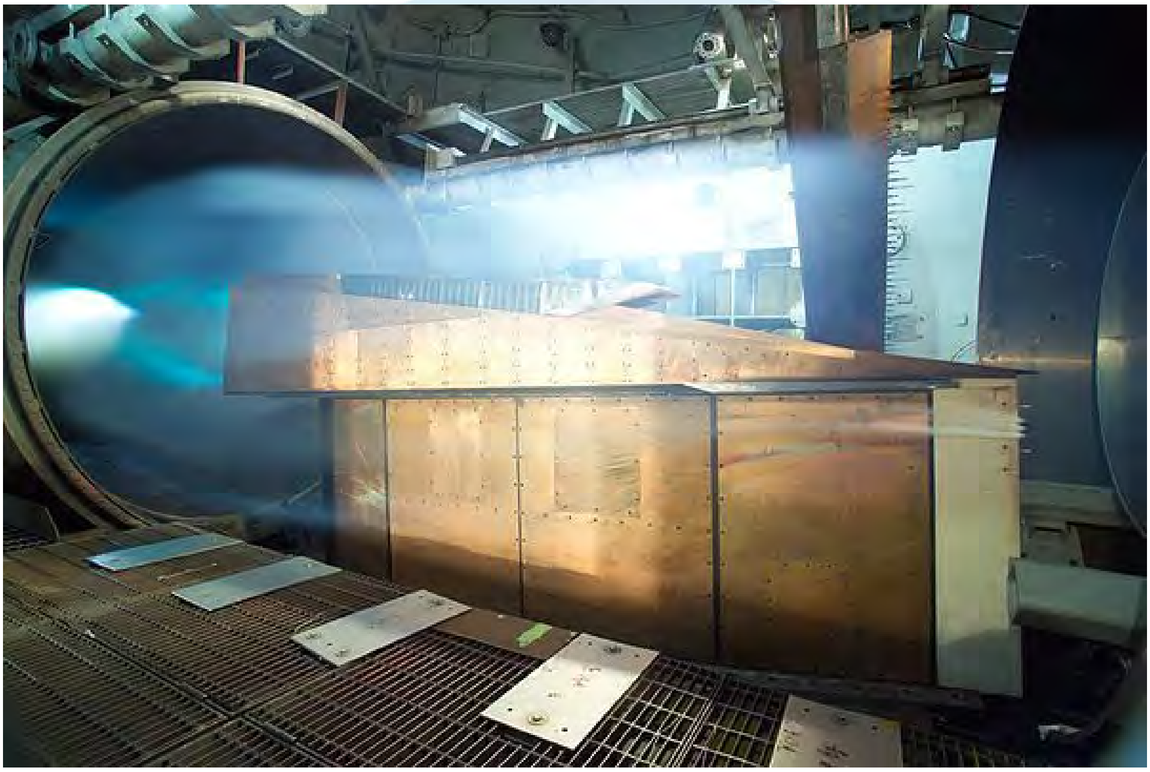
- Single stage vehicle
- No aerodynamic lift for the transatmospheric lifter

However they are true generally for all engines.

9.4.4 Initial propulsion requirements

A scramjet cannot produce efficient thrust unless boosted to high speed, around Mach 5, although depending on the design it could act as a ramjet at low speeds. A horizontal take-off aircraft would need conventional turbofan or rocket engines to take off, sufficiently large to move a heavy craft. Also needed would be fuel for those engines, plus all engine-associated mounting structure and control systems. Turbofan engines are heavy and cannot easily exceed about Mach 2-3, so another propulsion method would be needed to reach scramjet operating speed. That could be ramjets or rockets. Those would also need their own separate fuel supply, structure, and systems. Many proposals instead call for a first stage of droppable solid rocket boosters, which greatly simplifies the design.

9.4.5 Testing difficulties



Test of Pratt & Whitney Rocketdyne SJY61 scramjet engine for the Boeing X-51

Unlike jet or rocket propulsion systems facilities which can be tested on the ground, testing scramjet designs use extremely expensive hypersonic test chambers or expensive launch vehicles, both of which lead to high instrumentation costs. Tests using launched test vehicles very typically end with destruction of the test item and instrumentation.

9.5 Advantages and disadvantages for orbital vehicles

9.5.1 Propellant

An advantage of a hypersonic airbreathing (typically scramjet) vehicle like the X-30 is avoiding or at least reducing the need for carrying oxidizer. For example the space shuttle external tank holds 616,432 kg of liquid oxygen (LOX) and 103,000 kg of liquid hydrogen (LH2) while having an empty weight of 30,000 kg. The orbiter gross weight is 109,000 kg with a maximum payload of about 25,000 kg and to get the assembly off the launch pad the shuttle uses two very powerful solid rocket boosters with a weight of 590,000 kg each. If the oxygen could be eliminated, the vehicle could be lighter at liftoff and maybe carry more payload. That would be an advantage, but the central motivation in pursuing hypersonic airbreathing vehicles would be to reduce cost.

On the other hand, scramjets spend more time in the atmosphere and require more hydrogen fuel to deal with aerodynamic drag. Whereas liquid oxygen is quite a dense fluid, liquid hydrogen has much lower density and takes up much more volume. This means that the vehicle using this fuel becomes much bigger and gives even more drag.[34]

9.5.2 Thrust-to-weight ratio

One issue is that scramjet engines are predicted to have exceptionally poor thrust-to-weight ratio of around 2, when installed in a launch vehicle.[35] A rocket has the advantage that its engines have *very* high thrust-weight ratios (~100:1), while the tank to hold the liquid oxygen approaches a tankage ratio of ~100:1 also. Thus a rocket can achieve a very high mass fraction, which improves performance. By way of contrast the projected thrust/weight ratio of scramjet engines of about 2 mean a very much larger percentage of the takeoff mass is engine (ignoring that this fraction increases anyway by a factor of about four due to the lack of onboard oxidiser). In addition the vehicle's lower thrust does not necessarily avoid the need for the expensive, bulky, and failure prone high performance turbopumps found in conventional liquid-fuelled rocket engines, since most scramjet designs seem to be incapable of orbital speeds in airbreathing mode, and hence extra rocket engines are needed.

9.5.3 Need for additional propulsion to reach orbit

Scramjets might be able to accelerate from approximately Mach 5-7 to around somewhere between half of orbital velocity and orbital velocity (X-30 research suggested that Mach 17 might be the limit compared to an orbital speed of Mach 25, and other studies put the upper speed limit for a pure scramjet engine between Mach 10 and 25, depending on the assumptions made). Generally, another propulsion system (very typically, a rocket is proposed) is expected to be needed for the final acceleration into orbit. Since the delta-V is moderate and the payload fraction of scramjets high, lower performance rockets such as solids, hypergolics, or simple liquid fueled boosters might be acceptable.

9.5.4 Reentry

The scramjet's heat-resistant underside potentially doubles as its reentry system if a single-stage-to-orbit vehicle using non-ablative, non-active cooling is visualised. If an ablative shielding is used on the engine it will probably not be usable after ascent to orbit. If active cooling is used with the fuel as coolant, the loss of all fuel during the burn to orbit will also mean the loss of all cooling for the thermal protection system.

9.5.5 Costs

Reducing the amount of fuel and oxidizer does not necessarily improve costs as rocket propellants are comparatively very cheap. Indeed, the unit cost of the vehicle can be expected to end up far higher, since aerospace hardware cost is about two orders of magnitude higher than liquid oxygen, fuel and tankage, and scramjet hardware seems to be much heavier than rockets for any given payload. Still, if scramjets enable reusable vehicles, this could theoretically be a cost benefit. Whether equipment subject to the extreme conditions of a scramjet can be reused sufficiently many times is unclear; all flown scramjet tests only survive for short periods and have never been designed to survive a flight to date.

The eventual cost of such a vehicle is the subject of intense debate since even the best estimates disagree whether a scramjet vehicle would be advantageous. It is likely that a scramjet vehicle would need to lift more load than a rocket of equal takeoff weight in order to be equally as cost efficient (if the scramjet is a non-reusable vehicle).

9.5.6 Issues

Space launch vehicles may or may not benefit from having a scramjet stage. A scramjet stage of a launch vehicle theoretically provides a specific impulse of 1000 to 4000 s whereas a rocket provides less than 450 s while in the atmosphere,[36][37] potentially permitting much cheaper access to space. A scramjet's specific impulse decreases rapidly with speed, however, and the vehicle would suffer from a relatively low lift to drag ratio.

The installed thrust to weight ratio of scramjets compares very unfavorably with the 50-100 of a typical rocket engine. This is compensated for in scramjets partly because the weight of the vehicle would be carried by aerodynamic lift rather than pure rocket power (giving reduced 'gravity losses'), but scramjets would take much longer to get to orbit due to lower thrust which greatly offsets the advantage. The takeoff weight of a scramjet vehicle is significantly reduced over that of a rocket, due to the lack of onboard oxidiser, but increased by the structural requirements of the larger and heavier engines.

Whether this vehicle would be reusable or not is still a subject of debate and research.

9.6 Applications

An aircraft using this type of jet engine could dramatically reduce the time it takes to travel from one place to another, potentially putting any place on Earth within a 90-minute flight. However, there are questions about whether such a vehicle could carry enough fuel to make useful length trips, and there are heavy FAA regulations regarding aircraft that create sonic booms over United States' land.[38][39]

Scramjet vehicle has been proposed for a single stage to tether vehicle, where a Mach 12 spinning orbital tether would pick up a payload from a vehicle at around 100 km and carry it to orbit.[40]

9.7 See also

- Single-stage to orbit
- Liquid air cycle engine
- Precooled jet engine
- List of emerging technologies
- Atmospheric reentry
- Busemann's Biplane
- Pulse detonation engine
- Shcramjet
- The Hy-V Scramjet Flight Experiment

9.8 References

Notes

[1] Segal 2009, pp. 1.

[2] Calaguori, Nancy; Kidder, Bryan (2 May 2010). "Pratt & Whitney Rocketdyne Scramjet Powers Historic First Flight of X-51A WaveRider". *Press Releases*. Pratt & Whitney Rocketdyne. Retrieved 1 July 2010.

[3] "Experimental Air Force aircraft goes hypersonic". Associated Press. 3 May 2013. Retrieved 4 May 2013.

[4] Segal 2009, pp. 3–11.

[5] “Frederick S. Billig, Ph.D. (1933-2006)". *Innovation Hall of Fame*. University of Maryland. Retrieved 30 April 2010.

[6] “Milestones in the history of scramjets — UQ News Online — The University of Queensland”. University of Queensland, UQ News. Retrieved 18 August 2009.

[7] Roudakov, A.S., Y. Schickhman, V. Semenov, Ph. Novelli, and O. Fourt, “Flight Testing an Axisymmetric Scramjet: Russian Recent Advances,” 44th Congress of the International Astronautical Federation, Oct. 16–22, 1993, Graz, Austria

[8] A.Roudakov, V.Semenov, V.Kopchenov, J.Hicks “Future Flight Test Plans of an Axisymmetric Hydrogen-Fueled Scramjet Engine on the Hypersonic Flying Laboratory” AIAA 96-4572. 7th International Spaceplanes and Hypersonics Systems & Technology Conference November 18–22, 1996/Norfolk, Virginia

[9] A.Roudakov, V.Semenov, J.Hicks “Recent Flight Test Results of the Joint CIAMNASA Mach 6.5 Scramjet Flight Program” NASA/TP-1998-206548

[10] Dr. Phillip T. Harsha, Lowell C. Keel, Dr. Anthony Castrogiovanni, Robert T. Sherrill, *X-43A Vehicle Design and Manufacture* (pdf), *AIAA 2005-3334*

[11] C. McClinton. “X-43–Scramjet Power Breaks the Hypersonic Barrier” (pdf).

[12] Challoner, Jack (2009). *1001 Inventions That Changed the World*. Cassell Illustrated. p. 932. ISBN 978-1-84403-611-0.

[13] “Scramjet hits Mach 10 over Australia”, *New Scientist*, 15 June 2007, accessed 17 November 2010.

[14] Cabell, Karen; Hass, Neal; Storch, Andrea; Gruber, Mark. “HIFiRE Direct-Connect Rig (HDCR) Phase I Scramjet Test Results from the NASA Langley Arc-Heated Scramjet Test Facility”. *NASA Langley Research Center*. NASA Technical Reports Server. Retrieved 21 September 2011.

[15] “Woomera hosts first HIFiRE hypersonic test flight”. *Daily Telegraph*. 2009-05-24.

[16] “Scientists conduct second HIFiRE test”. Sydney Morning Herald Online. 2010-03-22.

[17] "'Success for hypersonic outback flight”. ABC Online. 2010-03-23.

[18] “X-51A races to hypersonic record”. C-Net News. 27 May 2010.

[19] “Hypersonic X-51A Scramjet Failure Perplexes Air Force” http://www.foxnews.com/scitech/2011/07/29/hypersonic-x-51a-scramjet-failure-p

[20] “X-51A Waverider Test Falls Short”http://www.youtube.com/watch?v=-mMLZPoU8JU

[21] “Researchers put spark into scramjets”. Australian Broadcasting Corporation, ABC News. 16 November 2010.

[22] “Hypersonic jet Waverider fails Mach 6 test”. British Broadcasting Corporation, BBC News. 16 August 2012.

[23] AP (2013-05-06). “Experimental hypersonic aircraft hits 4828 km/h”. *The Sydney Morning Herald*. Fairfax Media. Retrieved 2013-05-09.

[24] Want China Times: PLA tests high-speed missile

[25] The Washington Free Beacon: China Conducts First Test of New Ultra-High Speed Missile Vehicle

[26] Hill & Peterson 1992, pp. 21.

[27] Segal 2009, pp. 4.

[28] “Scramjets”. Orbitalvector.com. 2002-07-30. Retrieved 2009-08-18.

[29] Paull, A.; Stalker, R.J.; Mee, D.J. (1995). “Experiments on supersonic combustion ramjet propulsion in a shock tunnel”. *Jfm 296: 156-183*.

[30] Voland, R.T., Auslender, A.H., Smart, M.K., Roudakov, A.S., Semenov, V.L., Kopchenov, V. “CIAM/NASA Mach 6.5 scramjet flight and ground test”, AIAA-99-4848.

[31] “The Langley Arc-Heated Scramjet Test Facility Brochure”. Wte.larc.nasa.gov. 2005-11-17. Retrieved 2009-08-18.

[32] “The Langley Combustion-Heated Scramjet Test Facility Brochure”. Wte.larc.nasa.gov. 2005-11-17. Retrieved 2009-08-18.

[33] Rathore, Mahesh (2010). *Thermal Engineering*. Tata McGraw-Hill Education. p. 966. ISBN 9780070681132. Retrieved 14 September 2014. “A scramjet has very poor thrust to weight ratio (~2).”

[34] States, United; Assessment, Office of Technology; Congress, (2003-05-14). *pg 78*. Books.google.com. ISBN 978-1-4289-2233-4. Retrieved 2009-08-18.

[35] Varvill, R., Bond, A. "A Comparison of Propulsion Concepts for SSTO Reuseable Launchers", JBIS, Vol 56, pp 108-117, 2003. Figure 7.

[36] Kors, D.L. “Design considerations for combined air breathing-rocket propulsion systems.”, AIAA Paper No. 90-5216, 1990.

[37] Varvill, R., Bond, A. "A Comparison of Propulsion Concepts for SSTO Reuseable Launchers", JBIS, Vol 56, pp 108-117, 2003. Figure 8.

[38] http://elr.info/news-analysis/3/10067/faa-promulgates-strict-new-sonic-boom-regulation

[39] http://www.risingup.com/fars/info/part91-817-FAR.shtml

[40] Hypersonic Airplane Space Tether Orbital Launch (HASTOL) System

Bibliography

- Segal, Corin (2009). *The Scramjet Engine: Processes and Characteristics*. New York: Cambridge University Press. ISBN 978-0-521-83815-3.
- Hill, Philip; Peterson, Carl (1992). *Mechanics and Thermodynamics of Propulsion* (2nd ed.). New York: Addison-Wesley. ISBN 0-201-14659-2.
- Billig, FS “SCRAM-A Supersonic Combustion Ramjet Missile”, AIAA paper 93-2329, 1993.
- Ingenito A. and Bruno C “Physics and Regimes in Supersonic Combustion”, AIAA Journal, Volume 48, Number 3, 2010.
- “On the trail of the Scramjet” - the Lab. ABC Science Online. 17 October 2002
- “Revolutionary jet engine tested” BBC News. bbc.co.uk 25 March 2006
- French Support Russian SCRAMJET Tests.
- David Schneider (November–December 2002). “A Burning Question”. *American Scientist*. Retrieved August 13, 2011.
- Hypersonic Scramjet Projectile Flys in Missile Test. *SpaceDaily* September 4, 2001
- NASA website for National Hypersonics Plan
- X-43A NASA
- Hyshot Centre for Hypersonics, University of Queensland, Australia
- http://news.yahoo.com/s/nm/20070615/tc_nm/australia_jet_dc;_ylt=AjD55nNEoWlZGJ2UcFk9PrHQn6gB

9.9 External links

- “X-51 Sets World Record”. *Space.com*. Retrieved May 5, 2010.
- “Variable geometry inlet design for scram jet engine”. *US Patent & Trademark Office*. Retrieved October 7, 2005.
- “Liquid Air Cycle Rocket Equation Henry Spencer Comment”. *Propulsion Systems*. Island One Society. Retrieved December 27, 2005.
- The break through. - space.com
- “Revolutionary jet engine tested”
- “British company claims biggest engine advance since the jet "
- Scramjet combustor development-PDF file
- “Aerojet has new Mach 7 plus reusable hypersonic vehicle plans”

Chapter 10

Rocket-powered aircraft

Messerschmitt Me 163

A **rocket-powered aircraft** or **rocket plane** is an aircraft that uses a rocket for propulsion, sometimes in addition to airbreathing jet engines. Rocket planes can achieve much higher speeds than similarly sized jet aircraft, but typically for at most a few minutes of powered operation, followed by a glide. Unhindered by the need for oxygen from the atmosphere they are suitable for very high altitude flight. They are also capable of delivering much higher acceleration and shorter takeoffs.

Rockets have been used simply to assist the main propulsion in the form of Jet Assisted Take Off (JATO) also known as “Rocket Assisted Take Off” (RATO or RATOG). Not all rocket planes are of the conventional takeoff like “normal” aircraft. Some types have been air-launched from another plane, while other types have taken off vertically - nose in the air and tail to the ground ("tail-sitters"). It is also possible, that rocket planes launch vertically without changing their orientation.

Because of the heavy propellant use and the various practical difficulties of operating rockets, the majority of rocket planes have been built for experimental use, as interceptor fighters and space aircraft.

10.1 History

Rocket-powered flight was pioneered in Germany. The first aircraft to fly under rocket power was the Lippisch Ente, in 1928.[1] The Ente had previously been flown as a glider. The next year, in 1929, the Opel RAK.1 became the first purpose-built rocket plane to fly.

10.1.1 World War II

The Heinkel He 176 was the world's first aircraft to be propelled solely by a liquid-fuelled rocket, making its first powered flight on 20 June 1939 with Erich Warsitz at the controls.[2]

The first rocket plane ever to be mass-produced was the Messerschmitt Me 163 interceptor in 1944, one of several German World War II attempts at rocket-powered aircraft.[3] The Bachem Ba 349 "Natter" vertical takeoff manned rocket interceptor aircraft flew in prototype form. Projects which never even reached the prototype stage include the Zeppelin Rammer, the *Fliegende Panzerfaust* and the Focke-Wulf *Volksjäger*.[4]

The Japanese also produced approximately 850 Yokosuka MXY7 Ohka rocket-powered suicide attack aircraft in World War II.

Other experimental aircraft included the Russian Bereznyak-Isayev BI-1 that flew in 1942 while the Northrop XP-79 was originally planned with rocket engines but switched to jet engines for its first and only flight in 1945. A rocket assisted P-51D Mustang was developed by North American Aviation that could attain 515 mph.[5][6] The engine ran on fumaric acid and aniline, stored in two 75 gallon under wing drop tanks.[6] The plane was tested in flight in April 1945. The rocket engine could run for about a minute.[6]

Of much larger size, the Silbervogel antipodal bomber spaceplane was planned by the Germans late in World War II, however later calculations showed that it would not have worked, and would have been destroyed during reentry.[7]

10.1.2 Cold War era

In 1946, the Soviet Mikoyan-Gurevich I-270 was built partly using technology developed by Sergei Korolev in 1943 and 1932.[8][9]

In 1946 the rocket-powered Bell X-1 was the first aircraft to break the speed of sound in level flight and the first of a seris of NACA/NASA rocket-powered aircraft.[10] The North American X-15 and X-15A2 designs were used for around a decade and eventually reached Mach 6.7 and over 100 km in altitude.[11]

In the 1950s the British developed mixed power designs to cover the performance gap that existed in then-current turbojet designs. The rocket was the main engine for delivering the speed and height required for high speed interception of high level bombers and the turbojet gave increased fuel economy in other parts of flight, most notably to make sure the aircraft was able to make a powered landing rather than risking an unpredictable gliding return. The Saunders-Roe SR.53 was a successful design and was due to be developed into production when economics forced curtailment of most British aircraft programmes in the late 1950s. The advancement of the turbojet engine output, the advent of missiles, and advances in radar had made a return to mixed power unnecessary.

The development of Soviet rockets and satellites was the driving force behind the development of NASA's space program. In the early 1960s, American research into the Boeing X-20 Dyna-Soar spaceplane was cancelled due to lack of purpose; later the studies contributed to the Space Shuttle, which in turn motivated the Russian Buran (spacecraft). Another similar program was ISINGLASS which was to be a rocket plane launched from a Boeing B-52 Stratofortress carrier, which was intended to achieve Mach 22, but this was never funded. ISINGLASS was intended to overfly the USSR. No images of the vehicle configuration have been released.[12]

The Lunar Landing Research Vehicle was a mixed powered vehicle- a jet engine cancelled 5/6 of the force due to gravity, and the rocket power was able to simulate the Apollo lunar lander.[13]

Various versions of the Reaction Motors XLR11 rocket engine powered the X-1 and X-15, but also the Martin Marietta X-24A, Martin Marietta X-24B, Northrop HL-10, Northrop M2-F2, Northrop M2-F3, and the Republic XF-91 Thunderceptor, either has a primary or axillary engine.

The X-15's XLR99 rocket engine used ammonia and liquid oxygen.

The Northrop HL-10, Northrop M2-F2 and Northrop M2-F3 were examples of a lifting body which are aircraft which have very little if any wing and simply obtain lift from the body of the vehicle. Another example is backslider rockets in amateur rocketry.

10.1.3 Post Cold War era

The EZ-Rocket research and test airplane was first flown in 2001. EZ-Rocket was the first privately built and flown rocket-powered airplane.[14]

A second privately-developed rocket-powered aircraft flew just two years later, in 2003. SpaceShipOne functions both as a rocket-powered aircraft—with wings and aerodynamic control surfaces—as well as a spaceplane—with RCS thrusters for control in the vacuum of space.

The Rocket Racing League has developed three rocket racer aircraft since 2001, after initially evaluating and testing the EZ-Rocket in 2001. None are currently in production however.

Planned rocket-powered aircraft

- Reaction Engines Skylon
- Spaceship Two
- Lynx rocketplane
- ARES (martian rocketplane)
- Zero Emission Hyper Sonic Transport

The Lockheed NF-104A had rocket and air-breathing turbojet engines, shown here climbing with rocket power. The rocket used hydrogen peroxide and JP-4 jet fuel.

10.2 See also

- List of rocket aircraft
- List of vehicle speed records
- Rocket Racing League (RRL)

The Martin Aircraft Company X-24 lifting body built as part of a 1963 to 1975 experimental US military program

- Zero-length launch, launching air-breathing aircraft with rockets

10.3 References

Notes

[1] "Lippisch Ente." *The Internet Encyclopedia of Science: Experimental Aircraft.* Retrieved: 26 September 2011.

[2] Warsitz, Lutz. *The First Jet Pilot: The Story of German Test Pilot Erich Warsitz.* London: Pen and Sword Books Ltd., 2009. ISBN 978-1-84415-818-8.

[3] "The Messerschmitt Me-163 Komet." *plane-crazy.net.* Retrieved: 26 September 2011.

[4] Fliegende Panzerfaust - *Luft'46*

[5] Larry Davis - **DEVELOPING THE XP-86**

[6] Santiago - The Rocket-Boosted P-51 Mustang - Tuesday, December 28, 2010

[7] Parsons, Zach. *My Tank is Fight.* London: Citadel, 2006. ISBN 978-0-8065-2758-1.

[8] Bille and Lishock 2004, p. 9.

[9] 1943

[10] "Bell X-1." *allstar.fiu.edu.* Retrieved: 26 September 2011.

[11] "North American X-15 High-Speed Research Aircraft." *Aerospaceweb.org*, 24 November 2008.

[12] Day, Dwayne. "A bat outta Hell: the ISINGLASS Mach 22 follow-on to OXCART." *The Space Review,* 12 April 2010. Retrieved: 26 September 2011.

[13] Matranga, Gene J., C. Wayne Ottinger and Calvin R. Jarvis with C. Christian Gelzer. "Aerospace History #35 NASA SP-2004-4535: Unconventional, Contrary, and Ugly: The Lunar Landing Research Vehicle." *NASA,* 2005.

[14] Knapp, Alex (2014-06-18). "Bootstrapping To The Stars". Forbes. Retrieved 2014-06-19.

Bibliography

- Bille, Matt and Erika Lishock. *The First Space Race: Launching the World's First Satellites.* College Station, Texas: Texas A&M University Press, 2004. ISBN 978-1-58544-374-1.
- Caidin, Martin. *Wings into Space: The History and Future of Winged Space Flight.* New York: Holt, Rinehart and Winston Inc., 1964.
- Dornberger, Walter R. "The Rocket-Propelled Commercial Airliner". *Dyna-Soar: Hypersonic Strategic Weapons System, Research Report No 135.*. Minneapolis, Minnesota: University of Minnesota, Institute of Technology, 1956.
- Geiger, Clarence J. *History of the X-20A Dyna-Soar. Vol. 1: AFSC Historical Publications Series 63-50-I, Document ID ASD-TR-63-50-I.* Wright Patterson AFB, Ohio: Aeronautical Systems Division Information Office, 1963.
- Godwin, Robert, ed. *Dyna-Soar: Hypersonic Strategic Weapons System.* Burlington, ON: Apogee Books, 2003. ISBN 1-896522-95-5.
- Yenne, Bill. *The Encyclopedia of US Spacecraft.* London: Bison Books, 1985. ISBN 978-5-551-26650-1.

10.4 External links

- The official **Erich Warsitz** website (world's first jet pilot) about the world's first liquid-fuelled rocket aircraft, the legendary Heinkel He 176

10.5 Text and image sources, contributors, and licenses

10.5.1 Text

- **Turbojet** *Source:* http://en.wikipedia.org/wiki/Turbojet?oldid=627718398 *Contributors:* AxelBoldt, Bryan Derksen, Europrobe, Olivier, Tannin, Rlandmann, Andrewa, Julesd, GCarty, Wolfgang Kufner, Tempshill, JorgeGG, Eternal, Fredrik, Pibwl, Modulatum, SchmuckyTheCat, Fuelbottle, Eliashedberg, Wizzy, Greyengine5, Wolfkeeper, Mark.murphy, No Guru, Abqwildcat, Bobblewik, Alanl, Beatnick, HorsePunchKid, Icairns, Karl Dickman, Fluzwup, Michael Zimmermann, ZeroOne, Kbh3rd, Rcsheets, Meggar, Atlant, Bantman, Suruena, Alanhwiki, Dan100, Sylvain Mielot, DonPMitchell, Alanmak, Titoxd, FlaBot, Rz350, Chobot, YurikBot, Retaggio, Huw Powell, Wiki alf, Bjf, Speedevil, Djdaedalus, Warfreak, Fenrus, Eog1916, Sardanaphalus, SmackBot, Emoscopes, Jdoniach, Incnis Mrsi, Sanjay ach, Burbank, Srnec, Chris the speller, Thumperward, Mexcellent, Snowmanradio, Kcordina, Mugaliens, Mhrogers, Nakon, The PIPE, DohCam, LanternLight, ThurnerRupert, Vgy7ujm, LWF, Gm1121983, Bonzi, -js-, Stwalkerster, Octane, CmdrObot, RottweilerCS, Kablammo, Louis Waweru, Dtgriscom, Woody, Paquitotrek, Robzz, Ktappe, B7582, MER-C, .anacondabot, Magioladitis, Jeff Dahl, Swpb, Sodabottle, BilCat, Styrofoam1994, MartinBot, Red Sunset, Catmoongirl, Ianboggs, Pete6982, Msadraey, Philip Trueman, TXiKiBoT, Shreditor, Raryel, Greswik, Andy Dingley, Rleach1, SieBot, Lightmouse, Jongleur100, Zenibo, Mygerardromance, Dolphin51, SidewinderX, Loren.wilton, ClueBot, Lawrence Cohen, Boss344, Mild Bill Hiccup, Nimbus227, Rkiga, SoHome, Jellyfish dave, Rivertown, Dvikram, Wikiuser100, MystBot, Wyatt915, Addbot, Luzingit, Fi11222, M.nelson, Peti610botH, Tide rolls, Luckas-bot, Amirobot, AnomieBOT, The High Fin Sperm Whale, ArthurBot, LilHelpa, Clohuigt, .45Colt, Jgscala, Celebration1981, Mnmngb, Prari, Firstjetpilot, Surv1v4l1st, Inc ru, AchimD, Secret 0000, AstaBOTh15, Pinethicket, Hamtechperson, Muc is so cool, Full-date unlinking bot, Mono, Pilot850, Tbhotch, DexDor, Klantry01, Wham Bam Rock II, ShinyGee, Mmeijeri, Benjamin1414141414141414, Brandmeister, ChuispastonBot, Rememberway, ClueBot NG, Naynay253, Alonso 4ever, Frietjes, Widr, Helpful Pixie Bot, Mightyname, BG19bot, Milk5000, Dexbot, Fireandair, Pieter1963, Tobatar, Adirlanz, Monkbot, Utrutrzr and Anonymous: 138
- **Turbofan** *Source:* http://en.wikipedia.org/wiki/Turbofan?oldid=629137006 *Contributors:* Maury Markowitz, Xlation, Stevertigo, Zocky, Tannin, Sannse, Rlandmann, Julesd, GCarty, Choster, Doradus, Airboyd, Donreed, JosephBarillari, K1br, Rsduhamel, Mat-C, Wolfkeeper, BenFrantzDale, Iceberg3k, Bobblewik, Alanl, WhiteDragon, Iantresman, Trevor MacInnis, N328KF, Rich Farmbrough, Avriette, Andros 1337, Qutezuce, Adam850, Alistair1978, Kbh3rd, SElefant, Diomidis Spinellis, Deicas, Meggar, Smalljim, JDB1983, Clawson, Stahlkocher1, Arcenciel, The RedBurn, Amorymeltzer, Cmprince, Pauli133, Gene Nygaard, Dan100, Jimgeorge, Bobrayner, Xanthar, Nuno Tavares, Brhaspati, Pol098, Schzmo, GregorB, Mhiley, GraemeLeggett, Mandarax, BD2412, Mendaliv, Josh Parris, Ketiltrout, MichiK, Wiarthurhu, FlaBot, Dowlingm, Ysangkok, Mark83, Wgfcrafty, Chobot, YurikBot, Retaggio, Daverocks, Los688, Jaxl, Nick, Voidxor, Ospalh, Kashkhan, Dictoon, IrfanFaiz, Sardanaphalus, Attilios, SmackBot, Emoscopes, Reedy, Marc Lacoste, Ariedartin, Burbank, Zephyris, Hmains, Chris the speller, Thumperward, Angrist, CSWarren, Colonies Chris, Buttered Bread, Snowmanradio, Huon, Robma, The PIPE, Richard0612, Vina-iwbot, Ulfmichel, John, Twredfish, Jaganath, MilborneOne, Mbeychok, Cacetudo, P199, DagErlingSmørgrav, Mikes1988, JoeBot, CP\M, Daedalus969, McVities, Starcity ai, SithiR, Shannon.g, RottweilerCS, Kozuch, Nick Challoner, Thijs!bot, Epbr123, Barticus88, Kubanczyk, Drpixie, AndrewDressel, Robincross224, Dpenguinman, AntiVandalBot, Seaphoto, HolyT, Bongwarrior, 28421u2232nfenfcenc, BilCat, Wardie9025, Lilac Soul, RockMFR, Grim Revenant, Unnamedkid, Ayecee, Jiahui1992, Dawright12, HornColumbia, Clerks, StephenML, Chilukuri, C1010, Serge925, FEVB, Potatoswatter, Ldebain, Alterrabe, JCG33, Itsfullofstars, Jeff G., TobyDZ, Linefeed, Philip Trueman, Isaac Sanolnacov, TXiKiBoT, Davehi1, Shreditor, Cpzphantom, Someguy1221, Raryel, Nuance 4, Tangobar, Rouhiheki, K. Aainsqatsi, Pmarshal, SieBot, Altadena1, SilverbackNet, Lightmouse, Senor Cuete, Fratrep, Heimsdalgaten, Hamiltondaniel, Anyeverybody, Dolphin51, SidewinderX, YSSYguy, ClueBot, Binksternet, Ariadacapo, Nimbus227, Three-quarter-ten, Ondras999r, Schnieder69, Jiawei 91, Mgw89, Awbergh, DumZiBoT, Aaron north, Jht4060, Solarsail, Dave1185, Addbot, Fi11222, Jasper Deng, Mdnavman, Fireaxe888, NoJo15, HatemElattar, Apteva, Luckas-bot, Yobot, Grebaldar, Wikipedian2, Nallimbot, AnomieBOT, Dreidecker, The High Fin Sperm Whale, Xqbot, Sionus, MiniBill, Scrooke, GliderMaven, Rgvis, Gallium9, Pinethicket, I dream of horses, Abductive, MastiBot, Tupsumato, Horsewack, DexDor, TGCP, EmausBot, WikitanvirBot, Dewritech, Sp33dyphil, Agent L, NorthernKnightNo1, Mmeijeri, Fæ, Rexprimoris, Tim Zukas, ChuispastonBot, Teapeat, Rememberway, Stevenghetto257, JetBlast, Frietjes, Helpful Pixie Bot, Westnest, Mightyname, BG19bot, United7471, Metricopolus, Zedshort, 220 of Borg, Duxwing, Khazar2, Prj1991, JYBot, Mogism, Kbog, Pi64600, Ginsuloft, DonoNS, 1ndrw, Trackteur and Anonymous: 191
- **Propfan** *Source:* http://en.wikipedia.org/wiki/Propfan?oldid=627718466 *Contributors:* Maury Markowitz, Rlandmann, Mirv, Justanyone, Fuelbottle, Mor, Abqwildcat, Xmnemonic, PDH, Mzajac, Ericg, N328KF, Rich Farmbrough, Violetriga, Stahlkocher1, Jlascar, Admiral Valdemar, Dan100, Rossheth, Bruce89, Dgnelson, Hawaiian717, Wolfmankurd, Arado, Hydrargyrum, Ksyrie, CPColin, SmackBot, Burbank, Commander Keane bot, Trekphiler, KaiserbBot, Alexmcfire, Fitzhugh, The PIPE, Lester, Ъыь, Jmrog, Fnlayson, Cancun771, Mwhiz, Dricherby, Nikevich, BilCat, Aeroweanie, Afromme, Duch, STBotD, Bonadea, JavierMC, Amikake3, Youngvariety, Lamro, Senor Cuete, Dolphin51, Cochonfou, Mild Bill Hiccup, Nimbus227, Carriearchdale, Tkrocks11, LordJesseD, XLinkBot, Addbot, Jgrosay, Lightbot, A300st, The Bushranger, Luckas-bot, Wodawik, The High Fin Sperm Whale, ⍰⍰, Webwat, PistaLibreSV, Plane Person, TGCP, WikitanvirBot, Mmeijeri, Hoeksas, Frietjes, Therightmannigs, Kweetal, BattyBot, Ilkcs, Kbog and Anonymous: 52
- **Pulsejet** *Source:* http://en.wikipedia.org/wiki/Pulsejet?oldid=629119005 *Contributors:* Mav, Bryan Derksen, Tarquin, Ap, Maury Markowitz, DrBob, Winelight, Ericd, Xoder, Patrick, RTC, Tannin, Rlandmann, Aarchiba, GCarty, Stone, David Latapie, Omegatron, Flockmeal, Robbot, Gregors, Fredrik, Justanyone, Fuelbottle, Xanzzibar, Cyrius, Greyengine5, Wolfkeeper, Abigail-II, Everyking, Leonard G., Brockert, Bobblewik, Gadfium, Eregli bob, Sonett72, Trevor MacInnis, Rich Farmbrough, Pjacobi, Michael Zimmermann, Bobo192, Walkiped, Foobaz, Pearle, A2Kafir, Danski14, Linmhall, Velella, Gunter, Gene Nygaard, Mindmatrix, Uncle G, Kelisi, David Levy, Nightscream, G Clark, Caseman, YurikBot, Gyre, Hellbus, Hydrargyrum, Manegonel, Mslenc, WebPilot, GraemeL, Fram, Garion96, Benandorsqueaks, Groyolo, Sardanaphalus, KnightRider, SmackBot, Anarchist42, RedSpruce, Arny, Boris Barowski, Septegram, Gilliam, Keegan, Thumperward, Xchbla423, Trekphiler, Tsca.bot, Jumping cheese, Radagast83, ProtocolOH, Derek R Bullamore, The PIPE, NeilFraser, EdC, Matt S., KerryVeenstra, Unionhawk, Egmonster, W.F.Galway, Nabokov, Omicronpersei8, Thijs!bot, Shirt58, Mack2, Gökhan, JAnDbot, AniRaptor2001, Mark Rizo, Igodard, Father Goose, Jim Douglas, Bernd vdB, Simonxag, BilCat, Jonsg, Trusilver, ISC PB, Ramcharanr, Nwbeeson, Israel Walker, VolkovBot, BeckTechnologies, Cootiequits, Donarnold, No1likesme, Andy Dingley, SieBot, Lightmouse, Superbeecat, Ariadacapo, NiD.29, Starstylers, Nimbus227, DumZiBoT, XLinkBot, Rror, SilvonenBot, Magus732, TristramPW, CarsracBot, The Bushranger, Legobot, Luckas-bot, Yobot, AnomieBOT, DemocraticLuntz, Ciphers, JackieBot, LilHelpa, Xqbot, Idegmcsa, Chaheel Riens, Hyperboreer, FrescoBot, Vinceouca, Свифт, PigFlu Oink, Calmer Waters, Skyerise, RedBot, Salvidrim!, Dinamik-bot, Begoon, Aerothermodynamic, Weedwhacker128, DexDor, EmausBot, John of Reading, Pahazzard, Thkvortsov, ZéroBot, Whoop whoop pull up, Rememberway, ClueBot NG, Jack Greenmaven, Frietjes, Danim, Curtb60, Ghb3, ChrisGualtieri, Jcrbmc, Undead182, Monkbot, Mm.roy and Anonymous: 132

- **Valveless pulse jet** *Source:* http://en.wikipedia.org/wiki/Valveless_pulse_jet?oldid=592685637 *Contributors:* Waveguy, Leonard G., Brockert, Neilc, Pjacobi, Twiek, Devil Master, TheParanoidOne, Wildstar2501, Bushytails, Woohookitty, GrundyCamellia, Dullfig, Gaius Cornelius, Manegonel, Zephalis, SmackBot, Thumperward, Stepho-wrs, Larry Cottrill, Jumping cheese, Radagast83, Robofish, Sabate, Arch dude, Father Goose, JanGB, AtholM, Random Passer-by, BeckTechnologies, Biscuittin, Hertz1888, ProkopHapala, Celique, EoGuy, Snaxalotl, Mumiemonstret, Cerireid, Addbot, Cannizzaro S, Mike1975, La vita è dolce, LilHelpa, Xqbot, DingleNutZ, FoxBot, Rathkennamike, Slightsmile, Whoop whoop pull up, Rammaum, ClueBot NG, Schuy B., OrnJonasar, Astragon67 and Anonymous: 26
- **Pulse detonation engine** *Source:* http://en.wikipedia.org/wiki/Pulse_detonation_engine?oldid=628226012 *Contributors:* Maury Markowitz, Rlandmann, JidGom, Wik, Rei, Omegatron, Wernher, Yosri, Fuelbottle, Wolfkeeper, Tom harrison, Leonard G., N328KF, Cfailde, Meggar, Milovoo, Anthony Appleyard, Malo, Cal 1234, Gene Nygaard, Uncle G, Rjwilmsi, Arnero, Harmil, Gurch, Triku, StuffOfInterest, Anders.Warga, Nae'blis, Tierce, SmackBot, Nkrupans, Twerges, Chris the speller, Trebor, OrphanBot, Jbergquist, A5b, Robofish, Iridescent, CP\M, Will Pittenger, Butakun, Ldussan, Oosh, AntiVandalBot, Akradecki, Planofool, Krishvanth, Dricherby, Singularity, BilCat, LorenzoB, Wxcvbn, R'n'B, CommonsDelinker, Jwigton, Erisie, HirschiDude, Rondanielove, Ng.j, Chiongryan, GeiwTeol, Dravecky, Cyfal, Sfan00 IMG, EMBaero, Arakunem, Rosuav, Ajyo15, Davismargaret, Wahunga, XLinkBot, Qulser, Addbot, Twinzor, Cesiumfrog, Creolejazz, Luckas-bot, GB fan, ArthurBot, LilHelpa, Xqbot, GrouchoBot, FrescoBot, Augurar, Whoop whoop pull up, Sudip2118, Virtualerian, Shivamsetu, Blue predetor, Engineering Physicist Martin and Anonymous: 77
- **Motorjet** *Source:* http://en.wikipedia.org/wiki/Motorjet?oldid=627718539 *Contributors:* Maury Markowitz, Rlandmann, Cherkash, GCarty, Roo72, Mathrick, Hellbus, Adamrush, Salmanazar, Sardanaphalus, Chris the speller, Thumperward, After Midnight, Swpb, BilCat, Squids and Chips, VolkovBot, Tamorlan, AlleborgoBot, SieBot, BobShair, Lightmouse, Dolphin51, Muhends, Binksternet, Nimbus227, BobKawanaka, RP459, Addbot, Lightbot, Citation bot, Horiapaun, .45Colt, Mark Nye, Altes2009, DexDor, WikitanvirBot, Sumsum2010, Mmeijeri, Teaktl17, Frietjes, Helpful Pixie Bot, Shar946, Marigold100, Astragon672 and Anonymous: 13
- **Ramjet** *Source:* http://en.wikipedia.org/wiki/Ramjet?oldid=630943821 *Contributors:* TwoOneTwo, Robert Merkel, Maury Markowitz, Edward, Patrick, Arpingstone, Egil, Rlandmann, Aarchiba, Julesd, Xgkkp, Maximus Rex, Omegatron, Ed g2s, Pibwl, Justanyone, Meelar, Bkell, Fuelbottle, Kent Wang, Seano1, Diberri, Mor, Ploum's, Matt Gies, Greyengine5, Wolfkeeper, Mboverload, Bobblewik, Tagishsimon, Quadell, Gem fr, NoPetrol, Hugh Mason, Deglr6328, Trevor MacInnis, Rich Farmbrough, LoganCale, Pjacobi, YUL89YYZ, Femto, WorldDownInFire, Bobo192, DarylC, Savvo, Bobbis, Eric Kvaalen, Atlant, Snowolf, Babble, M3tainfo, Cal 1234, Pauli133, Deror avi, Siafu, DonPMitchell, Benbest, Schzmo, GregorB, SeventyThree, Rjwilmsi, Woodsja, SMC, CQJ, Taskinen, Bmicomp, Chobot, The Rambling Man, YurikBot, Daverocks, Dreammaker182, Witan, Hellbus, Ksyrie, Shaddack, Los688, Kyorosuke, Rbarreira, Catchiestzero, Vivaldi, Salmanazar, Some guy, Oldhamlet, Torgo, Sardanaphalus, SmackBot, Emoscopes, Hkhenson, Burbank, Commander Keane bot, Folajimi, Chris the speller, TimBentley, Hibernian, Colonies Chris, Stevekirk, Downwards, A5b, NeilFraser, Special-T, Iridescent, Ossifer, CmdrObot, Im.a.lumberjack, Pgr94, Fl295, Meno25, Yuzz, Mr pipps, RottweilerCS, Optimist on the run, JamesAM, Thijs!bot, Lanik42, Mack2, Canadian-Bacon, JAnDbot, Alexpg, Husond, MER-C, Albany NY, PhilKnight, Bongwarrior, SwiftBot, RegIP, MetsBot, BilCat, Archolman, Flo422, Sheila Rogers, J.delanoy, Hans Dunkelberg, Zedmelon, RenniePet, CeilingCrash, Remi0o, MatP, Plenumchamber, MrBeck, Petebutt, Crazymapleleaf, Cryonic07, SieBot, Mikemoral, Chiongryan, Cypoet, AMCKen, Callidior, Ravi tanwar80, Racergr, De728631, AnnEditor, GreyTrafalgar, Ariadacapo, Jmn100, 718 Bot, Barbarinaz, Vanished User 1004, DumZiBoT, Mr Larrington, Sajana rpg, Rameshaero168, Addbot, John Chamberlain, Tassedethe, Lightbot, Zorrobot, Luckas-bot, Tangopaso, Efa, Piano non troppo, Xufanc, Citation bot, Xqbot, Gigemag76, Idegmcsa, RibotBOT, Celebration1981, MrChrisRodriguez, LucienBOT, HJ Mitchell, Hawkingsstudent, Citation bot 1, HRoestBot, RedBot, MastiBot, Tupsumato, Gmkung, Deweyboy, RjwilmsiBot, DexDor, Alph Bot, Jackehammond, Sp33dyphil, Mmeijeri, Wikipelli, ZéroBot, Djapa84, TYelliot, Will Beback Auto, Rememberway, ClueBot NG, Senthilvel32, Frietjes, Helpful Pixie Bot, KLBot2, Saurabh.agrawal92, CitationCleanerBot, YFdyh-bot, Bradleyjohnsontv, Dr.x38, Pieter1963, Suzukisue, JamesHawthorne, Razibot, MopSeeker, Monkbot, Agupta22 and Anonymous: 159
- **Scramjet** *Source:* http://en.wikipedia.org/wiki/Scramjet?oldid=628227067 *Contributors:* The Epopt, Maury Markowitz, Edward, SGBailey, Gbleem, Egil, Rlandmann, Julesd, Whkoh, Mulad, Wik, Natevw, Rei, Lichtkind, Jerzy, Finlay McWalter, Donreed, Justanyone, Hadal, Jcmiller1215, Fuelbottle, Xanzzibar, Giftlite, Wolfkeeper, Gracefool, Mackerm, Bobblewik, Wmahan, Erich gasboy, Xmnemonic, WhiteDragon, Robert Brockway, Piotrus, Rdsmith4, Jmeppley, Peter bertok, LQ, DmitryKo, Noisy, Solitude, Rich Farmbrough, Guanabot, Ibagli, TerraFrost, Chairboy, Bobo192, Dreish, Apyule, Zwilson, Aquillion, Towel401, Mpeisenbr, Shadoks, Mrzaius, Etxrge, Rujholla, Ignatzmous, Atlant, Keenan Pepper, Doopokko, Rptb1, M3tainfo, Deacon of Pndapetzim, Cal 1234, Gene Nygaard, Siafu, Richard Arthur Norton (1958-), Mindmatrix, Jason Palpatine, Brunnock, Uncle G, Rainmaker, SDC, SeventyThree, GraemeLeggett, Mandarax, RedBLACKandBURN, Rnt20, Mendaliv, Josh Parris, Nightscream, Hulagutten, FlaBot, Arnero, Nomadtales, Chobot, DVdm, YurikBot, Wavelength, Piet Delport, Epolk, Stephenb, David Woodward, Gaius Cornelius, Ksyrie, Gcapp1959, Voidxor, Jeremy Visser, Alex Law, Oliverdl, NorsemanII, Bayerischermann, Tarkovsky, Smurrayinchester, AKAF, Defufna, Knowledgeum, IrfanFaiz, That Guy, From That Show!, Luk, Oldhamlet, Tinlv7, KnightRider, SmackBot, Emoscopes, Atomota, Brossow, Burbank, Gilliam, Hmains, Chris the speller, Mbrandall, Motterstatter, Trebor, Thumperward, Huge Bananas, Hibernian, Neo-Jay, Egg plant, Joema, KenFehling, Hkuenzi, Soumyasch, Iska, JHunterJ, Kothog, Yashesh, Iridescent, Timothykinney, Tony Fox, Pathosbot, Chetvorno, David Gates, FireFrie, Cofax48, N2e, Cydebot, Butakun, UncleBubba, Thijs!bot, Kubanczyk, Sagaciousuk, Andyjsmith, Smiklas, Dafydd Williams, I do not exist, Seaphoto, Instinct, Chanakyathegreat, Demophon, Johnwwatson, Yomin, Bongwarrior, Professor marginalia, Swpb, Mike409, Rivertorch, Dinosaur puppy, BilCat, A3 nm, Gwern, Brilliand, R'n'B, J.delanoy, Pharaoh of the Wizards, Javawizard, Lordofthe9, Rod57, Clerks, Dfoofnik, Underjack, Vanished user 39948282, Treisijs, Morganma, Random Passer-by, Fagiolonero, Bastian Friedrich, Jackfork, Agonyflips, Squalk25, Hmwith, Cthulhu985, TYLER, Billjc, Cablehorn, Cypoet, Denisarona, SidewinderX, ClueBot, AnnEditor, GreyTrafalgar, Arentath8, ElectricalTill, Uqhyper, CounterVandalismBot, Chimesmonster, Detroiterbot, TMV943, Noca2plus, ResidueOfDesign, Barbarinaz, ChesterTheWorm, Erudhalion, Noxia, Chaosdruid, MelonBot, Heyzeuss, DumZiBoT, Rpassaro, Jcaulfie, Orbnauticus, Jasynnash2, Addbot, Xp54321, DOI bot, Ronhjones, Ionia23, Doniago, R3ap3R, The Bushranger, StandardPerson, Ben Ben, Yobot, EnochBethany, Richard.e.morton, AnomieBOT, Guynk, John Holmes II, Efa, TheAMmollusc, Injust, Msskamel, Pnuematics, Lee6597, Камень, Eugene-elgato, JasonCW, GliderMaven, FrescoBot, Beaber, Hokies499, W Nowicki, Citation bot 1, Pinethicket, Tom.Reding, Jcsbija, RichardWayneSmith, Sachinkilkile, Jujutacular, Enemenemu, Suryamp, ArwinJ, Roflman123456, DexDor, Ifly6, Beyond My Ken, Advantecon, John of Reading, GoingBatty, JustinTime55, Sp33dyphil, Mmeijeri, Solomonfromfinland, Chasrob, Space25689, TDGA, Tlwm, Donner60, Rangoon11, ChuispastonBot, Wakebrdkid, ImaXami, Whoop whoop pull up, Rememberway, ClueBot NG, Incompetence, Brieschenk1985, Skywarrior.saravanan, Senthilvel32, Sudip2118, Frietjes, James T Farmer Jr, Bored873, Dakilla68, Widr, Hypersonic68, Pilotmario, Nevadaone, Helpful Pixie Bot, Virtualerian, BendelacBOT, 155blue, Xlicolts613, Go ahead punk, Nitrobutane, Cwobeel, DaltonCastle, Makecat-bot, Vishnuvardhanmana, Epicgenius, HappyDa, Lmcq, Monkbot and Anonymous: 303
- **Rocket-powered aircraft** *Source:* http://en.wikipedia.org/wiki/Rocket-powered_aircraft?oldid=627718509 *Contributors:* Lexor, Rlandmann, Wolfkeeper, Monedula, Eequor, N328KF, Rich Farmbrough, A2Kafir, Wendell, Alansohn, DonPMitchell, WadeSimMiser, GraemeLeggett, Palica, Allen3, Titoxd, YurikBot, Gaius Cornelius, Ospalh, Archer7, Sinus, SmackBot, Chris the speller, Carnby, J 1982, N2e,

Themightyquill, Steelpillow, JAnDbot, Txomin, Bzuk, Swpb, Nono64, Kott3670, Tatrgel, Joshua Issac, Sdsds, Muro de Aguas, SieBot, Lightmouse, Foofbun, Ramif 47, PixelBot, Posix memalign, NuclearWarfare, Addbot, Montgomery '39, Victor-435, The Bushranger, Yobot, AnomieBOT, Jim1138, Xufanc, Aldebaran, Sophus Bie, Fotaun, GliderMaven, Firstjetpilot, RedBot, DexDor, WikitanvirBot, Wikipelli, Hoeksas, Rememberway, Frietjes, Helpful Pixie Bot, Daydreamers, Swaxx, Writingalltheway, Filedelinkerbot and Anonymous: 24

10.5.2 Images

- **File:Air_Canada_GE90_Boeing_777-200LR.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/19/Air_Canada_GE90_Boeing_777-200LR.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Kristoferb
- **File:Air_starter_GE_J79-11A_by_BMW.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/3f/Air_starter_GE_J79-11A_by_BMW.JPG *License:* CC-BY-SA-3.0-2.5-2.0-1.0 *Contributors:* Own work *Original artist:* Sovxx
- **File:Albert_Fono'{}s_Patents_for_jet_engines_1928.jpg** *Source:* http://upload.wikimedia.org/wikipedia/en/3/37/Albert_Fono%27s_Patents_for_jet_engines_1928.jpg *License:* ? *Contributors:*

  I created this work entirely by myself.

  Original artist:

  Albert Fonó
- **File:Albert_Fono'{}s_ramjet-cannonball_in_1915.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/29/Albert_Fono%27s_ramjet-cannonball_in_1915.png *License:* CC-BY-SA-3.0 *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:RandomStringOfCharacters using CommonsHelper.
  Original artist: Albert Fonó. Original uploader was 718 Bot at en.wikipedia
- **File:Alpha_Jet_E47_2.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/bf/Alpha_Jet_E47_2.JPG *License:* CC-BY-SA-3.0 *Contributors:* photo taken by EyOne *Original artist:* EyOne
- **File:Argus_As14_RAFM.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/3e/Argus_As14_RAFM.jpg *License:* Public domain *Contributors:* Own work *Original artist:* Nimbus227
- **File:Aviacionavion.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/68/Aviacionavion.png *License:* Public domain *Contributors:*
- Turkmenistan.airlines.frontview.arp.jpg *Original artist:* Turkmenistan.airlines.frontview.arp.jpg: elfuser
- **File:Axial_compressor.gif** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/ca/Axial_compressor.gif *License:* Public domain *Contributors:* http://www.grc.nasa.gov/WWW/K-12/airplane/caxiala.html *Original artist:* NASA
- **File:Bloodhound_thor_arp_750pix.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/23/Bloodhound_thor_arp_750pix.jpg *License:* Public domain *Contributors:* Originally from en:wikipedia, its description page is/was here *Original artist:* Original uploader was en:User:Arpingstone at en:wikipedia
- **File:Brayton_cycle.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/3/3c/Brayton_cycle.svg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:CF6-6_engine_cutaway.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/f0/CF6-6_engine_cutaway.jpg *License:* Public domain *Contributors:* http://lessons.air.mmac.faa.gov/l2/NAL27/fig4/ *Original artist:* This image is a work of an unknown Federal Aviation Administration employee.
- **File:CFM56_P1220759.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e9/CFM56_P1220759.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* David Monniaux
- **File:Commons-logo.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/4a/Commons-logo.svg *License:* ? *Contributors:* ? *Original artist:* ?
- **File:Edit-clear.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/f/f2/Edit-clear.svg *License:* ? *Contributors:* The *Tango! Desktop Project*. *Original artist:*

  The people from the Tango! project. And according to the meta-data in the file, specifically: "Andreas Nilsson, and Jakub Steiner (although minimally)."
- **File:Folder_Hexagonal_Icon.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/4/48/Folder_Hexagonal_Icon.svg *License:* ? *Contributors:* ? *Original artist:* ?
- **File:Ge_cf6_turbofan.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/75/Ge_cf6_turbofan.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Sanjay Acharya
- **File:Geared_Turbofan_NT.PNG** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9f/Geared_Turbofan_NT.PNG *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Tosaka
- **File:GorgonIV_on_BlackWidow.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/0/08/GorgonIV_on_BlackWidow.png *License:* Public domain *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:Micki using CommonsHelper.
  Original artist: Original uploader was John Chamberlain at en.wikipedia
- **File:J85_ge_17a_turbojet_engine.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/56/J85_ge_17a_turbojet_engine.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Sanjay Acharya
- **File:Jar-jar-jet.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/15/Jar-jar-jet.jpg *License:* Public domain *Contributors:* English Wikipedia *Original artist:* ProkopHapala
- **File:Jet_engine.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4c/Jet_engine.svg *License:* CC-BY-SA-3.0-2.5-2.0-1.0 *Contributors:* self-made, vector version of en:Image:FAA-8083-3A Fig 14-1.PNG which comes from an FAA handbook *Original artist:* Jeff Dahl

- **File:Leduc_022.JPG** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e0/Leduc_022.JPG *License:* CC-BY-SA-2.5 *Contributors:* Own work (Bourget museum, in France) *Original artist:* Deep silence (Mikaël Restoux)
- **File:Me163efJM.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/56/Me163efJM.jpg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:NF-104.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4d/NF-104.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Nasa_ge_udf.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/c1/Nasa_ge_udf.jpg *License:* Public domain *Contributors:* Transferred from en.wikipedia; transfer was stated to be made by User:Duch.seb.
  Original artist: NASA Glenn Research Center (NASA-GRC) Original uploader was A300st at en.wikipedia
- **File:Ohain_USAF_He_178_page61.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/1e/Ohain_USAF_He_178_page61.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:Outer_nozzle_of_GEnx-2B_turbofan_engine.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/1b/Outer_nozzle_of_GEnx-2B_turbofan_engine.jpg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Olivier Cleynen
- **File:PDE_LongEZ_AFRL.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/8/82/PDE_LongEZ_AFRL.jpg *License:* Public domain *Contributors:* http://www.flightglobal.com/articles/2008/03/05/222008/us-afrl-proves-pulse-detonation-engine-can-power-aircraft.html (states the image is from the AFRL) *Original artist:* Air Force Research Laboratory
- **File:Pitotintake.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/8/87/Pitotintake.svg *License:* ? *Contributors:*
  self-made
  Original artist:
  K. Aainsqatsi
- **File:Portal-puzzle.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/f/fd/Portal-puzzle.svg *License:* ? *Contributors:* ? *Original artist:* ?
- **File:Progress_D-27_propfan_(Antonov_An-70).jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e3/Progress_D-27_propfan_%28Antonov_An-70%29.jpg *License:* CC-BY-SA-3.0 *Contributors:* An-70_takeoff.jpg
  Original artist: An-70_takeoff.jpg: Original uploader was Marianivka at en.wikipedia
- **File:Puls1Motor_en.gif** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/2c/Puls1Motor_en.gif *License:* CC-BY-3.0-rs *Contributors:* Puls1Motor.gif
  Original artist: Puls1Motor.gif: The original uploader was Aleksej fon Grozni at Serbian Wikipedia
- **File:Pulse_Jet_Engine.PNG** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/44/Pulse_Jet_Engine.PNG *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Tosaka
- **File:Pulse_Jet_schematic.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/21/Pulse_Jet_schematic.svg *License:* CC-BY-SA-3.0 *Contributors:*
- Pulse_jet.png *Original artist:* Pulse_jet.png: User:Topory
- **File:Question_book-new.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/9/99/Question_book-new.svg *License:* ? *Contributors:*
  Created from scratch in Adobe Illustrator. Based on Image:Question book.png created by User:Equazcion *Original artist:*
  Tkgd2007
- **File:Ramjet_P280b.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/f/f5/Ramjet_P280b.jpg *License:* Public domain *Contributors:* http://history.nasa.gov/SP-4404/app-b7.htm *Original artist:* NASA
- **File:Ramjet_operation.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/6c/Ramjet_operation.svg *License:* CC-BY-SA-3.0 *Contributors:* Based on Image:Ramjet operation.png *Original artist:* Vector image made by Cryonic07. Source
- **File:Ramon_Casanova_and_the_pulsejet_engine_he_constructed_and_patented_in_1917.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e8/Ramon_Casanova_and_the_pulsejet_engine_he_constructed_and_patented_in_1917.jpg *License:* CC-BY-3.0 *Contributors:* family picture *Original artist:* Jcrbmc
- **File:SJX61_1EngineTest20070221_TransitionToJP7.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/1/11/SJX61_1EngineTest20070221_TransitionToJP7.jpg *License:* Public domain *Contributors:* http://www.aiaa.org/documents/industry/presentations/MG_Bedke_High_Speed_Weapons.ppt *Original artist:* Maj Gen Curt Bedke, US Air Force
- **File:Scramjet_operation_en.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/2/22/Scramjet_operation_en.svg *License:* CC-BY-SA-3.0 *Contributors:*
- Scramjet_operation.png *Original artist:* Scramjet_operation.png: en:User:Emoscopes
- **File:Specific-impulse-kk-20090105.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4f/Specific-impulse-kk-20090105.png *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Kashkhan at English Wikipedia
- **File:Swept-propeller7.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9e/Swept-propeller7.svg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* Wolfmankurd
- **File:Symbol_list_class.svg** *Source:* http://upload.wikimedia.org/wikipedia/en/d/db/Symbol_list_class.svg *License:* ? *Contributors:* ? *Original artist:* ?

- **File:Text_document_with_red_question_mark.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/a4/Text_document_with_red_question_mark.svg *License:* Public domain *Contributors:* Created by bdesham with Inkscape; based upon Text-x-generic.svg from the Tango project. *Original artist:* Benjamin D. Esham (bdesham)
- **File:Turbo_ram_scramjet_comparative_diagram.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/57/Turbo_ram_scramjet_comparative_diagram.svg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* GreyTrafalgar
- **File:Turbofan3_Labelled.gif** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e5/Turbofan3_Labelled.gif *License:* CC-BY-SA-3.0 *Contributors:* Transferred from en.wikipedia; transferred to Commons by User:Micki using CommonsHelper. *Original artist:* Richard Wheeler (Zephyris). Original uploader was Zephyris at en.wikipedia
- **File:Turbofan_operation.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/75/Turbofan_operation.svg *License:* CC-BY-2.5 *Contributors:* Own work *Original artist:* K. Aainsqatsi
- **File:Turbofan_operation_lbp.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/7/77/Turbofan_operation_lbp.svg *License:* CC-BY-SA-3.0 *Contributors:* Own work *Original artist:* K. Aainsqatsi
- **File:Turbojet_operation-_axial_flow.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/e/e3/Turbojet_operation-_axial_flow.png *License:* CC-BY-2.5 *Contributors:* ? *Original artist:* ?
- **File:Turbojet_operation-_centrifugal_flow.png** *Source:* http://upload.wikimedia.org/wikipedia/commons/c/ce/Turbojet_operation-_centrifugal_flow.png *License:* CC-BY-2.5 *Contributors:* ? *Original artist:* ?
- **File:Turboreacteur_anime.gif** *Source:* http://upload.wikimedia.org/wikipedia/commons/9/9e/Turboreacteur_anime.gif *License:* CC-BY-SA-2.0-fr *Contributors:* Transferred from fr.wikipedia; transferred to Commons by User:Padawane using CommonsHelper. *Original artist:* Original uploader was Daniel BONNERUE at fr.wikipedia
- **File:WRDK.svg** *Source:* http://upload.wikimedia.org/wikipedia/commons/b/b4/WRDK.svg *License:* CC-BY-SA-3.0 *Contributors:* ? *Original artist:* ?
- **File:X-15_flying.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/a/a3/X-15_flying.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:X-43A_(Hyper_-_X)_Mach_7_computational_fluid_dynamic_(CFD).jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/5/55/X-43A_%28Hyper_-_X%29_Mach_7_computational_fluid_dynamic_%28CFD%29.jpg *License:* Public domain *Contributors:* http://www.dfrc.nasa.gov/Gallery/Photo/X-43A/HTML/ED97-43968-1.html *Original artist:* NASA
- **File:X24.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/6/61/X24.jpg *License:* Public domain *Contributors:* ? *Original artist:* ?
- **File:X43a2_nasa_scramjet.jpg** *Source:* http://upload.wikimedia.org/wikipedia/commons/4/4a/X43a2_nasa_scramjet.jpg *License:* Public domain *Contributors:* http://antwrp.gsfc.nasa.gov/apod/ap040329.html [1] *Original artist:*
- Original uploader was Milk's Favorite Cookie at en.wikipedia

10.5.3 Content license

- Creative Commons Attribution-Share Alike 3.0