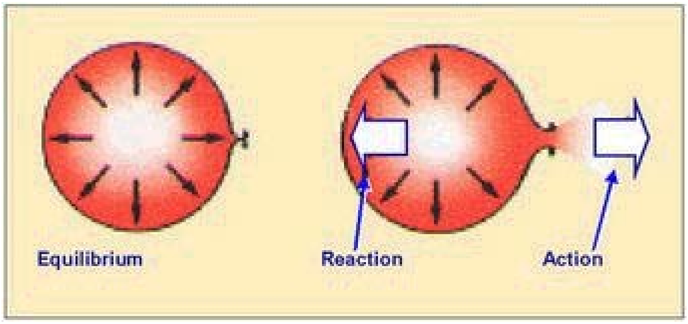
Basic Gas Turbine

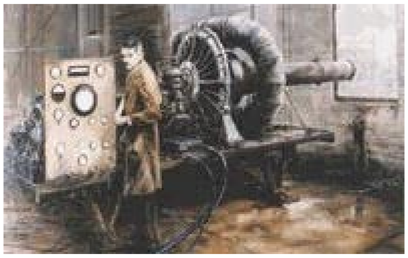
Introduction

Prior to the 1950's, very few people had heard of the 'Jet Engine'. However, the principle of using a jet reaction to propel an aircraft was understood. Producing the 'jet' through conventional or available technology was deemed to be the problem.

A French engineer named Rene Lorin patented a design very similar to that of the Ram Jet known today, in 1913. However it was only intellectual, as heat resisting materials had not been developed and aircraft at that time were most unsuitable.

The jet engine relies on Newton's 3rd Law, where every action has an equal and opposite reaction. An example of this is the balloon shown above. Here, gas is initially stationary inside the balloon. It is then accelerated through the the back, pushing the balloon forward. The thrust produced is equal to the mass exhausted through the back of the balloon, multiplied by the velocity, relative to the balloon.





Equilibrium, Reaction and Action

Frank Whittle

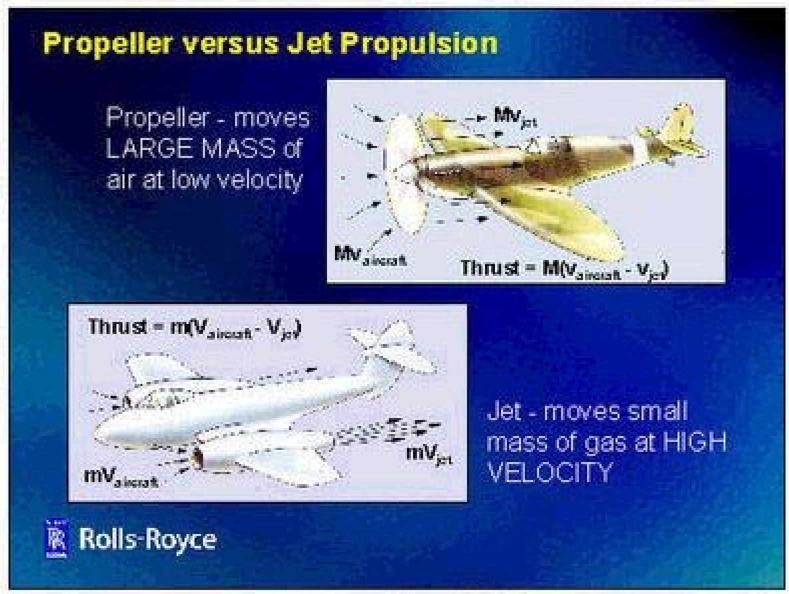
Thrust = Mass x Velocity

Propeller versus jet propulsion

Aircraft propellers and jet engines do not store their own supply of air like the balloon. Instead, they have a steady supply of air entering the front. The thrust is achieved by accelerating this gas, so that it leaves the rear faster than it arrives at the front.

The amount of thrust achieved is equal to the mass of air multiplied by the change in velocity. A propeller engine moves a large mass of air at low speed: thrust = $M(v_{aircraft} - v_{jet})$, whilst a gas turbine moves a smaller mass of air at a greater speed: thrust = $m(V_{aircraft} - V_{jet})$.

The big advantage of the jet engine is that it does not suffer from the high tip speed effects of fast propeller aircraft, where shock waves form, creating a lot of noise and drastically reducing efficiency. For this reason, propeller aircraft are limited to forward speeds significantly below the speed of sound. Gas turbine powered civil aircraft, on the other hand, cruise at high subsonic speeds, whilst military aircraft are capable of speeds well in excess of the speed of sound. This increase in speed leads to an increase in productivity as the same aircraft can perform more missions or carry more customers in a given time.



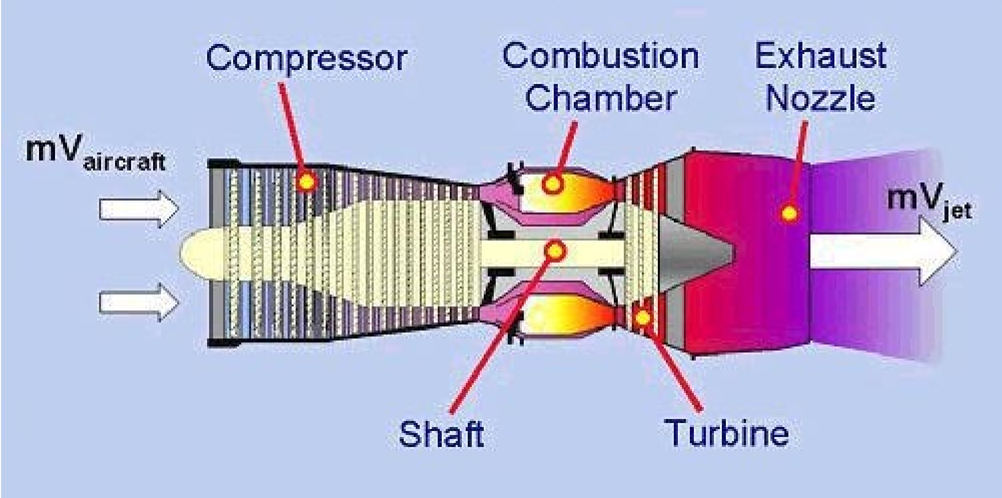
Propeller versus Jet Propulsion

Propeller - moves LARGE MASS of air at low velocity

Jet - moves small mass of gas at HIGH VELOCITY

Jet engine layout

So how is this achieved? A jet engine mechanically compresses the air it receives through a self driven compressor, prior to the combustion stage. The expanding exhaust gases drive a turbine which drives the compressor through the shaft.
These are then accelerated through the exhaust nozzle to produce thrust.



Different jet engine types

The engine in jet engine layout is called a turbojet. In this engine, all the air passes through the compressor, combustor and turbines. This type of engine is very powerful, but it is also very noisy and inefficient. Modern civil and military aircraft therefore use a variation on the turbojet, called the turbofan, or bypass engine. A large fan at the front of the engine feeds some air into the compressor, where it is combusted, whilst the rest is ducted around the outside of the engine and re-mixed with the exhaust gases at exit. The combined lower velocity and greater mass of the jet stream provides a net thrust with high propulsive efficiency (reduced Specific Fuel Consumption - SFC - or fuel consumption per unit thrust). The shroud of slow bypass air exhausted around the high velocity engine core exhaust also reduces the noise level.

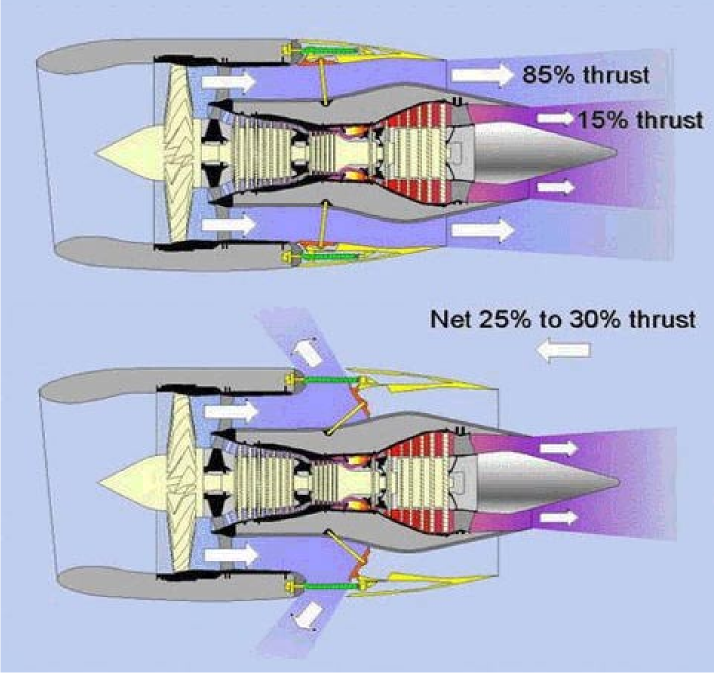
Related to the turbofan is a term called the bypass ratio. This is the ratio of the mass of air going down the bypass stream divided by the mass going through the engine core. The principal difference between modern civil and modern military engines is this bypass ratio. On an air superiority aircraft, such as the Eurofighter, the engine (EJ200) has a bypass ratio of only 0.4. Hence, the mass flow bypassing the engine is equal to 40% of the mass flow passing through the core. By comparison, bypass ratios on large modern civil engines can be as high as 9, with the fan providing over 80% of the total thrust. This is because on a civil aircraft, fuel consumption is the prime driver, whilst on a military engine, performance, or thrust of the engine for a given weight, dominates, along with the need to keep the frontal area of the engine small for supersonic flight.

One other feature unique to military engines is reheat. On this diagram, the two pale yellow blocks protuding into the gas flow downstream of the turbine are in fact the reheat stabilisers. In order to boost thrust, fuel can be added and burnt here, heating up the exhaust gasses and providing them with more energy to produce thrust. On the EJ200 engine, the thrust can be increased from 13,000 lbf without reheat to around 20,000 lbf with reheat. However, the corresponding fuel consumption more than doubles, so this thrust boost is only used briefly during critical manoeuvres such as take-off and in combat.

Reverse thrust

A feature used on both civil and military aircraft engines is reverse thrust. This is where some or all of the airflow exhausting the engine is directed forwards, producing a braking force when aircraft land.

Aircraft must be capable of stopping in the required distance without this force, but it provides an additional safety margin, particularly when the runway is wet. It also helps to reduce wear on the brakes and tyres.



Different jet engine types

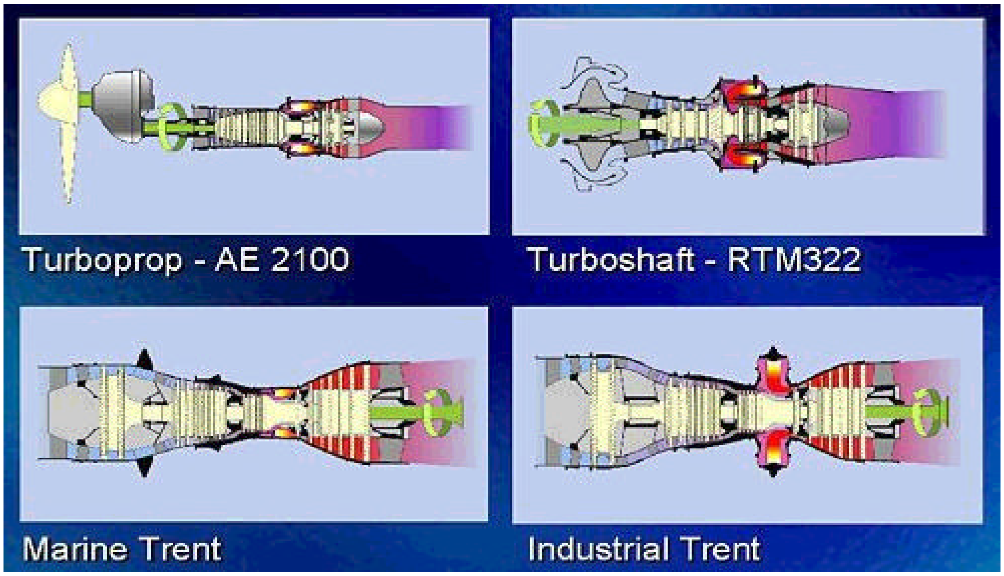
Mechanical drive

The gas turbine can also be used to provide mechanical power. This is achieved by putting more turbine stages at the back of the engine to extract more energy. One such example is the turboprop, where this mechanical power is used to drive a propeller. The example shown within the top right picture is the AE2100 engine which powers the Hercules transport aircraft.

The propeller acts rather like the fan on a turbofan engine, except that the effective bypass ratio is even higher with the exhaust gases providing only a small amount of residual thrust. As with the turbofan, this is achieved by enlarging the turbine, so that more power can be extracted from the exhausting gases, in order to drive the propeller. On modern engines, the extra turbine stages are often mounted on a separate shaft. This is a concept called a free power turbine (i.e. the turbine providing the power output can rotate at its own speed). The rest of the engine then becomes a gas generator. Its sole purpose is to provide exhaust gases at the correct condition to drive the power turbine. The gas generator and free power turbine could theoretically be mounted as separate units, connected by a large pipe, although for practical reasons, it is more convenient to mount the power turbine directly behind the gas generator.

This concept of using an additional turbine to extract mechanical power can be applied to other uses. Within the top right picture is a turboshaft engine (in this case a schematic of the RTM322 which powers the EH101 and Apache helicopters).

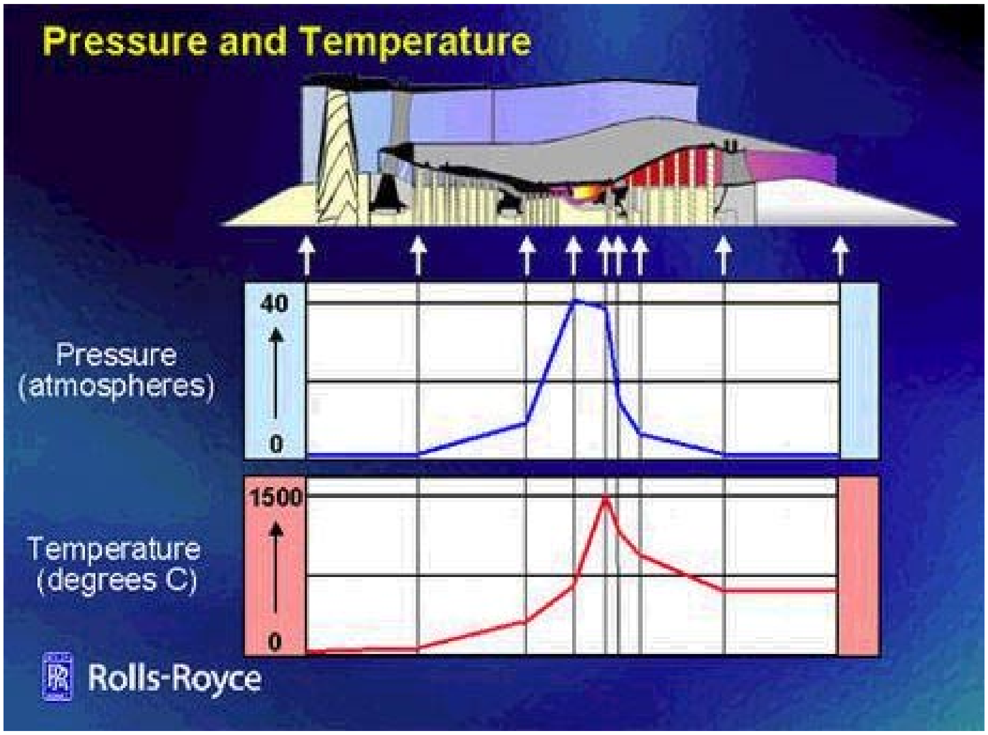
There are two other mechanical drive applications illustrated, the Marine Trent and the Industrial Trent engines. In the marine application, the drive shaft is used to power a propulsive devise such as a ship's propeller or a waterjet. The Industrial Trent provides 50MW, which can be used for electricity generation or to pump oil and gas by driving a separate compressor. Most of the components in both the Marine and Industrial Trent engines come from the Trent civil aero engine. However, the industrial engine, requires a novel combustor design to meet the more stringent ground-based environmental regulations. This type of combustor would not be feasible on an aircraft engine, as it is too large and heavy.



Pressure and temperature

All these engine stages work due to the relationship between pressure, volume and temperature. The product of the pressure and volume of a gas is proportional to the temperature of that gas.

The efficiency of the engine is governed by the maximum pressure and temperature achieved in the centre of the core. Advances in technology have given rise to significant increases. Improvements in compressor aerodynamics enable greater pressure rises to be achieved with fewer components. Combustion and Turbine components now operate in environments significantly in excess of their melting temperatures, requiring extensive cooling. Improvements in materials and cooling technologies have helped to fuel the improvements in efficiency and reduction in weight.



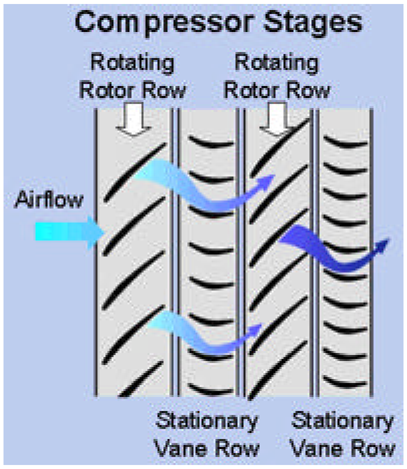
Axial compressor and turbine operation

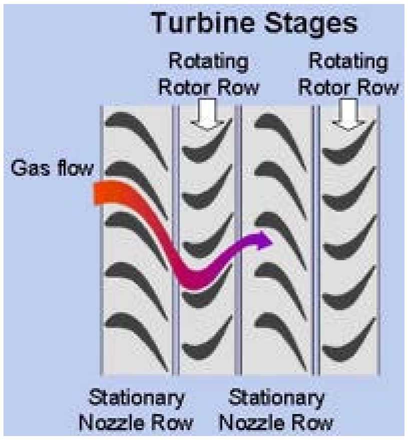
The compressors and turbines that we have seen so far are called axial devices, because the flow is lined up with the axis of the engine. They are made up of a series of rotating and stationary blade rows. A pair of rows (one rotating and one stationary) make up a stage.

In the case of a compressor, a rotating blade row uses the shaft power transmitted from the turbine to accelerates the flow onto stationary vanes. The vanes then convert this kinetic energy of the moving gas into pressure energy.

A turbine works like a compressor in reverse. In this case, the pressure energy in the gas is converted into kinetic or motion energy in a stationary vane row.This is directed onto a rotating row of blades (in this case moving down the page), which absorb the energy to drive the compressor, rather like a windmill.

Improvements in aerodynamics have enabled huge increases to the levels of work we can supply or extract using a single compressor or turbine stage. This has helped improve engine power, weight and cost.





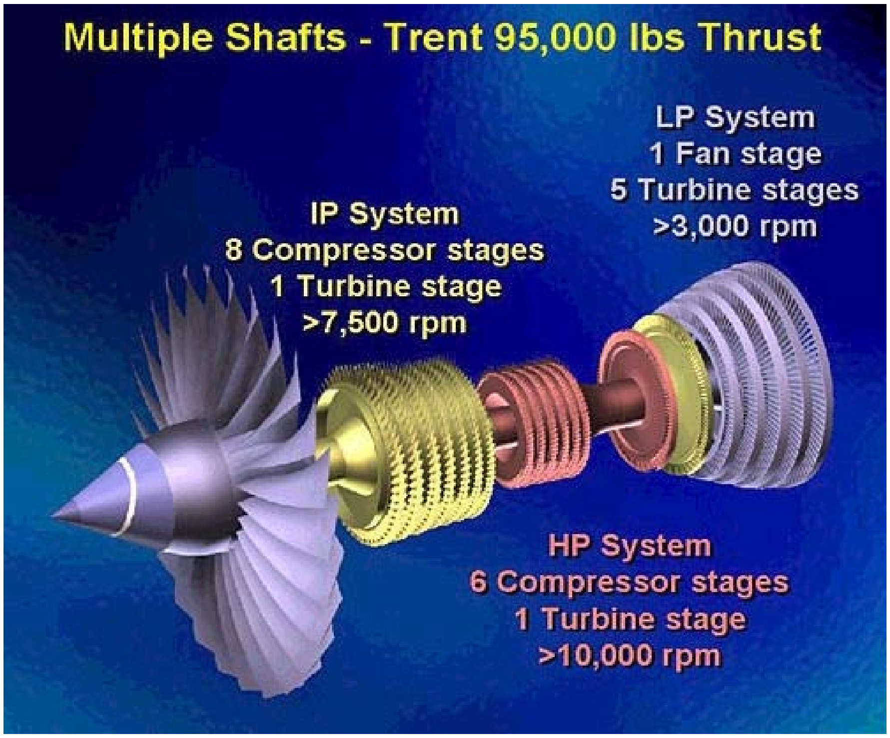
Multiple shafts

These compressor and turbine stages are mounted in series (one behind the other) on a shaft. Most modern engines use multiple shafts to better match the requirements of the different parts of the engine.

The Rolls-Royce RB211 and Trent Engines are unique in having three shafts, as shown here. In this case, only the rotating blade rows are shown, but you can see how many stages there are.

The fan needs to rotate relatively slowly, due to stress limits and blade tip speed requirements. If it rotated too fast, the centrifugal loads would tear it apart and the flow at the blade tip would be highly supersonic, causing shock formations leading to significant efficiency penalties and noise. Because the fan generates so much of the thrust, a large number of turbine stages are required to power it (in this case 5). In fact, this is due to the fact that the fan is compressing a huge mass of air, whereas the turbine only has the engine core air to power it. However, you can see that it is generally much easier to extract work from a turbine than it is to supply it through a compressor, as only single turbine stages are required to power the HP and IP compressors.

As the air going through the engine core is compressed, the blade height and radius reduces. In order to maintain a reasonable blade velocity with the reducing radius, the shaft rotational speed needs to increase. Thus, using three shafts ensures that each compressor and turbine stage can run closer to its ideal operating condition. This means that the engine is lighter, shorter and stronger. Also, each shaft can be scaled independently, making it simpler to build a range of engine sizes based around common technology.

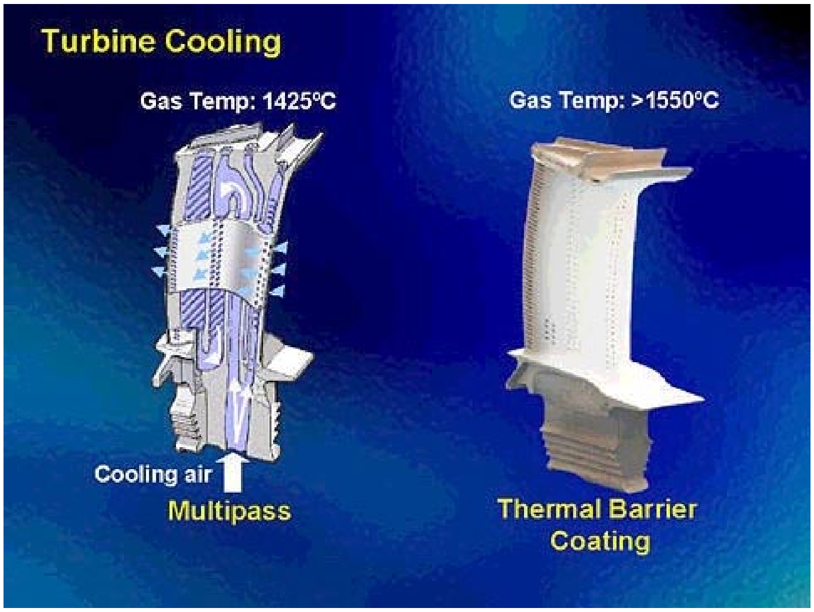


Turbine cooling

Turbines have to survive in conditions hotter than the melting temperature of the metals. This is made possible by passing cooler air through them. However, this air is often over 600°C so is still not exactly cold.

The cooling air absorbs some of the heat as it passes through the blade and is then exhausted through holes in the surface to provide an additional protective blanket.

Further increases in gas temperature can be achieved by coating the blade with a ceramic. This material can withstand higher temperatures than the base metal and acts as a thin insulating layer.



Multipass and thermal barrier coating]

Combustor operation

The combustor is at the heart of the engine, as it is where the fuel is burnt. Without that, the engine would produce no power. Its objective is to burn that fuel efficiently, producing the lowest possible emissions across the entire operating range of the engine.

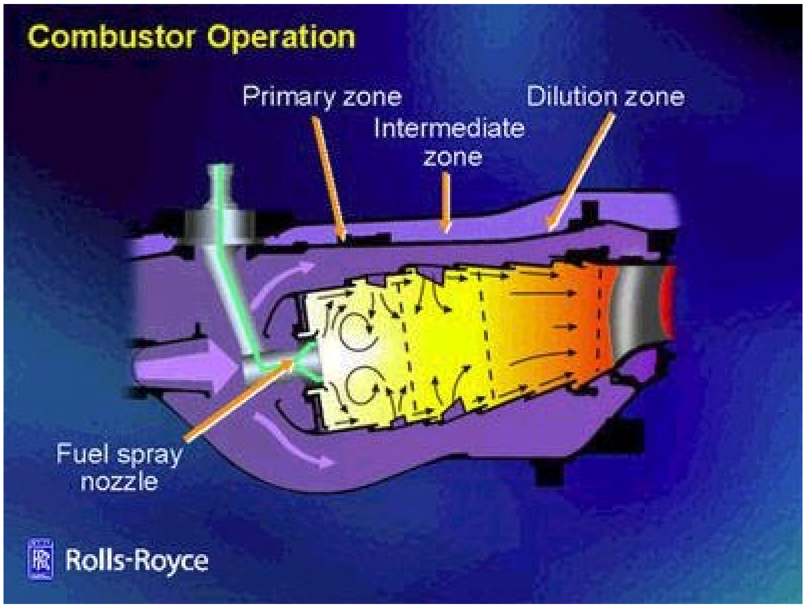
The first task of the combustor is to slow down the air leaving the compressor in the diffuser. This is necessary, as the flame would otherwise be blown out. The front end of the combustor works rather like cupping your hand around a candle flame. This creates a recirculating zone within which the flame can stabilise.

Fuel is injected through a nozzle (burner) into this "dead zone" and is mixed with a small amount of air in the primary zone. This rich mixture (large amount of fuel for a given amount of air, or high fuel to air ratio) ensures that the flame is stable when the engine throttle setting is reduced, even at high altitudes.

More air is then introduced through ports in the combustion chamber walls, as shown by the arrows. The burning then continues into the secondary zone, where the mixture is less rich. However, at the exit of the secondary zone, where almost all of the burning has been completed, the temperatures are still too high. Therefore, additional air is added in the dilution zone to control the temperatures. As stated earlier, the turbine downstream of the combustor has to withstand very high temperatures and stresses, due to the centrifugal loads. These stresses are highest towards the base of the blade, so the radial temperature profile in the combustor is controlled, with the peak temperatures around two thirds of the way up the blade.

As well as all this mixing and dilution, cooling air is also needed to stop the combustion chamber itself from melting. Cooling air is ejected rather like films on turbine blades, providing a protective blanket over the metal. Modern combustors also make extensive use of thermal barrier coatings to further insulate the metal from the extreme gas temperatures.

Marine engines use the same style of combustor as the aerospace counterparts, although the need to accommodate different fuels requires minor modifications to the burners.



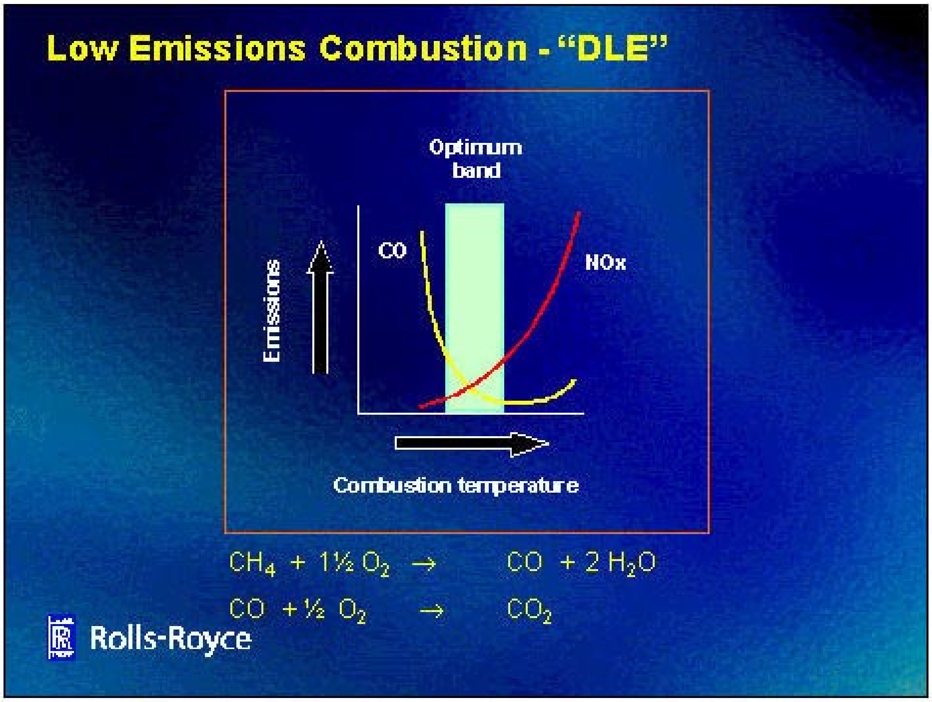
Low emissions combustion

The difficulty in reducing emissions is emphasised by this chart. Carbon monoxide is produced when incomplete combustion occurs. Increasing combustion temperatures improves burning and thus reduces carbon monoxide emissions.

Nitrogen is the dominant element in the atmosphere. Raising the temperature of air causes it to react with oxygen, producing nitrogen oxides (NOx). The higher the air temperature and exposure time to these temperatures, the greater the production of NOx.

There is an optimum band, where both CO and NOx emissions are low. The ideal combustor would therefore always burn fuel within this band, independent of the engine operating condition.

In real aero combustors, there are significant variations in the gas temperatures leaving the combustor, due to variations in the mixing process, along with the fact that there are a discrete number of burners supplying fuel. This has an adverse effect on emissions as well as the turbine operating environment.



Low Emissions Combustion - "DLE"

$CH_4 + 1\frac{1}{2} O_2 \rightarrow CO + 2 H_2O$

$CO + \frac{1}{2} O_2 \rightarrow CO_2$

Rolls-Royce

Reduction in emissions - aero engines

Significant improvements in emissions have been made. With the drive for reduced fuel consumption, engine operating temperatures have increased. This, combined with improvements in mixing, has resulted in substantial reductions in levels of unburnt hydrocarbons and carbon monoxide, which are caused by incomplete combustion.

Nitrogen Oxide emissions increase at higher combustion temperatures. In spite of these raised mean temperatures, improvements in control over burning have reduced the peak gas temperatures and exposure time associated with the hot spots, lowering levels of

NOx. However, less progress has been achieved than with carbon monoxide and unburnt hydrocarbon emissions.