361 (Gateshead) Squadron

Propulsion Revision Notes

The Piston Engine

In 1903, the Wright brothers made the first powered aeroplane flight using a piston engine in their plane.

There are many types of piston engines including those that burn solid or liquid fuel externally (such as steam engines) however aircraft piston engines are internal combustion engines as **liquid** fuel is burnt **inside** the engine.

A piston engine has a **cylinder** in which fuel (and air) is compressed by a **piston**, and is then ignited, which releases energy, which pushes the piston back down the cylinder.

Combustion

The burning the fuel/air mixture is called **combustion** and is a chemical reaction.

Although a fuel/air will burn at atmospheric pressure, more power is released when the mixture is compressed which results in great gain in power and better fuel consumption.

The movement of the piston is **linear** (in a straight line) however to be useful in an aircraft we need a **rotary** motion able to turn a propeller.

Examples of systems that convert linear motion to rotary motion are:

- Spanners – pulling on the end of a spanner causes the nut held in the other end to rotate.
- Bicycle petal and crank – pushing on the pedal with your foot causes the chainwheel to rotate.

The Crankshaft

A piston engine uses a crankshaft to convert the linear motion of the piston into rotary motion.

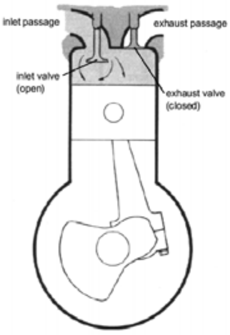
The piston is linked to the crankshaft by the **Connecting Rod**.

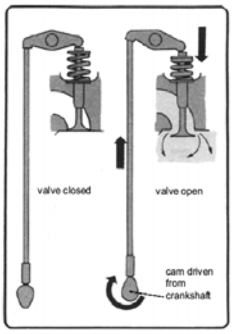
Inlet & Exhaust Valves

An engine needs passages into the cylinder to allow the fuel/air mixture in (**inlet**) and to let the burnt gasses out (**exhaust**).

These passages are opened and closed by inlet and exhaust **Valves** that are operated by a **Cams** on a **Camshaft**, which is driven by the crankshaft using gears, chains or belts.

To start an engine it must be turned by external means until a fuel air mixture has entered the cylinder and been compressed. An Electric Spark produced by a Sparkplug then ignites the mixture.





Some Technical Terms

- **Stroke** – the distance travelled by the piston between top dead centre (**TDC**) and bottom dead centre (**BDC**) and vice versa. In one stroke the crankshaft rotates through 180^o.
- **Top Dead Centre** – TDC occurs when the piston reaches the highest point in its travel.
- **Bottom Dead Centre** – BDC occurs when the piston reaches the lowest point in its travel.
- **Gudgeon Pin** – this joins the connecting rod to the piston.
- **Crank Pin** – this joins the connecting rod to the crankshaft.

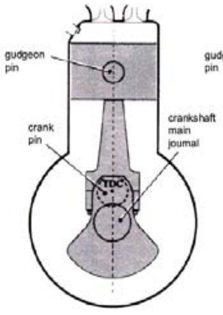


Fig 1-5a Top Dead Centre

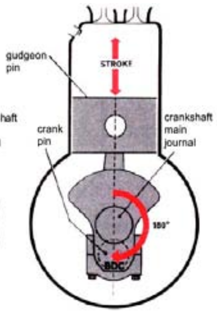


Fig 1-5b Bottom Dead Centre

- **Crankshaft Main Journal** – this is the central shaft of the crankshaft.

At TDC and BDC, a **straight line** can be drawn through the gudgeon pin, the crank pin and the crankshaft main journal.

The Four Stroke Cycle

The engine must carry out four strokes of the piston to operate.

The first stroke takes in the charge, the second stroke compresses it, in the third stroke the charge is burnt and in the fourth stroke the burnt gasses are exhausted from the cylinder.

These four strokes are known as:

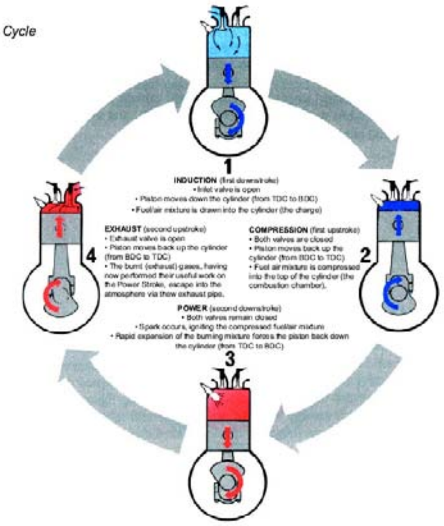
- **Induction** (Suck)
- **Compression** (Squeeze)
- **Power** (Bang!)
- **Exhaust** (Blow)

Once the engine is started, these four strokes repeat until either the fuel is cut off, or the ignition is switched off.

The crankshaft revolves twice for every four strokes, and only one of these strokes produces power.

In the **simple four stroke** cycle the valves open or close at either TDC or BDC, and ignition occurs at TDC.

The 4-Stroke Cycle



INDUCTION (first downstroke)
- Inlet valve is open
- Piston moves down the cylinder (from TDC to BDC)
- Fuel/air mixture is drawn into the cylinder (the charge)

COMPRESSION (first upstroke)
- Both valves are closed
- Piston moves back up the cylinder (from BDC to TDC)
- Fuel air mixture is compressed into the top of the cylinder (the combustion chamber).

POWER (second downstroke)
- Both valves remain closed
- Spark occurs, igniting the compressed fuel/air mixture
- Rapid expansion of the burning mixture forces the piston back down the cylinder (from TDC to BDC)

EXHAUST (second upstroke)
- Exhaust valve is open
- Piston moves back up the cylinder (from BDC to TDC)
- The burnt (exhaust) gases, having now performed their useful work on the Power Stroke, escape into the atmosphere via thew exhaust pipe.

Modified Four Stroke Cycle

To make the engine operate more efficiently, a modified four stroke cycle is used.

In this modified cycle:

- The inlet valve opens before TDC and is not closed until after BDC.
- The exhaust valve is opened before BDC and is not closed until after TDC.
- The charge is ignited before TDC on the compression stroke

Some technical terms:

- **Valve Lead** – means the inlet valve opens before the piston has reached TDC and the exhaust valve opens before BDC.
- **Valve Lag** – means the inlet valve closes after the piston has passed BDC and the exhaust valve closes after the piston has passed TDC.
- **Valve Overlap** – means that the inlet and exhaust valves are open together. It is a period when the inlet valve opens before TDC and the exhaust vale does not close until after TDC.
- **Ignition Advance** – this describes the fact that ignition occurs before the piston reaches TDC on the compression stroke.

All timings are described in degrees of rotation (e.g. 120^{o} before TDC).

Ineffective crank Angle occurs near TDC and BDC where a large rotation of the crankshaft results in a small linear movement of the piston.

Valve are spring loaded into the closed position and the camshaft that operates them turns at **half crankshaft speed** so each valve only opens and closes once for each two revolutions of the crankshaft.

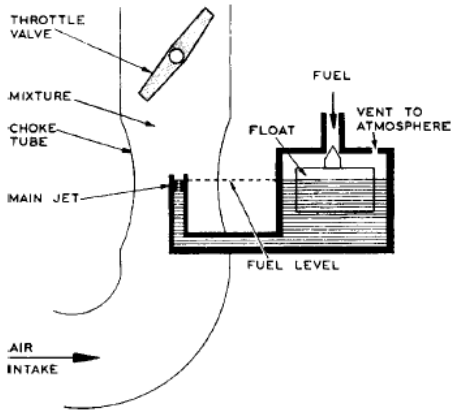
Carburation

The object of carburetion is to provide the engine with a combustible mixture of air and fuel in the right quantities. The mixture must be mixed in the right proportions and be governable to control the power output. Both carburettors and fuel injectors can be used to do this.

Simple Carburettor

Main parts of a simple carburettor are:

- **Air Intake and Choke Tube** – Air enters the air intake and passed through the choke tube which has a narrow section. Because of this the air speeds up and the pressure is reduced (Bernoulli's Theorem in Principles of Flight.
- **Main Jet** – This is located in the choke tube. The reduced pressure sucks fuel from the jet into the air flowing to the cylinders.
- **Float Chamber and Float Mechanism** – This maintains the level of fuel in the main jet and works like a ball valve in a toilet cistern.
- **Throttle Valve** – This is on the outlet side of the carburettor after the choke tube and controls how much mixture can enter the engine cylinders.

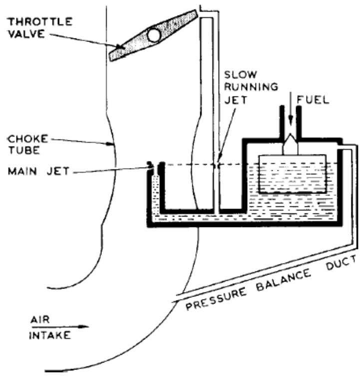


The fuel being sucked from the main jet leaves as a spray due to the small size of the hole in the jet and forms a fine mist when mixed with the airflow.

As the throttle is opened the airflow increases and speeds up. This speeding up increases the pressure drop and results in more fuel being sucked from the main jet.

The throttle cannot be allowed to fully close as that would stop the engine, so there is always a small gap even when the throttle lever is set to its slowest position.

To ensure that enough fuel continues to flow at slow speeds, the carburettor is fitted with a **Slow Running Jet**, which allows fuel to be sucked into the engine in these conditions.



Carburettor Refinements

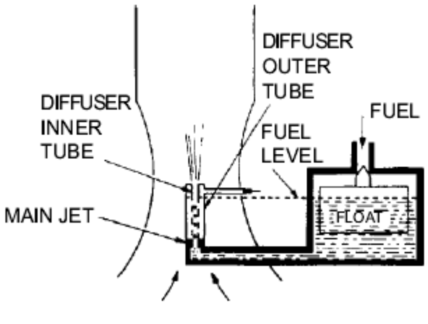
A normal **Air to Fuel Ratio** is **15 to 1 by weight** (not volume). The air to fuel ratio is also sometimes called the **Mixture Strength**.

A mixture that has an excess of fuel is called a **Rich** mixture.

A mixture that has an excess of air is called a **Lean** mixture.

In a more refined carburettor there other devices to more precisely control the mixture strength. (In a simple carburettor the mixture strength tends to increase (become richer) as the throttle is opened. Two possible ways to reduce the amount of fuel allowed to enter the choke tube are:

- Using a moveable **Needle** in the main jet to reduce the size of the main jet as the throttle is opened.
- Using a **Diffuser Tube** to allow air into the main jet to reduce the amount of fuel allowed to flow as the throttle is opened.



There are times where you may need to change the mixture strength deliberately.

- A slightly weak mixture gives better fuel economy, but less power so can be used for economic cruising.
- A slightly rich mixture gives more power for take-off or climbing.

Mixture can be changed in these circumstances by a number of means:

- Using a moveable **Needle** in the main jet
- Having more than one main jet and making one or more inoperable when a weak mixture is required
- Having a secondary choke tube so that both can be used when high power is needed.

Accelerator Pump

This is fitted to inject extra fuel into the chock tube when the throttle is opened to provide more power then needed for engine acceleration.

Direct Fuel Injection

Many modern engines use fuel injection where fuel is injected directly into the cylinder during the induction stroke.

Engines with fuel injection can operate inverted (upside down) unlike carburettor engines. The length of time an engine can operate inverted may be limited by the need to maintain adequate lubrication and cooling.

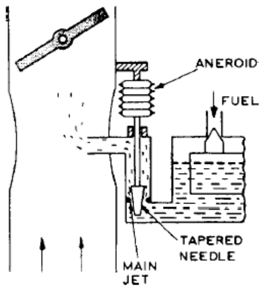
Special Features of Piston Aero Engines

Air Supply

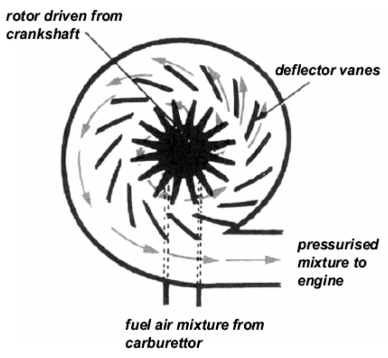
As an aircraft climbs, the surrounding air pressure becomes lower, so there is a risk that the mixture will become too rich if the amount of fuel reaching the cylinders is not reduced.

This can be done using an aneroid capsule, which expands when the aircraft climbs. This expanding capsule can be used to operate a needle valve to reduce the size of the main jet.

However this low air pressure and reduction in fuel flow also reduces the power of the engine. (e.g. At 18,000 feet there is only about 50% of the sea-level power.)



Supercharging



A supercharger is a centrifugal pump, driven by the engine crankshaft that is used to “boost” the air pressure entering the cylinders. It is located between the throttle valve and the cylinders.

As well as improving performance at high altitude, a supercharger can increase power at se level.

Automatic boost control measures manifold pressure and controls throttle valve movement based on the throttle lever setting selected by the pilot.

To avoid over-boosting, the pilots throttle lever is “gated”

Turbocharger

A turbocharger is similar to a supercharger, however it is driven by a turbine that is powered by exhaust gases.

Ignition Systems

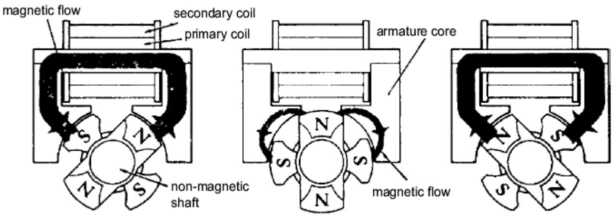
The Magneto

A magneto is a small dynamo that generates a low voltage current, which is then transformed into a series of low voltage impulses.

The impulses are fed to sparking plugs that provide a high temperature spark, which ignites the mixture in the cylinders.

The engine crankshaft powers the magneto.

Aero engines have dual ignition systems for safety and better performance.



(a) core flux maximum (b) core flux zero (c) core flux maximum (reversed)

The essential parts of a magneto are:

- The **permanent magnet system**, which provides the magnetic field to induce a current into the primary winding.
- The **armature**, which consists of the **primary** and **secondary** windings, both would around a soft iron core.
- The **contact breaker**, a mechanically operated switch, timed to break the primary circuit when the current flow is at its maximum. The contact breaker setting (**gap)** is important. An incorrect gap could affect the **timing** and result in a weak spark at the wrong time.
- The capacitor (**condenser**), which reduces burning or pitting of the contact breaker points.

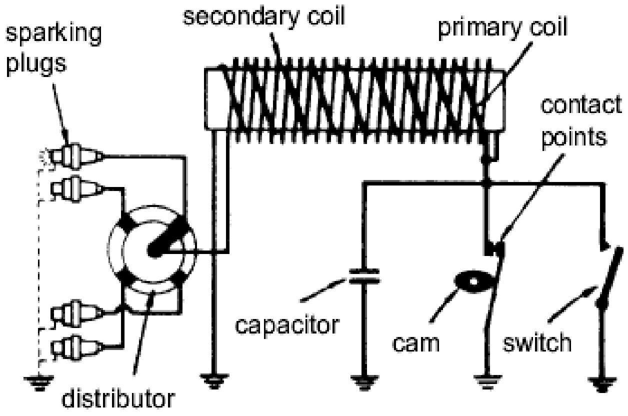
When the magnet system revolves in the armature, an electromotive force is induced into the **primary winding**. The strength of the electromotive force depends on the **speed of rotation** and the **strength of the magnet**.

The current produced by the primary is too weak to produce a spark at the sparking plug, so to achieve this the contact breaker points are opened which causes the primary winding magnetic field to collapse. This collapse induces a high voltage into the secondary winding.

The Distributor

The distributor is an engine driven rotary switch, which consists of a **rotor** that is connected to the secondary winding in the magneto, and turns inside a cap, which has brass **segments** that are connected to the spark plugs. It switches the high voltage to the correct spark plug. The rotor turns at half engine speed.

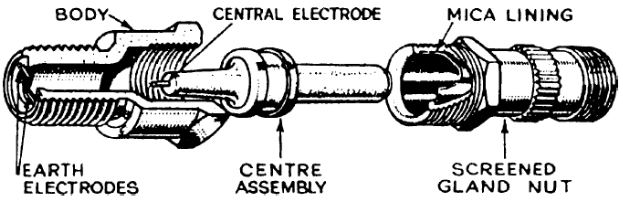
The firing order of an engine is arranged to even out the load on the crankshaft. On a four-cylinder engine the firing order is usually 1,3, 4, 2 (with number 1 cylinder being at the front of the engine).



Sparking Plugs

Sparking plugs consist of two electrodes separated by a small **gap**. The high voltage from the secondary jumps the gap and produces a spark.

The main parts of a sparking plug are:



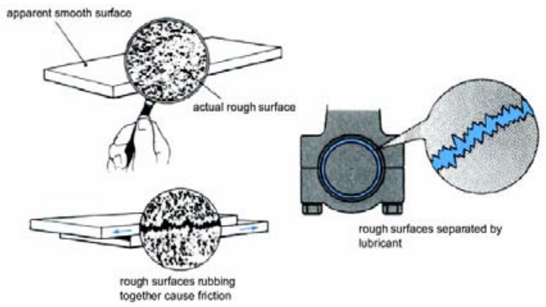
- A hollow steel body which screws into the cylinder. The lower end of this cylinder carries the **earth electrodes**.

- A centre assembly comprising the **centre electrode** and its **insulation**.

- A hollow **gland nut** that holds the assembly together and also forms a **screen against radio interference**.

Each engine needs a particular type of sparking plug and it needs to be serviced regularly to ensure the plug is clean and the gap is correct. (The gap gradually increases as the electrodes erode. Each type of spark plug has a recommended gap for best performance.)

Lubrication and Cooling



Lubrication is a way of reducing friction and wear between two sliding surfaces.

Friction is the resistance that has to be overcome to allow movement between sliding surfaces.

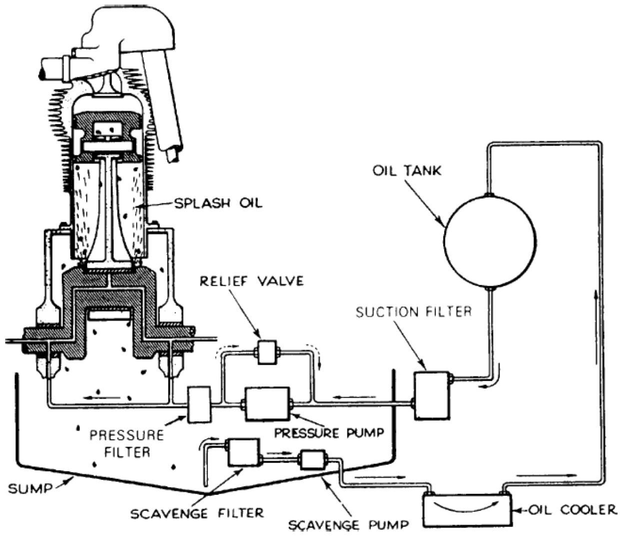
Wear is the loss of material resulting from the 2 surfaces sliding together.

Any substance placed between 2 moving surfaces to reduce friction is called a lubricant.

A lubricating film has 3 layers, 2 outer ones that stick to the moving surfaces and an inner one moving between them. The thinner the lubricant, the more easy the movement. The thicker (more **Viscous**) the lubricant the more force is required to move the surfaces.

A lubricant for an aero engine should be of a suitable viscosity for maximum loads, and retain this viscosity over the full range of engine temperatures.

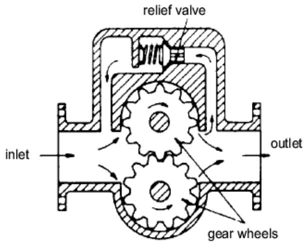
Aero Engine Lubricating System



Oil is circulated from a tank. It is pumped though the engine and back into the tank. Far more oil than is needed for lubrication is circulated, and the extra flow is used for cooling.

Oil is delivered from the tank, through a filter by a pump that circulates it though channels in the engine. The oil to the bearings at a pressure of around 60 lb/sq in or 4.5 kg/sq cm. Oil escaping from the bearings "**splash lubricates**" other moving parts.

The oil then collects in the sump below the engine and is pumped (by the "**Scavenger Pump**") through a filter and **Oil Cooler**, back to the oil tank. The oil cooler dissipates the excess heat absorbed by the oil during its passage through the engine.



The most common type of oil pump is **Spur** gear pump.

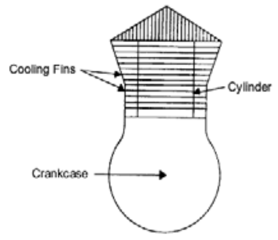
To prevent the oil pressure becoming too high at high engine speeds, a pressure relief valve is fitted.

The scavenger pump is always of a higher capacity than the pressure pump.

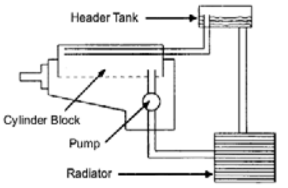
Cooling System

Of the total heat produced by an engine, 50% is used to produce work, 40% passes through the exhaust and the engine absorbs 10%.

To prevent overheating a cooling system is used.



Air Cooled Engine

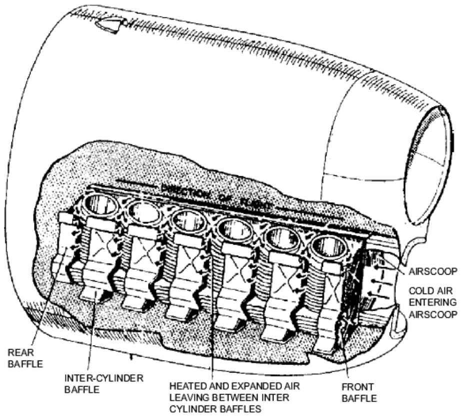


Liquid Cooled Engine

Air Cooling

In an air-cooled engine the outer surfaces of the engine cylinders a cylinder heads are **finned** and air is directed over these surfaces.

Air-cooling is light, cheap and easy to maintain. Air-cooling cannot maintain temperatures accurately so air-cooled engines tend to have shorter life.



Liquid Cooling

In a liquid cooled engine a coolant is circulated through passages (or **jackets**) in the engine block.

The basic coolant is water with an **anti-freeze** agent added. The normal mixture is **70% water** and **30% ethylene glycol**.

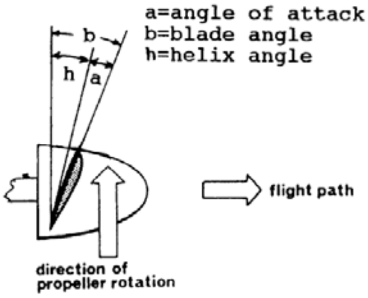
The coolant must not be allowed to boil, so the cooling system is pressurised which results in the boiling point of the liquid being raised which allows the engine to operate at a higher and more efficient temperature.

Comparison

Liquid cooling is more costly and complex, and also need more maintenance than air-cooling. However a liquid cooled engine can hold parts at a more even temperature. Consequently a liquid cooled engine has a longer life between overhauls and is more efficient. Liquid cooled engines can also be more easily streamlined and thus produce less drag on an aircraft.

Propellers

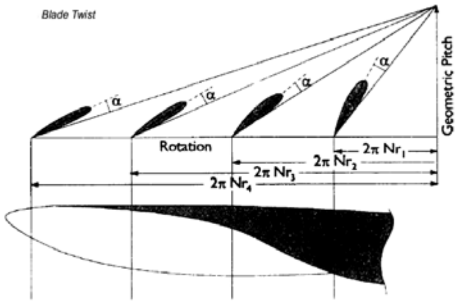
A propeller consists of 2 or more **blades** mounted on a **hub**. The hub fits onto "**propeller shaft**", which supplies engine power to make the propeller rotate. The purpose of the propeller is to convert the torque (a rotational force) delivered from the engine into thrust (a linear force), which will propel the aircraft through the air.



Each propeller blade is an **aerofoil** - that is, a cross-section of a blade is the same shape as the cross-section of a wing. When a propeller blade is spun through the air by the propeller shaft, an aerodynamic lift force is generated on the blade. In the case of the propeller we call the force thrust.

There are two problems that would occur if a propeller had a fixed blade angle:

- Firstly, the angle of attack at the tip might reach the stalling angle, hence there would be no thrust and a huge drag penalty at that part of the propeller.
- Secondly, with all the blade sections operating at different angles of attack, only a small part of the propeller could be operating at an efficient angle of attack.



The solution is to vary the blade angle progressively from root to tip. In fact, this has been common practice since the days of the Wright brothers, and all propeller blades now have a twist in them to give a large blade angle (called a "**coarse**" angle) at the root, and a progressively smaller blade angle (a "**fine**" angle) towards the tip. This "**blade twist**" allows the blade to maintain an efficient angle of attack along the full length of the propeller blade.

As forward speed increases the helix angle of the propeller path also increases, hence the blade's angle of attack (blade angle minus helix angle) decreases.

At some high forward speed, the angle of attack will approach the zero lift figure, and thrust will reduce to zero - just what is not wanted at very high speeds! Conversely, at lower speeds the angle of attack will increase and so will the thrust (as long as the angle of attack is not so high that the blade stalls).

However, a combination of high thrust and low forward speed is inefficient in terms of engine power needed (to counter the extra rotational drag that is generated on the propeller along with the high thrust), fuel used and distance flown. Clearly, between these extremes there will be just one speed at which the propeller is operating at its optimum angle of attack, and hence is at its most efficient. All these limitations can be overcome if we have some means of varying, in flight, the angle at which the propeller is set into the hub.

The term used for the blade angle in this context is "**pitch**":

- A "**Fixed-pitch propeller**" is one whose blade angle at the hub cannot be changed.
- A "**Variable pitch propeller**" is one whose pitch can be changed in flight.
- "**Coarse pitch**" is when the blade pitch angle is at the highest angle in its designed range
- "**Fine pitch**" is when the angle is at its smallest.

With fixed-pitch propellers, the pitch angle chosen is usually that which suits the normal top speed of the aircraft.

Fixed-pitch propellers are, however, relatively cheap and they are well suited to light aircraft fitted with low-powered piston engines. Changes in thrust for different flight conditions - take-off, climb, cruise, descent etc - are regulated by the engine throttle control, which changes engine rpm (and hence propeller rpm).

With variable-pitch propellers, the engine and propeller combination is allowed to run at selected, efficient rpm throughout a wide range of flight conditions. Changes in thrust are selected by varying the propeller's pitch angle. For example, if more thrust is needed, the pitch angle is **coarsened** (i.e. increased) and at the same time engine power is increased by feeding more fuel to it (i.e. opening the throttle).

The engine/propeller speed is kept at its pre-selected value by the constant speed unit (CSU), described in the next paragraph. When the pitch and the engine power are increased to make the propeller produce more thrust, the coarser angle also makes the propeller produce more rotational drag - i.e. torque. This is why part of the action to get more thrust is to increase the engine power, so the engine can produce more torque to counter that from the propeller. The torque is measured and displayed in the cockpit, where it is used to assess the performance of the power plant.

Constant Speed Unit (CSU)

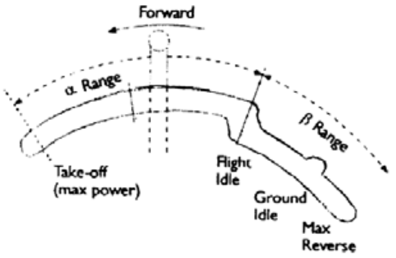
The **CSU** senses changes in engine speed by means of a **flyweight governor** driven by the engine gearbox. The governor controls a servo system, which feeds engine oil pressure to a piston. The piston alters the propeller pitch through cams and bevel gears, which change the piston's linear motion to the rotation needed to coarsen or fine the pitch of each blade.

When the engine speed falls below the set rpm, the governor fly-weights open a valve allowing the oil to flow to the rear of the piston, thereby moving the piston to the left and fining the propeller. As the rpm recovers the flyweights resume their balanced position closing the valve and hydraulically locking the propeller in the desired position). If the engine overspeeds the flyweights open the valve to coarsen the propeller pitch until the rpm is again restored with the fly-weights in the balanced position.

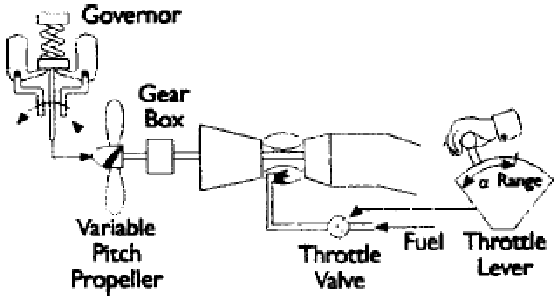
Variation of the blade pitch angle can be achieved automatically when varying the power of the engine, or selected manually. On small piston engined aircraft, the engine rpm and power are altered with different controls; engine rpm by direct control of the CSU, whilst engine power is adjusted using the throttle. Once the rpm is selected it is maintained by the CSU regardless of throttle movement.

A power lever and a condition lever generally control turboprop engines.

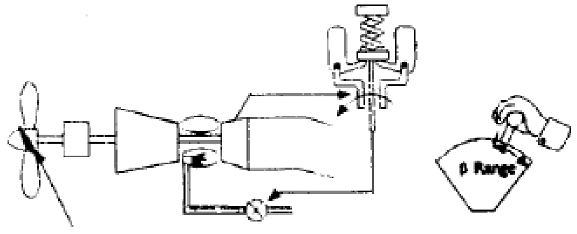
Power Lever



The power lever is used to control the power plant during all normal flight and ground operations (Fig 5-9a). The control works in 2 separate segments, the alpha (a) range and the beta (b) range. The alpha range controls the power plant during all normal flight conditions by adjusting the engine fuel flow, with the CSU adjusting propeller blade angle to maintain selected rpm. In the beta range the pilot controls the propeller pitch overriding the CSU. A separate governor adjusts engine fuel flow to maintain engine rpm.



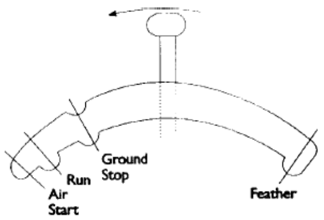
Alpha Control



Beta Control

Condition Lever

The condition lever is an override control and has the following discrete functions:

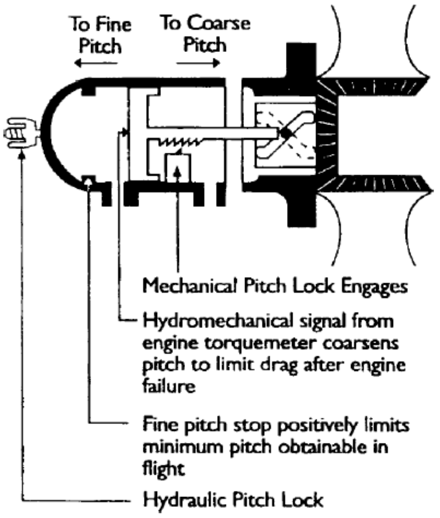


- HP shut-off cock position.
- Normal running position.
- Air start position.
- Propeller feathering position.

Propeller Safety Devices

Various safety systems are fitted to override the control system should a malfunction occur. If control were lost the propeller would slam into fine pitch because of the centrifugal turning moment (**CTM**) of the blade. The effect of this would be dangerous in 2 respects:

- The torque required to turn the blades would be replaced by a windmilling torque, which would assist the engine. Thus there would be a grave danger of engine and propeller overspeed.
- The propeller would cause a very high drag force to be applied to the aircraft. This would be particularly dangerous in multi-engined aircraft, as it would give rise to a severe asymmetric condition.



The propeller control system has a number of safety devices to avoid overspeed and high drag caused by system failure. These are:

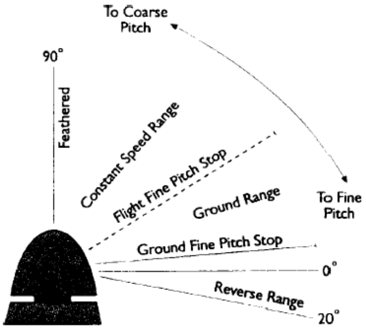
- **Fine Pitch Stop**. This is a mechanical stop, which limits the degree of fine pitch that can be achieved in flight. For ground operations such as engine starting and the use of reverse pitch, the stop is disengaged, but it automatically re-engages after take-off.
- **Mechanical Pitch Lock**. A mechanical pitch lock is incorporated in case of oil pressure loss or overspeed being sensed. The mechanical stop is a ratchet lock, which prevents

the propeller blades fining off, whilst still allowing them to move towards the coarse position if required.
- **Hydraulic Pitch Lock**. This system operates a valve to trap the oil in the increase pitch side of the mechanism. It operates earlier than the mechanical pitch lock thus preventing impact when the ratchet is engaged. It acts when oil pressure loss is sensed.
- **Automatic Drag Link**. A torque signal is fed to the controller, and if this falls below a certain value it indicates the propeller is at too fine a pitch for the flight mode. The blades are then moved into the fully coarse or feathered position. This situation could arise with either a CSU or engine failure.

As the oil pump for propeller operations is engine driven, a separate electrically driven pump is incorporated to complete the feathering operation whilst the engine is slowing down or stopped, and to enable the propeller to be unfeathered prior to engine restart.

Propeller Operations

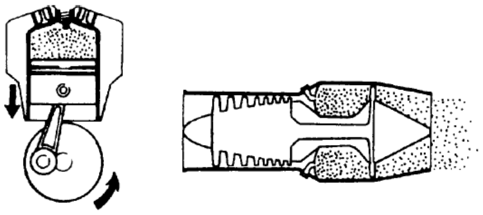
- **Feathering**. Feathering of the propeller is normally carried out when the engine is shut down during flight. When feathered the propeller blade is presented with its leading edge facing into the direction of travel, thus reducing drag.
- **Reverse Pitch**. Reverse pitch can be used both for braking on landing and for ground manoeuvring. When selected, the fine stops are disengaged and the propeller blades are allowed to move past the flight fine position and into reverse pitch. This is a pilot selected manoeuvre with the engine speed being governed by its own fuel system governor.
- **Ground Fine**. This blade angle is adopted during start up, to reduce the load on the engine.



The Jet Engine

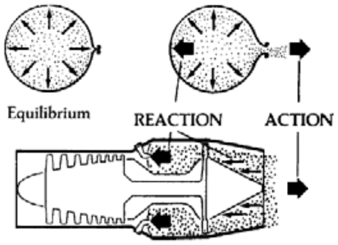
Hero of Alexandria demonstrated the principle of jet propulsion as long ago as the first century AD.

However, the jet engine, as we know it, did not become a practical possibility until **1930** when **Sir Frank Whittle** patented the design of his first reaction motor suitable for aircraft propulsion.



In both the gas turbine and the motor car engine air is compressed, fuel is mixed with it and the mixture is burnt. The heat which results produces a rapid expansion of the gas and this is used to do work.

In the car engine the burning is intermittent and the expanding gas moves a piston and crank to produce rotary or shaft power which drives the car wheels.



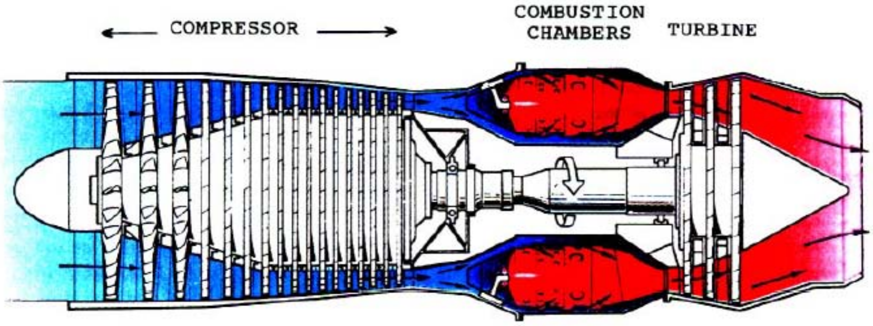
However, in the jet engine the burning is continuous and the expanding gas is simply forced out through a pipe or nozzle at the back of the engine - and confusion often arises, not so much regarding how the jet engine works but why it works. It is often thought that it works by ‘pushing’ the exhaust gas against the atmosphere - but in that case how would a rocket engine work in the vacuum of space?

The answer is that the jet engine, like the rocket, works by **REACTION**, on the principle expounded by the 17th century scientist **Sir Isaac Newton** - to every action there is an equal and opposite reaction.

Layout of the Jet Engine

The jet engine is basically a gas generator - a machine for generating a large volume of gas, which is forced out of the rear of the engine to produce a reaction in the form of forward thrust. The engine is therefore designed to collect a large volume of air, compress it, mix fuel with it and burn the mixture to produce the expansion which forces the gas out of the nozzle.

The engine has three main components a **compressor**, a **combustion chamber** and a **turbine**.



The Compressor

The compressor, situated at the front of the engine, performs two functions - it draws air into the engine and it compresses it (in some engines by up to **30 atmospheres**) before delivering it into the combustion chamber.

Jet engine combustion will, in fact, work at atmospheric pressure, but efficiency and fuel consumption improve considerably when the pressure of the air is increased.

Compressors may be **centrifugal** or **axial**, the latter consisting of a number of stages of alternate rotating and stationary aerofoil-section blades which force the air through a convergent annular duct.

Many modern engines have more than one compressor because a high degree of compression requires a large number of compressor rows or '**stages**'.

Each stage has an optimum speed for best efficiency - the smaller the blades the higher the speed. If all the stages are on the same shaft, only a few of them will be operating at their optimum speed - the majority will be running either too fast or too slow. This problem is overcome by dividing the compressor into 2 or 3 parts, each driven by its own turbine and each rotating at its optimum speed. By this means, compression ratios up to 30:1 can be achieved, resulting in extremely high efficiency and very low specific fuel consumption.

The Combustion Chamber

The air from the compression section, at anything up to 450 lb/sq in, passes into the combustion chamber. This is an annular steel '**flame tube**' or ring of tubes designed to achieve the most efficient combustion of the fuel/air mixture so that the maximum possible heat energy is extracted from the fuel in order to give the greatest rise in temperature and hence expansion of gas.

The combustion chamber has a number of burners to vaporise the fuel before mixing it with the compressed air. **Igniters** are provided to initiate combustion. Unlike the piston engine, combustion is continuous.

The Turbine

As a result of the burning of the air/fuel mixture, gas velocity and temperature in the combustion chamber increase rapidly and the gas is forced out of the rear of the engine, through the **turbine**. The turbine consists of one or more stages of alternate rotating and stationary aerofoil-section **blades**. It is attached by a shaft to the compressor, and in the simplest form of jet engine, the turbojet, its function is to absorb just enough energy from the gas stream to keep the compressor rotating at its optimum speed - the remaining energy provides the thrust.

The complete rotating assembly - compressor, shaft and turbine - is carried on bearings and is known as a '**spool**'. In a **multi-spool** engine, each compressor is driven by one or more turbine stages.

In the turbojet and in another turbine derivative, the **turbofan**, the turbine is designed to absorb just sufficient energy from the gas stream to drive the compressors, leaving the remainder to provide the thrust. In other derivatives, the **turboprop** and **turboshaft**, there is an additional turbine, which is designed to absorb as much energy as possible from the gas stream in order to drive the propeller or power output shaft respectively.

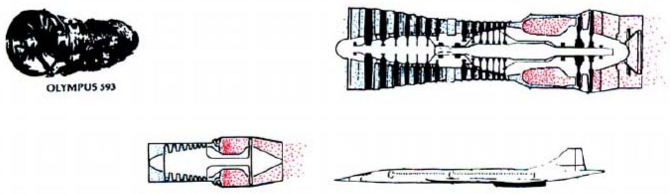
Main Types of Gas Turbines

There are 4 main types of gas turbine engines - the first 2, **turbojet** and **turbofan**, are '**reaction**' engines, deriving their power from the reaction to the jet.

As indicated above, the second two, the **turboprop** and **turboshaft**, operate on a different principle, where the energy in the gas is used to drive a separate turbine which is connected to a propeller or power output shaft.

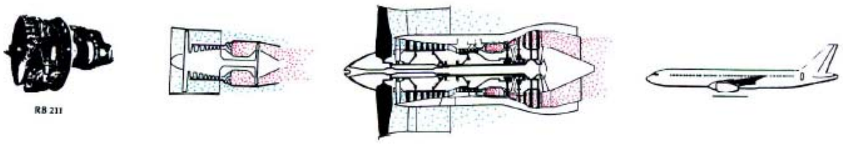
Turbojet

The turbojet, the simplest and earliest form of gas turbine, is used principally in high-speed aircraft where its relatively low frontal area and high jet velocity are advantages. Examples are the **OLYMPUS 593** in the **Concorde** supersonic transport and the **VIPER** in a variety of military aircraft including the **Dominie/HS125**.



Turbofan

The **turbofan** is probably the most common derivative of the gas turbine for aircraft propulsion. It is a '**bypass**' engine, where part of the air is compressed fully and passes into the combustion chamber, while the remainder is compressed to a lesser extent and **ducted around the hot section**. This bypass flow either rejoins the hot flow downstream of the turbine, as in the SPEY, or is exhausted to atmosphere through an annulus surrounding the hot exhaust, as in some versions of the **RB 211**. In both cases the result is reduced overall jet velocity, giving better propulsive efficiency at lower aircraft speeds, lower noise levels and improved specific fuel consumption, features which make the turbofan ideal for both civil and military aircraft.



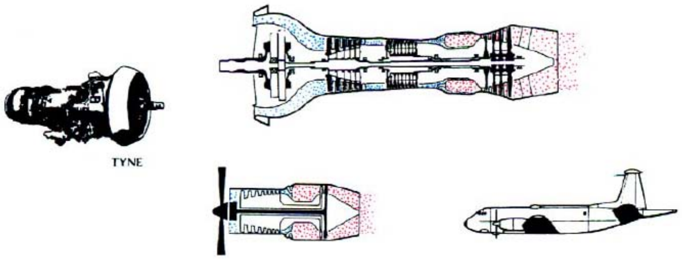
Examples are the **RB 211** in the **Boeing 747** and **757**, the **SPEY** in the **1-11** and **F28**, the **ADOUR** in the **Jaguar** and **Hawk**, and the **RB 199** in the Tornado. The **PEGASUS** in the **Harrier** is a variation of the turbofan.

Turboprop

The turboprop is a turbojet with an extra turbine, which is designed to absorb all the energy remaining in the gas stream after sufficient has been removed to drive the compressor; in practice there is always a small amount of 'residual' thrust in the exhaust gases.

The '**power'** turbine drives the propeller through a **reduction gear**, usually at the front of the engine.

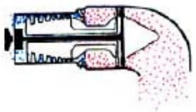
The turboprop is a very efficient power unit for relative low speed, low altitude aircraft (e.g. **400 knots/30,000 ft**) though recent strides in propeller technology, in the pursuit of quietness and economy, have demonstrated the feasibility of a new generation of high speed propeller driven aircraft. The power of this type of engine is measured in total equivalent horsepower (**tehp**) or kilowatts (**kW**) - the shaft horsepower (**shp**) plus the residual thrust.

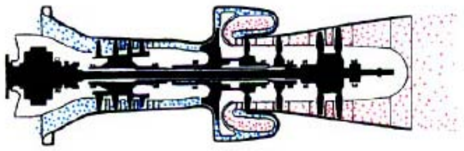


Examples of the turboprop are the **DART** in the **748** and **F27** and the **TYNE** in the **Transall C-160** and **Atlantic**.

Turboshaft

The turboshaft is virtually a turboprop without a propeller, the power turbine being coupled to a reduction gearbox or directly to an output shaft. As with the turboprop, the power turbine absorbs as much of the remaining gas energy as possible and the residual thrust is very low. The power of this type of engine is normally measured in shaft horsepower (**shp**) or kilowatts (**kW**). The most obvious application of the turboshaft is the **helicopter**, where the engine drives both the main and tail rotor, though turboshafts are widely used in **industrial** and **marine** application, including **power** and **pumping stations**, **hovercraft** and **ships**.



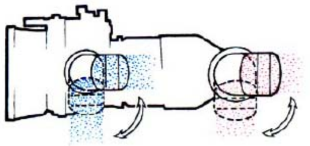


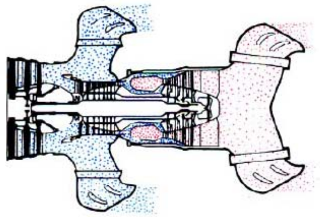
Examples of the turboshaft are the **GEM** in the **Lynx** and the **GNOME** in the **Sea King** helicopters, and industrial and marine versions of the **RB 211** and **OLYMPUS.**

Variations

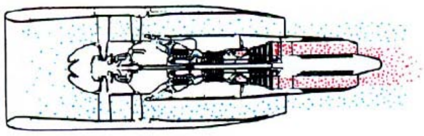
Developments which add to the applications of the jet engine include:

- **Vectored Thrust**. Thrust vectoring is a means of changing the direction of the jet and hence the reaction or thrust in order to meet the requirements of **V/STOL** (vertical or short take-off and landing) aircraft. An example is the **PEGASUS** turbofan, which powers the **Harrier**, where the engine has 4 linked swivelling nozzles, which direct the jet downward for **VTOL**, through an arc to rearward for forward flight. In the Pegasus the fan or bypass air is discharged through the front 2 nozzles and the hot exhaust gas through the rear 2.

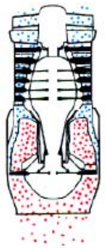




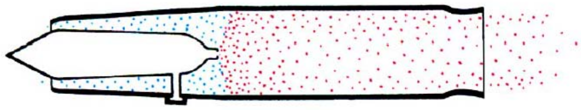
- **Geared and Variable-Pitch Fans**. The geared fan is a development of the turbofan aimed principally at reducing fan noise by reducing its speed via a reduction gearbox while maintaining a high engine speed for maximum efficiency. Geared fans with variable pitch blades allow even greater ease of engine control and flexibility of aircraft operation.



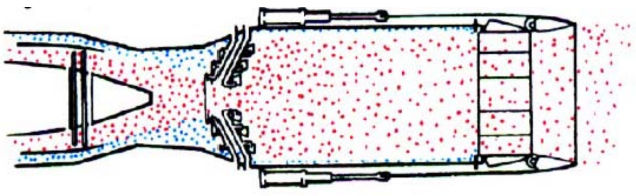
- **Liftjets**. Liftjets are very compact turbojets, which are installed vertically in an aircraft to provide purely vertical thrust for take-off, hovering and landing. Liftjets are shut down during forward flight.



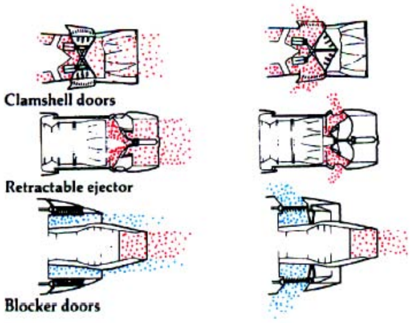
- **Ramjets**. A ramjet is virtually a turbojet from which the compressor and turbine have been removed. Compression is achieved by the ‘ram’ pressure in the intake and for this reason the engine can operate efficiently only above about Mach 1 - the speed of sound. The ramjet has no moving parts and is the simplest of all air-breathing engines.



- **Afterburning**. Afterburning or reheat provides a means of increasing thrust without increasing the engine’s frontal area. Unlike a piston engine, the fuel in a jet engine is burned in an excess of air, so there is still a certain amount of oxygen present in the exhaust. These gases will therefore support combustion and it is possible to burn additional fuel in the jet pipe to increase the exhaust velocity and consequently increase the thrust of the engine. In a turbofan, where the bypass air provides even more oxygen, thrust increases up to 100% are possible by this method; it is normally applied to military engines for short-duration boost, e.g. for take-off or combat

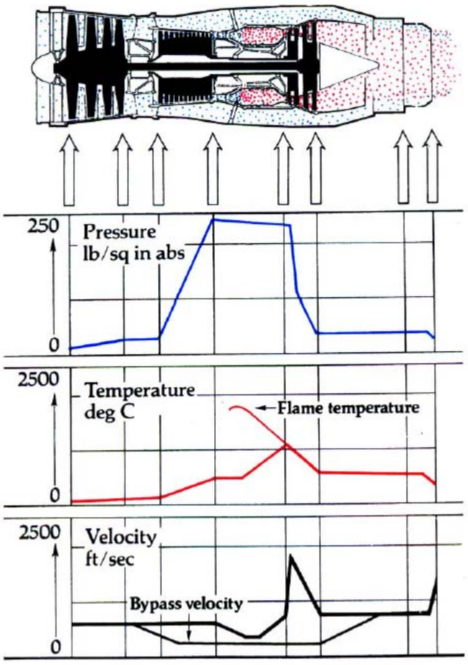


- **Reverse Thrust**. Thrust reversal is simply a method of altering the direction of the jet reaction, like thrust vectoring, to meet an aircraft's operational requirement, in this case slowing the aircraft after landing. The jet deflection is achieved by 3 main methods; one uses clamshell-type deflector doors to reverse the exhaust gas stream; the second uses a retractable ejector to do the same thing; the third, used on high bypass ratio turbofans, uses blocker doors to reverse the cold stream airflow, which provides the majority of the thrust.



Pressures, Temperatures and Velocities

The picture below indicates the pressures, temperatures and velocities, which occur in a **Rolls-Royce Spey** engine, the arrows above the table indicating the part (stage) of the engine where they apply.



Rockets

Rocket Propulsion

Jet engines will not work in space; they need the Earth's atmosphere, because they draw in air and use the oxygen in it to burn fuel to operate the engine. Rockets are much simpler and they carry fuel (or "**propellants**") that do not need atmospheric oxygen. A rocket is basically a tube, closed at one end, containing a propellant. The propellant burns very quickly, producing a fast-moving exhaust flow. The propellant might be a liquid chemical fuel (e.g. **kerosene/paraffin**) with an oxidizing agent (**liquid oxygen**), or it might be a **solid chemical**.

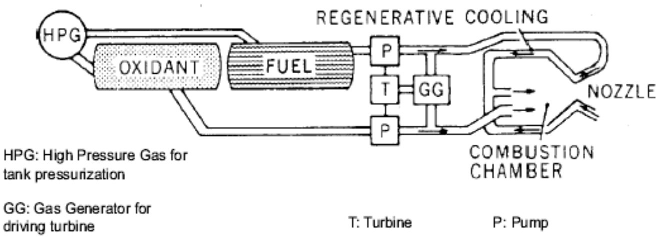
Rocket Theory

Rocket propellants burn quickly or react together violently to produce a fast exhaust flow. This is an '**action**'; and **Newton's third law** states that every action must have an **equal and opposite reaction**. The reaction to this rearward gas flow is a forward thrust on the rocket itself.

The magnitude of the force is given by **Newton's second law**, which states that force is proportional to the rate of change of momentum (mass times velocity). **In simple terms, this means that the larger the force produced by the burning fuel, then the faster the rocket will move!** Note that all this is independent of the medium (e.g. air) that the rocket may be in. Thrust is derived from the reaction to the gas momentum. NOT BY PUSHING ON THE MEDIUM. A rocket works perfectly well in the vacuum of space – and in fact benefits from the absence of air resistance.

The Rocket Motor

The heart of a rocket motor is the **combustion chamber** and **exhaust nozzle**. At every instant, the momentum of exhaust products is producing a forward thrust, which is transmitted to the forward walls of the combustion chamber and on to the rocket. If the burning is even, the thrust will be constant with time. If we ignore all other forces, the rocket will accelerate forwards in accordance with Newton's second law, **Force = Mass x acceleration** or F ¸ M = a. For example a 5000 kg thrust engine in a 5000 kg rocket will give an acceleration equal to the force of gravity (1g). However, as fuel is used, weight falls and the same 5000 kg thrust on the rocket, now reduced in weight to, say, 2500 kg will give an acceleration of 2g.

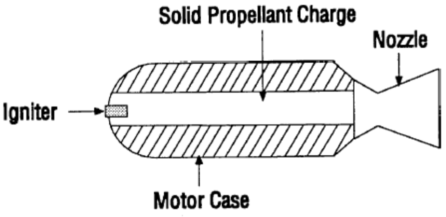


Apart from combustion to produce thrust, liquid propellants are put to other uses, particularly in a large rocket motor. In a rocket that uses liquid oxygen (the oxidant) and kerosene (the fuel), liquid oxygen is pumped directly to the combustion chamber, but some is also used to drive a pump turbine. Pumping is needed because of the enormous fuel consumption of large rocket engines – the 5 engines of the Saturn V (which took the manned craft Apollo 11 to the moon) used 12 tonnes of fuel per second! Gaseous oxygen from the gas generator can also be used as a power source for ancillary equipment.

The kerosene fuel is pumped along a very long tortuous path around the rocket nozzle, before entering the combustion chamber. There are 2 reasons for this arrangement:

- The exhaust gases flow through the nozzle at very high temperatures (typically 3,000°C), which could destroy the material of the nozzle very quickly, so the kerosene flowing through the tubes round the nozzle cools the metal – this function is called **regenerative cooling**.
- As the kerosene cools the nozzle it gets hot and is next fed to the combustion chamber, and because it has been pre-heated, it **vaporizes** more speedily. This improves the combustion process.

Solid Propellant Rocket



This form of rocket has no moving parts and is by far the simplest in construction; it is reliable, and solid propellants are comparatively safe and easy to handle. However, it is difficult to control the exact thrust output of a solid propellant and the performance of solid fuels is generally not as high as that of liquids.

Efficiency and Specific Impulse

For conventional air-breathing engines the fuel consumption gives a good indication of the efficiency of the motor. Rocket engineers rarely mention fuel consumption, as it would be embarrassingly high by comparison with other large engines. They use another term to quantify the rocket engine efficiency, called **Specific Impulse (SI)**. Here "impulse" means the force applied (i.e. the thrust) multiplied by the duration of its application – a measure of the momentum change achieved. "Specific" Impulse is this figure, divided by the mass of the propellants used. Thus, SI indicates the effectiveness of the propellant in producing a change in velocity of the vehicle it is propelling. For example, if propellant A can produce the same thrust for the same time as propellant B, but uses less mass than B in doing so, then A has a higher SI than B – i.e. it is more efficient than B.

SI = thrust (in kg) x time (in seconds) ¸ mass of fuel used (in kg). The thrust kg mathematically cancels out the mass kg leaving **seconds**. In other words, **the unit for SI is seconds**. An SI of 250 seconds, a typical value, would mean that 1 kg of propellant would give 250 kg of thrust for one second, or 25 kg of thrust for 10 seconds, or 2.5 kg of thrust for 100 seconds, and so on; thrust and time are interchangeable in the equation. The actual burning time would depend on the nature of the fuel and the combustion conditions.

Typical Fuels

Liquid Hydrogen and Liquid Fluorine. Liquid hydrogen and liquid fluorine offer one of the highest SIs for the bi-propellant, 390 seconds at sea level (480 in space). However, there are disadvantages:

- Liquid hydrogen boils at –253°C, so special storage and fuel tanks are needed to stop it evaporating rapidly.
- Liquid hydrogen has a very low density – one fourteenth of that of water – so huge fuel tanks are needed for quite a small mass of liquid hydrogen.
- Fluorine is highly toxic, it boils at - 188°C, and it is one of the most chemically active elements known, combining with every gas except nitrogen, chlorine and inert gases. You can imagine the storage problems!
- Finally, when the 2 liquids combine and combust they produce hydrofluoric acid, a very corrosive substance that is used for etching glass!

Liquid Hydrogen and Liquid Oxygen. The SI of liquid hydrogen and liquid oxygen nearly matches that of hydrogen and fluorine, and the product of combustion – i.e. steam, is harmless. The low density and temperature of liquid hydrogen remain a problem, but liquid oxygen is less demanding on storage as it is relatively dense (1.14 times that of water). The liquid hydrogen/ oxygen combination has much to offer – in fact it is used for the main engines of the Space Shuttle.

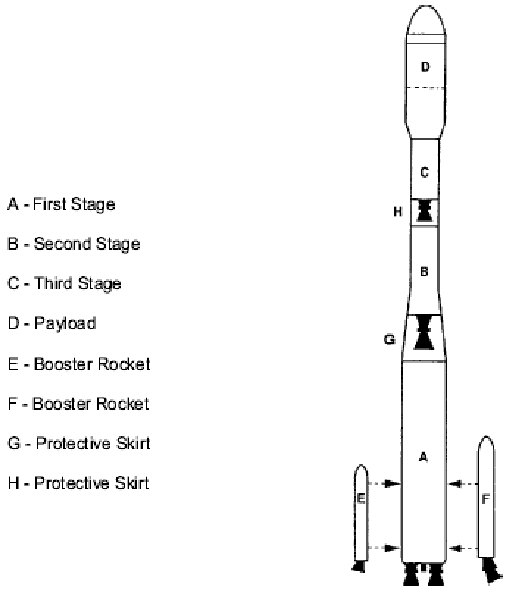
Liquid Oxygen and Kerosene. Kerosene is cheap, plentiful and safe to handle. More importantly, its relative density of 0.8 (i.e. 80% of that of water) requires smaller tanks than liquid hydrogen; and it can be stored at normal temperatures. Despite having a lower SI than liquid hydrogen/oxygen, it has been a most useful propellant for the United States programme in the past and is still used for the Soviet **Vostock** craft.

Unsymmetrical Dimethyl Hydrazine and Red Fuming Nitric Acid (UDMH and RFNA). UDMH with RFNA is an effective but unusual fuel combination. A small amount of fluorine is normally added to prevent the nitric acid from eating away the steel fuel tanks. The 2 liquids do not boil off. The combination also has the advantage of being self-igniting – the propellants ignite on contact and so no ignition system is required. There are however, obvious dangers in handling these chemicals.

Multi-Stage Rockets

At launch, a rocket has to lift its payload, plus its own weight and that of all its fuel. Typically, a single rocket might burn for 3 minutes and reached a height of 60 km, which is not high enough for any viable orbit. One solution would be to have a lot more fuel available at launch – but this would mean much more weight at launch (extra fuel plus extra tanks).

A much more efficient technique is to use multi-stage rockets. In the diagram, the huge first stage (A) does the giant's share of the job – lifting itself and the rest of the assembly off the ground and accelerating it to, say, 3 km/sec and a height of 80Ê km. Stage A is now dead weight, so explosive bolts release it and it falls to Earth, breaking up and burning as it does so. Meanwhile, the second stage rocket (B) ignites and continues to accelerate the assembly to, say 6 km/sec and 150Ê km. Stage B has a much easier job than stage A, as it has a much smaller mass to propel, and the atmospheric drag is a tiny fraction of what it was earlier in the flight. In our example, stage B is in due course discarded as was stage A, and the third stage (C) ignites to take the payload up to orbit height and speed.



Depending upon the mass of the payload, some assemblies might have only 2 stages, whilst others might have 3 stages plus booster rockets (E and F), of various types and capability, clamped to the outside of stage A for launch. The booster rockets can be the liquid-fuelled or the solid-fuelled type. They are normally used in pairs, with either 2 or 4 on one vehicle. They can be mixed (liquid and solid fuel) when 4 are used, but not for 2 or 3, as their differing power and burning times would cause asymmetric thrust which could throw the vehicle off course, and could even make it crash. Typical burning times for booster rockets are around 45 seconds (solid fuel) and 2 minutes (liquid). Boosters are jettisoned as soon as they have used up their fuel.

There might also be more than one satellite in the payload (S). In this case the third stage motor would switch off at the desired orbit height and speed, and the satellite in the nose cone would separate. The aerodynamic cone itself, which merely protects the satellite from air pressure and friction in the lower atmosphere – would probably have been discarded earlier. This satellite would almost certainly have its own rocket for adjusting, or even changing, its orbit. This on-board rocket would have small **thruster nozzles** on all sides for changing the satellite's attitude (for example, to point its aerials in a specific direction), plus a main nozzle at the back for propulsion purposes (e.g. to adjust orbit speed, or to change orbit). The second satellite would be taken by the third stage rocket to another orbit height, or to another part of the sky at the same orbit height as the first, according to the jobs the satellites will have to do.

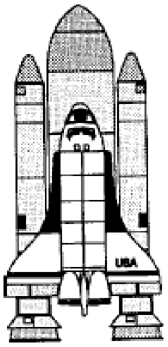
Re-Usable Vehicles

From the earliest days the cost of launching hardware into space was huge. Most launch rockets can be used only once. Having placed their payload into Earth orbit, they either remain in orbit as pace debris, or re-enter the atmosphere and burn up. To reduce costs, the Americans and the Russians both developed reusable launch vehicles. The American version is called the **Space Shuttle** and the Russian version is called **Soviet Shuttle Buran**. The American space agency **NASA** designed the Space Shuttle, to carry satellites in its cargo bay and launch them into orbit. It can simply place them into it own standard orbit at about 300 km above the ground, but if a higher orbit is needed, the satellite will have a built-in rocket. Such a rocket would, of course, be much smaller and cheaper than one that would be needed to lift the satellite all the way from the ground. The Space Shuttle can also be used to retrieve satellites from their orbits and repair them for re-release or bring them back to Earth for further work – a capability first proved during the Shuttle missions in 1984. The **Hubble Space Telescope** was a highly publicized repair operation in space, successfully carried out during a Shuttle mission.

The Space Shuttle

At launch, the American Space Shuttle has 4 main parts:

- Two **solid-fuel rocket boosters** (**SRBs**)
- One **external tank** (**ET**)
- One **orbiter**



During take-off the Shuttle is propelled by its own rocket engine fuelled from the **ET** together with the **2 x SRBs**. The **SRBs separate at a height of 45 km**, some **2 minutes into the flight**. The booster rockets are parachuted to earth and are retrieved for future use. The next stage to depart is the ET. This falls away at a height of 120 km, nearly 9 minutes into the flight. The ET burns up when re-entering the Earth's atmosphere and is only part of the vehicle that is not re-useable. The Shuttle has 2 on-board engines called orbital manoeuvring system (**OMS**), which are used to position the vehicle in the required orbit before commencing the mission. For the return to Earth the OMS is used to correctly position the Shuttle into the descent attitude and trajectory for re-entry. Once it enters the atmosphere, the Shuttle can also use aerodynamic controls, and in due course, it lands like a glider – but on a very long runway!

The Soviet Shuttle

The **Soviet Shuttle Buran** has no engines of its own and for launching it relies solely upon the booster rockets it piggybacks.